



Master Thesis in Mechanical Engineering

**Development and performance evaluation of
innovative joining processes for cast aluminium
components**

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"Welcome to the real world! It sucks. You're gonna love it."
- Monica Geller

United Nations Sustainable Development Goals

The United Nations Sustainable Development Goals (SDGs), adopted in 2015 as part of the 2030 Agenda for Sustainable Development, establish 17 goals and 169 targets that aim to foster prosperity while protecting the planet. Research in materials engineering and manufacturing contributes to this agenda by developing technologies that promote resource efficiency, innovation, and environmental protection. The present study, which evaluates adhesive bonding and friction stir welding (FSW) of aluminium die-cast alloys for automotive applications, supports several SDGs, particularly SDG 9, SDG 12, and SDG 13.

SDG 9: Industry, Innovation and Infrastructure

Target 9.4 says "upgrade infrastructure and retrofit industries to make them sustainable, with increased resource-use efficiency and greater adoption of clean and environmentally sound technologies". This study supports this target by examining alternative joining methods such as high-performance adhesives and FSW, the work contributes to innovation in manufacturing processes that improve efficiency and reduce environmental impact. The results provide knowledge that can be integrated into industrial practice, thereby strengthening the technological base of the automotive industry in line with **Target 9.5** that says "enhance scientific research, upgrade technological capabilities of industrial sectors".

SDG 12: Responsible Consumption and Production

This work contributes to **Target 12.2** which says "achieve the sustainable management and efficient use of natural resources" and **Target 12.5** that says "substantially reduce waste generation through prevention, reduction, recycling, and reuse". By analysing durability under oil ageing and comparing surface treatments, the study generates data that help to extend the lifetime of adhesive joints in service. Longer-lasting components reduce the need for frequent replacements, minimising raw material use and waste generation. Furthermore, by enabling the reliable use of lightweight aluminium alloys, the research indirectly supports more resource-efficient automotive production and a circular economy approach.

SDG 13: Climate Action

This research aligns with **Target 13.2** saying to "integrate climate change measures into national policies, strategies and planning", as lightweighting is a recognised strategy in both EU and UN frameworks to reduce emissions from the transport sector. By improving the reliability of lightweight aluminium components in vehicles, the study indirectly reduces fuel consumption and greenhouse gas emissions over the vehicle lifecycle. It also supports **Target 13.3** which says to "improve education, awareness-raising and human and institutional capacity on climate change mitigation", as the results contribute to knowledge dissemination in the field of sustainable materials engineering.

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Abstract

This thesis investigates the development of innovative bonding methods for die-cast aluminium components, addressing the increasing demand for lightweight and sustainable joining technologies in the automotive industry. Aluminium alloys, particularly $AlSi_{10}Mg$, offer significant weight reduction and recyclability benefits, yet their joining remains challenging due to oxide layers, casting porosity, and heterogeneous microstructures. To overcome these limitations, two advanced adhesive systems, a cyclic olefin-based hot-melt film (LS-XU) and a silane-modified polymer (Teroson MS 939), were experimentally evaluated and compared. Also, friction stir welding (FSW), a solid-state joining process, was evaluated as a different innovative process, besides adhesive bonding.

Experimental work encompassed single lap joint testing under various surface preparations (degreasing, sanding, and phosphoric acid anodization), durability assessments under hydraulic oil immersion, 90° peel tests, and internal pressure tests. Surface energy characterisation provided further insight into the effect of as-cast versus machined substrates. Complementary finite element models, implemented in ABAQUS®FE using cohesive zone modelling, were developed to replicate experimental behaviour and validate the observed joint responses.

Results showed that adhesive type and surface treatment strongly influence performance. LS-XU joints consistently failed adhesively, with anodized surfaces showing the best performance, though oil ageing caused severe shrinkage and loss of integrity. Teroson MS 939 joints exhibited more ductile responses, and cohesive or mixed failure modes, confirming superior energy absorption. Peel testing confirmed its greater viscoelastic dissipation (~ 4.4 N/mm) compared with LS-XU (~ 3.2 N/mm). Internal pressure tests also highlighted its superior capacity, sustaining loads above 4 kN versus LS-XU's brittle failure below 2.5 kN. FSW, by comparison, delivered an order-of-magnitude higher peel resistance (~ 80 N/mm) and superior pressure capacity, reinforcing its role in safety-critical joints.

Numerical simulations reproduced experimental load-displacement curves, validating cohesive zone modelling as a predictive design tool, with hyperelastic-cohesive model for the MS polymer and traction-separation formulation for the adhesive debonding of LS-XU.

Concluding, the research highlights the potential of MS polymer adhesives for semi-structural and sealing applications in automotive assemblies, while confirming FSW as the most robust option for primary structural joints. Cyclic olefin-based HMA, despite offering dimensional stability, are unsuitable for oil-rich environments. By clarifying the interplay between adhesive chemistry, surface treatment, and substrate condition, this thesis provides a scientific basis for adopting innovative bonding methods in aluminium-intensive vehicles.

Keywords: Die-cast aluminium, adhesive bonding, friction stir welding

Resumo

Esta dissertação investiga o desenvolvimento de métodos inovadores de união para componentes em alumínio fundido sob pressão. As ligas de alumínio, em particular a $AlSi_{10}Mg$, oferecem benefícios significativos em termos de redução de peso e reciclabilidade, na indústria automóvel, mas a sua união é um desafio devido às camadas de óxido, porosidade e microestruturas heterogêneas. Para ultrapassar estas limitações, foram avaliados experimentalmente dois sistemas adesivos avançados — um *hot-melt* (HMA) à base de olefinas cíclicas (LS-XU) e um polímero modificado com silano (Teroson MS 939) — e comparados entre si. Além disso, *friction stir welding* (FSW), um processo de soldadura em estado sólido, foi também estudado como alternativa inovadora à ligação adesiva.

O trabalho experimental incluiu ensaios de juntas sobrepostas simples com diferentes preparações de superfície (desengorduramento, lixagem e anodização), testes de durabilidade por imersão em óleo hidráulico, ensaios de descolagem a 90° e testes de pressão interna. A caracterização da energia superficial forneceu informação adicional sobre o papel das condições de substrato em estado fundido e maquinado. Modelos numéricos complementares, desenvolvidos em ABAQUS®FE com recurso a *cohesive zone modelling*, foram implementados para reproduzir o comportamento experimental e validar as respostas observadas.

Os resultados mostraram que o tipo de adesivo e o tratamento de superfície influenciam fortemente o desempenho. As juntas com LS-XU apresentaram falhas adesivas, com a anodização a melhorar a resistência, mas revelaram perda de integridade após envelhecimento em óleo. As juntas com Teroson MS 939 exibiram falhas coesivas ou mistas e melhor absorção de energia. Os ensaios de descolagem confirmaram a sua maior dissipação viscoelástica (~ 4.4 N/mm) em comparação com LS-XU (~ 3.2 N/mm). Nos testes de pressão interna destacou-se igualmente, suportando cargas superiores a 4 kN, enquanto o LS-XU falhou de forma frágil abaixo de 2.5 kN. Já FSW apresentou uma resistência ao descolamento uma ordem de grandeza superior (~ 80 N/mm) e maior capacidade de pressão, reforçando o seu uso em uniões estruturais críticas.

As simulações numéricas reproduziram as curvas experimentais de força – deslocamento, validando o *cohesive zone modelling* como ferramenta preditiva de projeto, com o modelo hiperelástico-coesivo para o polímero MS e a formulação tração – separação para a descolagem adesiva do LS-XU.

Concluindo, a investigação destaca o potencial dos adesivos poliméricos MS para aplicações semi-estruturais e de vedação em componentes automóveis, sendo FSW a opção mais robusta para uniões estruturais primárias. Os HMA à base de olefinas cíclicas revelaram-se inadequados para ambientes com exposição a óleos.

Palavras-chave: Alumínio fundido, ligações adesivas, *friction stir welding*

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1 Introduction

1.1 Background and motivation

Aluminium is one of the most widely used engineering materials due to its favourable combination of properties, including high strength-to-weight ratio, corrosion resistance, excellent formability and recycling potential [1]. However, the successful utilisation of aluminium in structural applications is highly dependent on the development of reliable bonding methods. Unlike steel, which can often be welded with relative ease, aluminium presents intrinsic challenges for joining. Its surface is rapidly covered by a stable aluminium oxide film, which hinders wetting during welding and reduces adhesion in bonded joints. In addition, aluminium's high thermal conductivity and low melting temperature complicate fusion-based welding processes, while its relatively low modulus of elasticity makes it sensitive to stress concentrations that often arise in mechanically fastened joints [2]. As a result, the performance of aluminium structures is strongly influenced by the quality of the joints, which frequently become the critical points determining overall strength, fatigue resistance, and long-term durability.

The importance of effective bonding methods has grown as aluminium has become increasingly central to the automotive industry. Driven by environmental regulations and the push for lightweight design, manufacturers are replacing heavier steel components with aluminium, particularly in body-in-white and structural assemblies [1, 3]. Die-cast aluminium, in particular, offers substantial advantages for the automotive sector, as it enables the economical production of complex geometries with high dimensional accuracy [3]. Yet, the very features that make die-cast aluminium attractive also introduce difficulties in joining: porosity, oxide inclusions, and microstructural heterogeneity compromise the performance of conventional bonding techniques [4].

Thus, while the use of aluminium supports the broader goals of improved fuel efficiency and reduced emissions, the development of innovative joining methods remains essential to unlock its full potential. The automotive industry, with its demanding requirements for safety, crashworthiness, and long-term reliability, provides a critical testbed for such advances. Among the most promising options are adhesive bonding, which enables uniform stress distribution, joining of dissimilar materials, and enhanced rigidity and crash resistance in aluminium structures [5]. Also, there is friction stir welding (FSW), a solid-state process that produces high-integrity aluminium joints with minimal distortion and superior mechanical properties [6]. Together, these methods represent significant progress beyond conventional fastening and fusion welding, and showcase the industry's shift toward more reliable, efficient, and lightweight joining strategies.

1.2 Objectives

The aim of this thesis is to investigate and compare advanced joining techniques for aluminium alloys, with a particular emphasis on adhesive bonding and friction stir welding (FSW), in order to evaluate their performance and applicability within the automotive industry. The study seeks to provide a deeper understanding of the mechanical behaviour of aluminium joints, the influence of surface preparation, and the potential of solid-state processes such as FSW to address the challenges traditionally associated with aluminium joining. To achieve this objective, a combination of experimental testing and numerical analysis was carried out. Single lap joint tests, durability tests, peel tests, and internal pressure tests were performed to characterise the mechanical performance of the joints under representative service conditions. In parallel, finite element models were developed in ABAQUS®FE to replicate the single lap joint and internal pressure tests, thereby providing additional insight into stress distributions and damage mechanisms, and complementing the interpretation of the experimental results.

1.3 Research methodology

To achieve the objectives of this thesis, the research was organised into four complementary stages that combined literature analysis, laboratory testing, and numerical modelling:

- **Literature review:** Survey of innovative bonding methods such as adhesive bonding and friction stir welding (FSW), with focus on aluminium alloys and industrial applications in the automotive sector.
- **Experimental work:** Preparation of aluminium single lap joints using adhesives under three surface conditions (degreased, sanded, anodized), performing durability tests, peel tests and internal pressure tests. For FSW peel and internal pressure tests were also done.
- **Numerical analysis:** Development of finite element models using cohesive zone modelling (CZM) to simulate adhesive layer behaviour and obtain numerical validation of results.

1.4 Thesis outline

This thesis is structured into seven main sections. The introductory chapter outlines the background and motivation of the study, presents the research problem, and defines the objectives pursued throughout the work.

Chapter 2 starts with a review on the state of the art in the field of aluminium bonding methods, with a conventional methods review. Then, innovative methods

as adhesive bonding and friction stir welding are extensively reviewed, with process details and relating them to the context of this thesis.

Chapter 3 clarifies the experimental procedures used throughout this work, as well the manufacture of the specimens for the test performed and materials used.

Chapter 4 presents the results and discussion of the testing done throughout this thesis, following the experimental procedures.

Chapter 5 presents the finite element modelling approaches adopted in this study and discusses the corresponding numerical validation.

Chapter 6 presents the summary of the appended papers, focusing on a brief description of their objectives and main conclusions.

Chapter 7 aggregates the main conclusions obtained during this research project, as well as suggestions to further improve and/or continue the work developed.

2 Literature review

The performance and durability of aluminium structures are closely tied to the effectiveness of the bonding methods employed. A wide range of techniques has been developed for joining aluminium, from traditional mechanical fastening and welding to more recent innovations such as adhesive bonding and friction stir welding. Each method offers distinct advantages and limitations, particularly when applied to die-cast aluminium components, where porosity, oxide layers, and microstructural features can make the joining process more complex.

This literature review first examines conventional approaches, including mechanical fastening and welding methods, before focusing on adhesive bonding and friction stir welding as innovative alternatives that have gained increasing relevance in automotive applications.

2.1 Conventional bonding methods for aluminium

The selection of appropriate bonding techniques for aluminium has long been influenced by its distinct material characteristics. The presence of a stable surface oxide layer, high thermal conductivity, and relatively low modulus of elasticity complicates many traditional joining processes. These factors often result in joints that are prone to premature failure, whether through stress concentrations in mechanically fastened assemblies or through porosity and cracking in welded structures [7,8]. Despite these limitations, mechanical fastening and welding have historically been the most common approaches for joining aluminium.

2.1.1 Mechanical fastening

Mechanical fastening techniques, such as riveting, bolting, and the use of threaded fasteners, have been extensively employed in aluminium structures due to their simplicity and well-established design principles. Their advantages include ease of assembly, disassembly for maintenance, and independence from metallurgical compatibility issues, making them a practical choice for early applications of aluminium [8].

However, when applied to aluminium, particularly die-cast alloys, these methods introduce several drawbacks. The drilling or punching of holes required for fasteners leads to stress concentrations, which are especially detrimental given aluminium's lower elastic modulus and limited fatigue strength compared to steel. In die-cast components, pre-existing porosity and inclusions further exacerbate the risk of crack initiation around fastener sites [9,10]. Additionally, the added mass of fasteners undermines the lightweighting benefits of aluminium, while galvanic corrosion becomes a concern when fasteners are made from dissimilar metals and exposed to humid or saline environments.

Self-piercing rivets (SPR) have been developed as a refinement of conventional riveting, eliminating the need for pre-drilled holes and providing strong mechanical interlocking between sheets [8]. SPR only rose to prominence in recent decades, initially through its adoption by Audi for joining structural panels in the all-aluminium Audi A8. Its subsequent application expanded to space frame designs, such as the Audi A2, and later to monocoque structures exemplified by Jaguar, marking a significant progression in its use within aluminium-intensive vehicle manufacturing [11]. Nevertheless, for die-cast aluminium, the brittle microstructure and variable thickness of castings limit the applicability of SPR, as the high local deformation required during riveting can induce cracking [3]. As such, while mechanical fastening remains relevant, its limitations in die-cast applications highlight the need for alternative bonding methods. The fundamental steps of the self-piercing riveting process, including rivet penetration, flaring, and the formation of a mechanical interlock, are illustrated in Figure 1, providing a clear visualisation of how this technique eliminates the need for pre-drilled holes.

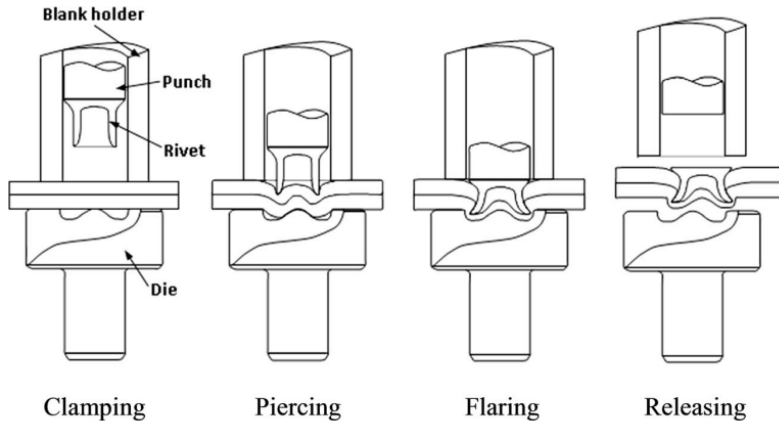


Figure 1: Schematic diagram of the four stages of a SPR process, [12].

2.1.2 Fusion welding methods

Fusion welding processes, including metal inert gas (MIG) and tungsten inert gas (TIG) welding, have traditionally been used to join aluminium components. For wrought aluminium alloys, these processes can deliver satisfactory joints when carefully controlled. However, aluminium's high thermal conductivity necessitates high heat input, leading to significant distortion, while its low melting temperature increases the risk of burn-through in thin sections [13]. In die-cast alloys, these challenges are compounded by porosity and entrapped gases, which often manifest as weld porosity and hot cracking, thereby reducing joint integrity [3].

Resistance spot welding (RSW), a dominant joining method for steel automotive structures, has also been adapted to aluminium but with limited success. Aluminium's higher electrical conductivity and lower electrical resistance require sub-

stantially greater currents than steel, accelerating electrode wear and reducing process efficiency. Furthermore, the persistent oxide layer disrupts current flow and leads to inconsistent weld quality. For die-cast aluminium, these problems are particularly acute, rendering RSW unsuitable for most applications beyond simple sheet assemblies [14].

Overall, welding methods are constrained by aluminium's metallurgical characteristics, especially in die-cast alloys where porosity and oxide inclusions are unavoidable. While mechanical fastening and welding remain widely used in certain aluminium structures, their limitations in the context of die-cast components have driven research toward more advanced bonding technologies that can deliver higher structural reliability and durability.

2.2 Adhesive bonding of aluminium

Adhesive bonding is one of the oldest joining techniques, with origins in natural resins and glues used since antiquity. Its modern engineering relevance began with the development of synthetic polymers such as phenolics and epoxies in the early 20th century. A decisive breakthrough occurred during World War II, when bonded aluminium honeycomb panels were introduced in aerospace, demonstrating that adhesives could provide lighter and stiffer structures compared to riveted joints. Since then, adhesive bonding has been widely adopted across aerospace, automotive, construction, and electronics industries, supported by continuous advances in adhesive formulations and processing methods [15, 16].

Compared with welding or fastening, adhesive bonding provides continuous load paths, reducing stress concentrations and improving fatigue resistance. Unlike fusion welding, it avoids heat-affected zones and associated defects such as porosity or hot cracking, which are especially problematic in die-cast alloys [17]. This demonstrated the potential of adhesives to reduce weight, increase stiffness, and distribute stresses more uniformly than welded, riveted or bolted joints.,

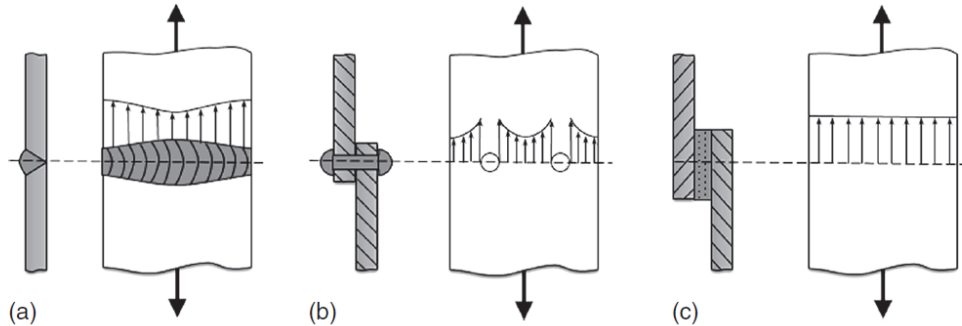


Figure 2: Stress distribution as a function of (a) welding, (b) riveting, and (c) bonding technologies [16].

The performance of bonded joints is often interpreted through several comple-

mentary theories of adhesion, each highlighting different mechanisms at the adhesive-substrate interface. The mechanical interlocking mechanism describes how adhesion can result from the penetration of adhesive into surface roughness or porosity. Adsorption theory focuses on the establishment of molecular interactions such as van der Waals forces, hydrogen bonding, or even covalent bonds. The electrostatic theory attributes adhesion to charge-based attractions between adhesive and substrate surfaces. Finally, diffusion theory explains bonding as a consequence of molecular interpenetration across the interface. These mechanisms often operate in combination to provide better adhesion. For metallic substrates such as aluminium, where inert oxide layers and contamination can limit direct bonding, adhesion is best explained as the union of adsorption, mechanical interlocking, and chemical interactions [16,18]. Figure 3 presents a scheme of all theories of adhesion previously mentioned.

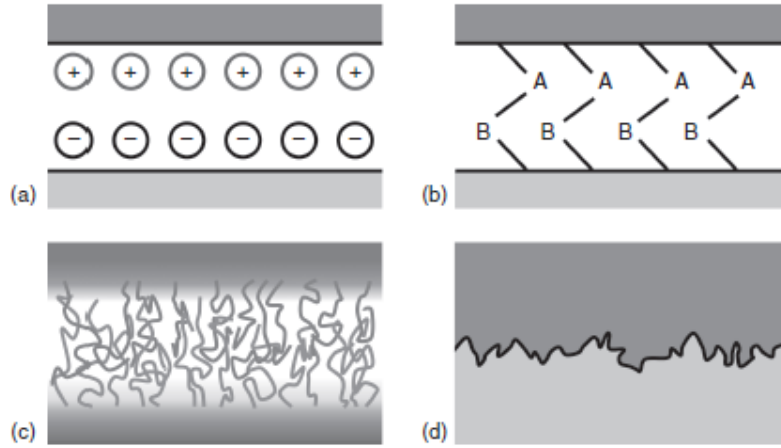


Figure 3: Bonding mechanisms: (a) electrostatic attraction, (b) adsorption, (c) diffusion and (d) mechanical interlocking [16].

Adhesive bonding also allows joining dissimilar materials (e.g., aluminium-to-steel or aluminium-to-composite), which is central to contemporary multi-material lightweight vehicle structures. In practical applications such as automotive body-in-white designs, adhesives offer additional utility by functioning as sealants and providing vibration damping—enhancing NVH (noise, vibration, harshness) performance while enabling streamlined surface aesthetics [5,8].

In the automotive industry, adhesive bonding has become indispensable for joining aluminium parts within weight-critical, high-performance architectures. Its capability for rapid curing, crash performance enhancement, and joining of dissimilar substrates aligns well with the demands of modern vehicle manufacture. However, these benefits must be balanced against challenges of cycle time, impact durability, environmental resilience, and end-of-life sustainability.

One of the main challenges in adhesive bonding is the presence of a weak bound-

ary layer on the substrate surface, formed by contaminants, loosely bound oxides, or residues from manufacturing. This layer often becomes the preferred path for failure, reducing bond strength and durability. Overcoming this issue requires deliberate surface preparation, which eliminates or stabilises the weak layer and ensures a robust interface for adhesion, as discussed in the following section.

2.2.1 Aluminium surface treatments

The performance and durability of adhesive joints in aluminium alloys are strongly influenced by the state of the surface. Aluminium naturally forms a stable oxide film (Al_2O_3) which, while protective against corrosion, is chemically inert and inhibits wetting and adhesion. In die-cast aluminium, this challenge is compounded by surface contamination from mould release agents and microstructural heterogeneities, which further impair bond quality. For these reasons, surface pre-treatment is considered one of the most decisive steps in achieving reliable and durable adhesive bonds [5, 8, 17].

Surface treatments are required to make the adherend receptive to the adhesive, ensuring that the surface is mechanically sound and resistant to ageing, corrosion, and applied loading. Their main purpose is to create the physical and chemical conditions necessary for reliable adhesion. This involves removing weak boundary layers such as oils or oxides, increasing surface energy to maximise molecular contact during curing, creating textures or porous structures that enhance stress distribution, and passivating the surface to protect it from contamination or corrosion [18].

Surface treatment technologies for aluminium alloys can be broadly divided into mechanical, chemical and electrochemical treatments [18–20]. Mechanical treatments, including machining, sanding, and grit blasting, increase surface roughness and promote mechanical interlocking. While relatively simple and cost-effective, they may embed abrasive particles into the substrate and provide limited durability, which is why they are often combined with other methods.

Chemical treatments focus on altering surface chemistry through wet processes. Alkaline degreasing and acid pickling are widely used to remove contaminants and oxides. Conversion coatings, particularly silane-based systems, are increasingly employed as sustainable alternatives to chromates. Silanes form covalent bonds both with the aluminium oxide surface and with adhesive functional groups, improving adhesion and providing good durability under humid and thermally cycled conditions [21].

Inside electrochemical treatments, anodising is the most prominent example of an electrolyte process, particularly suited for aluminium because it transforms the naturally unstable oxide layer into a controlled, reproducible structure, composed of a dense barrier layer that protects against corrosion and a porous outer layer that enhances adhesive bonding [5, 18].

Among the various anodising processes applied to aluminium for adhesive bonding, chromic acid anodising (CAA), sulphuric acid anodising (SAA), and phosphoric acid anodising (PAA) are the most relevant.

CAA forms a thin, compact oxide with excellent corrosion resistance and good primer adhesion (typical thickness $\sim 0.5 - 2.5 \mu\text{m}$), but its reliance on hexavalent chromium has brought stringent regulatory pressure (e.g., EU REACH “sunset” dates and ongoing restriction proposals), prompting a sustained shift away from CAA in many sectors [22].

SAA generates thicker oxide layers, typically around $5 \mu\text{m}$, with fine pores that improve adhesion and provide reasonable corrosion resistance at relatively low cost, making it attractive for some industrial applications. However, SAA-treated joints tend to lose performance more quickly under hot-wet or cyclic conditions [18,20].

In contrast, the anodic film generated in PAA consists of two parts: a dense inner barrier layer that provides corrosion protection and a porous outer layer with large, uniform pores. This porous morphology is critical because it allows primers and adhesives to penetrate the oxide and establish both mechanical interlocking and chemical bonding. This structure provides superior bond strength and long-term durability, particularly in humid environments, and explains why PAA has become the benchmark treatment in critical bonding applications, increasingly preferred over both CAA and SAA despite its higher process complexity [5, 18, 22]. Figure 4 shows an idealised cell structure for the growth of an oxide after anodisation surface preparation (typical cell wall thickness and pore diameters for aluminium shown) [16].

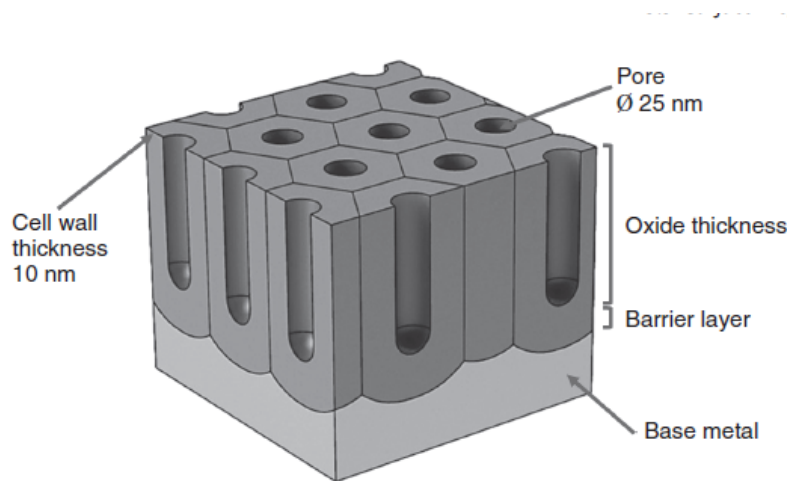


Figure 4: Ideal anodic film generated in PAA, for aluminium substrates [16].

2.2.2 Adhesive classification

Adhesives are best organised using several complementary classifications rather than a single taxonomy, because selection and qualification depend on chemistry,

the nature of the solid network, the cure mechanism, the form of supply, and the intended engineering function.

A chemistry-based classification groups systems by the polymer network they form, for example epoxide, urethane, silicone, acrylic, cyanoacrylate, or imide. Chemistry signals typical ranges of stiffness, toughness, glass-transition temperature, and substrate affinity, so it is the natural first filter at concept stage. The standard monographs use chemistry as the backbone for comparing families and for anticipating interfacial behaviour on metals and polymers [23–25].

A second axis classifies adhesives by the morphology of the solid network after cure, namely thermoset, thermoplastic, or elastomeric. Thermosets create an irreversible crosslinked network with higher creep resistance and typically higher service temperature. Thermoplastics solidify without crosslinking and can later be softened by heat, which aids reworkability and forming but limits performance at elevated temperature. Elastomeric networks prioritise extensibility and energy dissipation, improving peel tolerance and impact resistance at the cost of stiffness. Viewing the adhesive through this network lens links material choice to joint compliance, allowable strain, and the operational temperature window [16, 23, 26].

A third and highly practical axis is cure mechanism and activation. This classification focuses on how the network forms and how the process is triggered in production. Representative mechanisms include polyaddition and polycondensation, free-radical polymerisation, and ionic polymerisation. Activation may be thermal, moisture-driven, anaerobic on active metals, ultraviolet, or electron beam. Delivery may be one-part or two-part, with direct consequences for pot life, green strength, fixture time, and process robustness. This axis is essential for planning mix-meter-dispense operations, setting heat schedules, and defining in-line quality controls [16, 26, 27].

A fourth axis considers form factor and formulation. Adhesives are supplied as films, pastes, cartridges, pellets intended for hot-melt application, and pressure-sensitive tapes. They may be solvent-borne, water-borne, or one hundred percent solids. Form factor governs rheology, wetting, gap-filling capability, fillet control, volatile content, and compatibility with automated deposition. It also determines how readily the process can comply with environmental and occupational requirements, including limits on volatile organic compounds and the need for enclosed dispensing cells [16, 25, 28].

An engineering or functional axis separates structural, semi-structural, and non-structural or sealant systems based on performance in standard tests and on retention after environmental conditioning. Structural systems are expected to deliver durable shear strength and fracture toughness with retention after hot-wet exposure. Semi-structural systems trade stiffness for peel and impact tolerance where compliance and energy absorption are required. Non-structural and sealant systems

prioritise sealing, movement accommodation, and weathering performance. This functional lens connects directly to design allowables, safety factors, and validation plans in transport and other safety-critical sectors [16, 18, 24].

A final axis organises adhesives by service class. The same nominal strength can be acceptable or unacceptable depending on the time and environment in which it must be retained. Temperature class, resistance to humidity and hydrolysis, resistance to fuels, oils, and solvents, and stability under ultraviolet radiation and ozone are central to this classification. At this stage the interaction between surface pretreatment and environment is also considered, since durable performance depends on a compatible interface as well as a suitable bulk network [16, 23, 24].

In practice, effective selection combines all of these schemes. Chemistry and network type narrow the field to candidates with appropriate intrinsic properties. Cure mechanism and form factor align those candidates with manufacturing constraints and quality assurance. Functional and service classifications then determine whether the adhesive can meet the operating envelope and lifetime requirements of the joint, given the chosen substrates and surface pretreatments [16, 25, 26].

MS polymer adhesives

Modified-silane polymer adhesives, more commonly known as silyl-terminated polyethers (STPEs), have emerged over the last decades as versatile alternatives to traditional polyurethane and silicone systems. These materials were first commercialised in the late 1970s under the trade name “MS Polymer,” developed by Kaneka, but the terminology has since expanded to include designations such as silane-modified polymers (SMPs) and silyl-modified polyethers [29, 30]. Their chemical structure is based on a polyether backbone terminated with trialkoxysilane functional groups, which undergo hydrolysis and condensation in the presence of ambient moisture. This mechanism forms siloxane crosslinks that provides elasticity, adhesion, and durability, while avoiding the release of corrosive by-products such as acetic acid in acetoxysilanes or hazardous isocyanates in polyurethane systems [25, 31]. As a result, they occupy a hybrid position between silicones and polyurethanes, combining the favourable handling, weathering, and paintability characteristics of both chemistries.

The curing process of these adhesives is central to their performance. Hydrolysis of the terminal alkoxysilanes generates silanols, which subsequently condense to form Si–O–Si crosslinks. The presence of suitable catalysts accelerates this reaction and influences cure depth, speed, and final mechanical properties. Historically, organotin catalysts dominated, but the drive towards environmentally safer alternatives has led to the widespread adoption of tin-free systems, such as organotitanates, guanidines, and amidines [32]. This shift reflects both regulatory pressures and industry demand for adhesives with lower toxicity and improved sustainability profiles. The

versatility of formulation is further enhanced by the incorporation of fillers, plasticisers, adhesion promoters, and tackifiers, which allow tailoring of the final product to meet diverse application requirements, from elastic sealants to high-strength adhesives [25].

In terms of material performance, modified-silane polymer adhesives are characterised by strong, often primerless adhesion to a wide range of substrates, including metals, plastics, mineral materials, and painted surfaces. This broad compatibility is attributed to the silane chemistry, which provides a balance of polar and non-polar interactions at the interface [18]. Unlike silicones, these polymers are reliably paintable, including under wet-on-wet conditions, and unlike polyurethanes, they are free from isocyanates and solvents, thereby achieving low volatile organic compound (VOC) emissions [33]. Their resistance to ultraviolet radiation is superior to polyurethanes, which often degrade under long-term exposure, although silicones remain the most stable under extreme weathering [5]. Mechanical properties are highly tunable, ranging from low-modulus sealants to tougher adhesive formulations, with elongation at break values that allow for substantial joint movement without cohesive failure. Many commercial products comply with ISO 11600 classification, particularly the F-25LM category, which requires low modulus behaviour and the capacity to accommodate 25% joint movement [34].

Despite their many advantages, modified-silane polymer adhesives exhibit limited resistance to harsh chemicals, such as solvents and fuels, when compared to polyurethane systems, and their maximum service temperature is generally lower than that of silicones, which are engineered for high-temperature resilience [33]. Similarly, while adhesion to metals, coated substrates, and plastics is often primerless, bonding to glass and ceramics may require primers or specially formulated grades [5]. These boundaries of performance have defined the niche for modified-silane polymer adhesives, positioning them as a complementary technology rather than a universal replacement.

The automotive industry provides a particularly relevant context in which to examine their use. Modified-silane polymer adhesives are used for body seam sealing and trim attachment in paint-shop and final-assembly operations, where paintability and primerless adhesion are decisive advantages [33,35]. The ability to apply sealants during the body shop process and subsequently over-paint them without surface defects simplifies manufacturing workflows and ensures aesthetic consistency across the vehicle body. Their elastic character allows them to absorb vibration and accommodate differential thermal expansion between joined materials, contributing to improved noise, vibration, and harshness (NVH) performance [36]. Compared with polyurethane-based sealants, they offer superior resistance to ultraviolet degradation in exterior seams, reducing the risk of chalking and cracking, and their solvent, and isocyanate-free formulations help manufacturers meet stringent occupational

health and environmental standards [18]. However, in critical applications such as direct glazing, under-hood joints, or regions exposed to fuels and high temperatures, polyurethane and silicone adhesives remain dominant due to their higher resistance in these specific conditions [37]. Consequently, the role of modified-silane polymer adhesives in the automotive sector is best defined as providing durable, paintable, and environmentally favourable solutions for non-structural sealing and bonding, thereby complementing rather than supplanting the more specialised chemistries in demanding load-bearing or high-exposure areas.

Hot-melt adhesives

Thermoplastic adhesives, commonly referred to as hot-melt adhesives (HMA), are solids at room temperature that soften on heating, flow to wet the adherends, and regain strength on cooling. This reversible softening enables controlled debonding and rework when heat is reapplied, which is one reason HMAs are widely used in high-throughput assembly and temporary fixturing. Their processability rests on thermal variables rather than immediate chemical cure: viscosity in the melt governs wetting, “open time” defines the period after application during which parts can still be joined, and “set time” is the interval to achieve useful handling strength as crystallisation or vitrification proceeds. These features eliminate solvent drying and the associated volatile organic compound emissions, which is advantageous for health, safety, and environmental compliance [18, 25, 26, 38].

Formulation follows a well-established architecture. A representative unfilled HMA contains roughly one third base polymer, one third tackifier resin, one third wax, and about one percent antioxidant, although the exact ratios are tuned to the substrate and process window [38]. The polymer provides cohesive strength, hot tack, and the basic thermal envelope. The tackifier lowers melt viscosity, promotes wetting, and contributes to dissipative energy under peel. The wax package sets open time and set speed by controlling crystallisation kinetics and can raise heat resistance by increasing the softening point of the solidified blend. Stabilizers limit thermo-oxidative degradation during residence in the melter and recirculation through applicators [39, 40]. The resulting bond is sustained by mechanical interlocking, chain diffusion where possible, specific interfacial interactions, and van der Waals forces. Durable performance depends on achieving adequate wetting and interfacial compatibility during the short molten stage [18, 25].

Two technology paths are most relevant in engineering design. Non-reactive HMAs such as EVA, APAO, polyamide, and saturated polyester blends develop strength solely by cooling, so their creep resistance and peel-versus-shear balance track the viscoelastic spectrum between the glass transition at the low end and softening or melting at the high end. Reactive HMAs, exemplified by moisture-curing polyurethane hot-melts, are applied as melts for rapid handling strength

and then build a lightly crosslinked network post-assembly, which elevates heat resistance and suppresses creep relative to the purely thermoplastic baseline [18,26]. In both families, the interplay among base polymer, tackifier compatibility, and wax crystallisation determines failure temperatures in standard creep-type tests and the locus of failure under peel or cleavage [39].

Because HMAs wet and solidify against the adherend, surface state and joint design are central to performance. High-energy, clean surfaces favour adhesive failure transitions toward cohesive modes. Plasticisers or oils in substrates, or insufficient wetting within the open time, drive the opposite outcome. Practical specifications therefore pair room-temperature shear data with temperature-dependent peel and creep metrics that reflect the intended service envelope [41].

These attributes underpin broad industrial use. In electronics manufacturing, debondable tapes and temporary wafer-support systems rely on thermal-release or UV-release pressure-sensitive formulations that hold dies during dicing and processing, then release on stimulus to avoid damage and residue [42,43]. In packaging, HMAs dominate case and carton sealing and have enabled intelligent labels that integrate CO_2 -responsive colorimetric systems for freshness indication within modified-atmosphere packs, providing a reversible visual signal without solvent-based coatings [44]. In transportation and general product assembly, hot-melts are used for trim, carpets, wire harness fixation, headliners, foams, and other non-structural or semi-structural tasks where rapid set and controlled peel are desirable and service temperatures are moderate [26,39].

A current development route targets multi-material hot-melts based on cyclic olefin copolymers (COCs). COCs are amorphous thermoplastics produced from norbornene and ethylene that offer tunable glass-transition temperature, very low water sorption, high chemical resistance, optical clarity, and good dimensional stability [45,46]. These properties make COCs attractive matrix candidates for HMAs that must bridge dissimilar substrates while maintaining tight tolerances and moisture-robust performance. The literature on COC processing and bonding provides a toolbox to manage polarity and interfacial adhesion. Oxygen plasma, UV-ozone, and vacuum-UV treatments raise surface energy and introduce polar functionality. Solvent-assisted and “tacky-layer” routes enable rapid, low-temperature COC–COC bonding without channel deformation, and can withstand significant internal pressures without leakage when properly executed [46–48].

For automotive bonding, cyclic olefin copolymer-based hot-melt systems offer a useful but nuanced trade-off: their amorphous hydrocarbon backbone yields very low water uptake, good chemical resistance, tight dimensional stability, and a tunable glass-transition window, which together support moisture-robust bonds that hold tolerances under thermal cycling in interiors, lighting modules, and protected under-hood zones; however, the same low-polarity surface that underpins moisture

resistance also means inherently low surface energy, so reliable adhesion to metals, coated glass, and polar engineering polymers typically requires polarity “bridging” in the formulation and often explicit surface activation or primers at the adherend, for example oxygen-plasma or UV/ozone treatments that introduce oxygenated groups and raise surface energy on COC and related thermoplastics [45, 46].

In practice, these attributes map to clear advantages—clean, solvent-free processing, rapid set, low fogging, and humidity stability in assemblies such as trim, optical housings, sensor covers, and selected battery-pack auxiliaries, but also to design constraints due to the lack of compatibilised tackifier packages and proper pretreatment, joints to polar substrates remain interface-limited. Also, although COC grades allow T_g tuning, long-term creep resistance at elevated cabin or enclosure temperatures must be validated at the joint level using peel and creep metrics rather than room-temperature shear data alone. These implications align with automotive durability requirements for adhesively bonded structures while leveraging the surface-engineering toolbox and bonding protocols already demonstrated for COC, making COC-based hot-melts promising for mixed-substrate modules when formulated and pretreated to overcome their low-energy surface [5, 49].

2.2.3 Joint configuration and failure modes

The geometry of an adhesive joint plays a decisive role in determining its overall performance, governing both stress distribution and eventual failure mechanisms. Optimising overlap length, adherend thickness, and joint shape is therefore fundamental to achieving reliable structural behaviour. Increasing overlap length can improve strength, but only up to a critical limit beyond which stress concentrations remain localised at the ends of the overlap [50]. Similarly, spew fillets or tapering of adherends can alleviate edge stresses and delay crack initiation, thereby enhancing durability under static and fatigue loading. Figure 5 presents possible adhesive joints configurations.

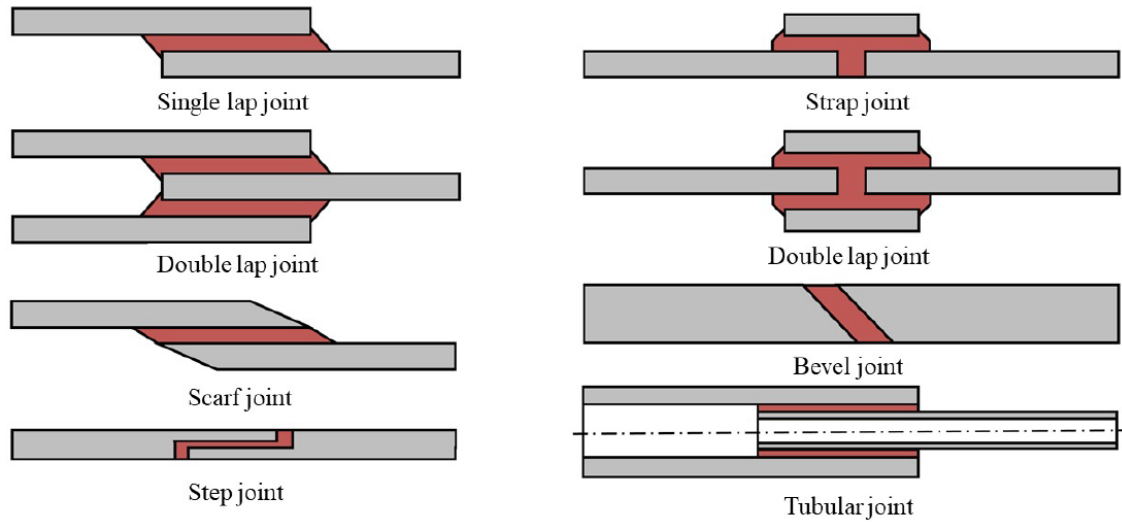


Figure 5: Possible adhesive joint configurations [51].

Figure 6 illustrates the principal loading modes that adhesive joints may experience, namely shear, tension, peel, and cleavage. Each loading condition generates distinct stress distributions within the bondline, strongly influencing joint performance and the likelihood of specific failure modes.

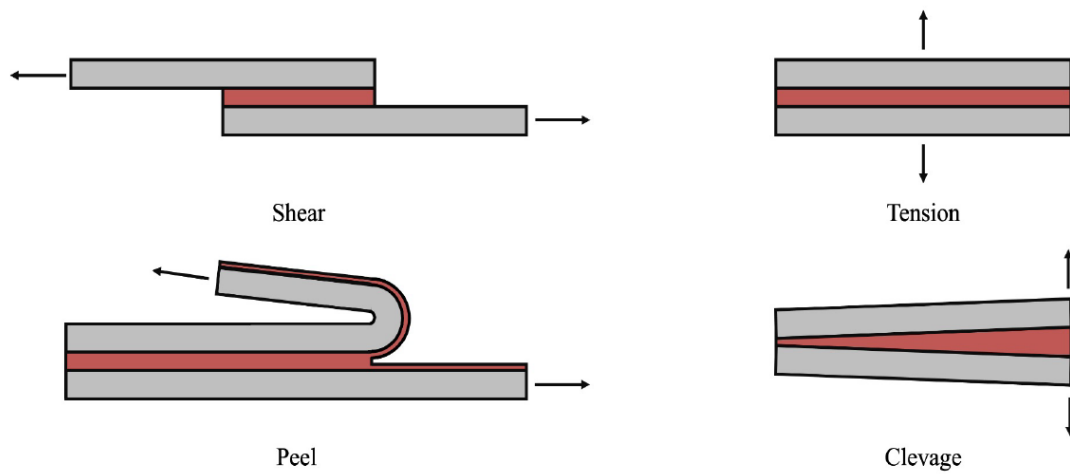


Figure 6: Loading modes in adhesive-bonded joints [51].

Failure modes in adhesively bonded joints are typically classified as adhesive, cohesive, or adherend failure. Adhesive failure occurs at the interface between adhesive and substrate and is often associated with poor surface preparation or inadequate chemical compatibility. Cohesive failure, by contrast, takes place within the bulk of the adhesive and indicates that the interfacial bond exceeded the intrinsic strength of the polymer. Adherend failure arises when the substrate itself yields or fractures prior to adhesive rupture, a condition more likely in thin or weak adherends [51]. In

practice, many bonded joints exhibit mixed-mode failures, particularly under complex loading conditions. Figure 7 presents the failure modes previously described.

Joint geometry further influences how these failure modes manifest. Peel-dominated designs, such as cantilever or wedge joints, tend to encourage adhesive failure due to stress concentrations at the bondline extremities, while shear-dominated geometries more frequently display cohesive or mixed failure [16, 52].

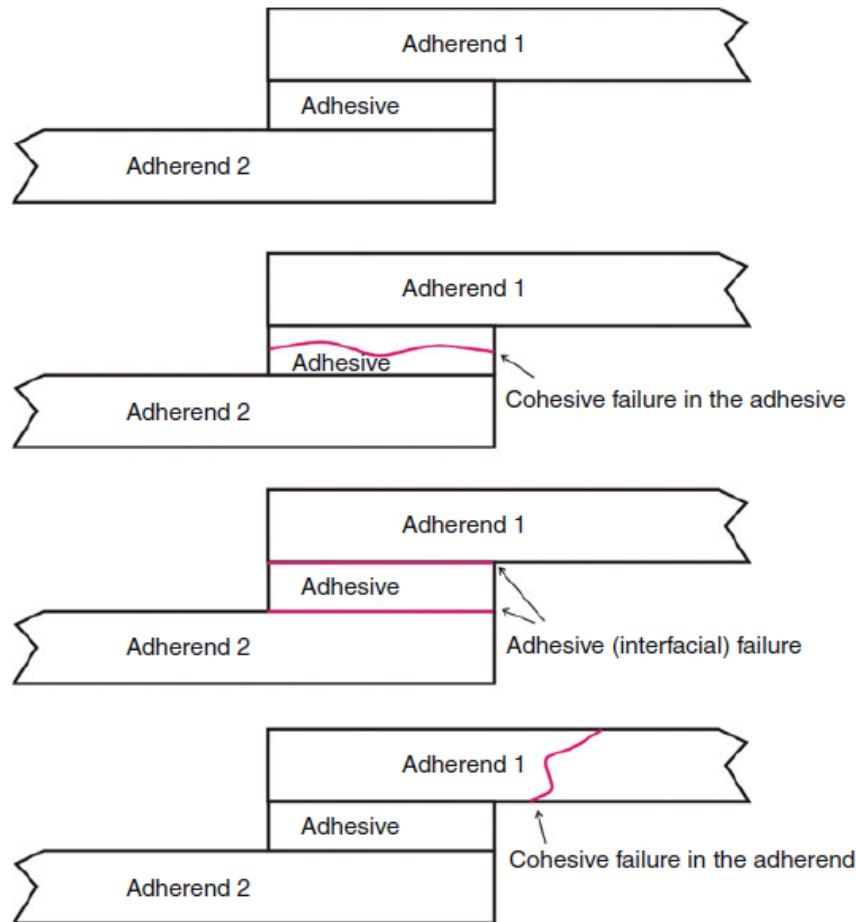


Figure 7: Adhesive joints possible failure modes [18].

From an engineering design perspective, tailoring joint geometry to minimise peel stresses and promote stable, predictable cohesive failure is generally desirable. As such, joint geometry is not merely a geometric consideration but a key parameter controlling durability, reliability, and the ultimate safety of bonded structures across industries ranging from aerospace to automotive.

2.3 Friction stir welding

Friction stir welding (FSW) represents a groundbreaking advancement in aluminum joining, notably distinguished by its solid-state mechanism, which avoids the complications common to traditional fusion welding. Under FSW, a non-consumable,

shouldered tool with a profiled pin is rotated and traversed along a joint line while being pressed into the aluminium workpieces. Frictional and plastic-deformation heating raise the temperature locally to a sub-solidus regime, so the material softens without melting [53]. Figure 8 shows a schematic drawing of the FSW process.

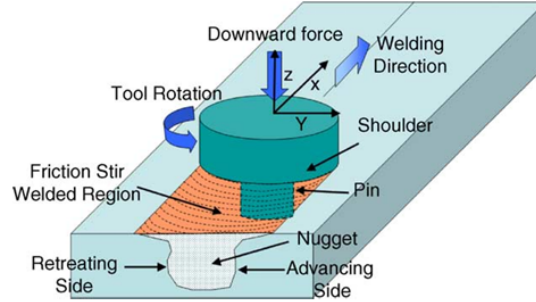


Figure 8: Schematic drawing of friction stir welding [53].

Microstructurally, FSW produces a characteristic stir zone of dynamically recrystallized, ultrafine grains, often arranged in “onion-ring” patterns. Surrounding this, the thermo-mechanically affected zone (TMAZ) shows deformed but discernible parent structure, while the heat-affected zone (HAZ) experiences only thermal influence. This refined microstructure confers enhanced mechanical qualities compared to many fusion welds [54]. Figure 9 presents a scheme of microstructural zones presented in FSW.

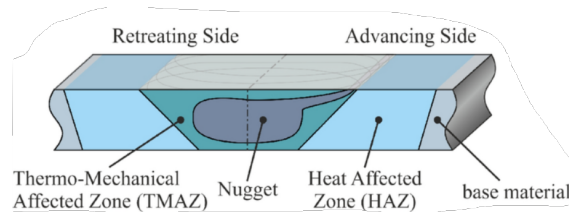


Figure 9: Overview of microstructural zones of FSW. Adapted from [54]

Since solidification is avoided, defects typical of fusion welding of aluminium, such as hot cracking, porosity and liquation, are largely mitigated, with beneficial consequences for distortion control, strength retention, and fatigue performance. In-depth reviews show that the improved microstructural stability and joint morphology translate to high transverse tensile and fatigue strengths in 5xxx/6xxx series alloys relative to comparable arc welds, provided weld geometry is smooth and process parameters are within an appropriate thermal window [53, 55, 56].

For die-cast aluminium components, which are widely used in the automotive industry due to their low cost and design flexibility, FSW also offers distinct advantages. Traditional fusion welding of die-cast alloys is difficult because of gas

porosity and oxide inclusions that form during casting and cause weld defects. In FSW, since the process avoids melting, these defects are not aggravated in the same way, allowing stronger and more consistent welds in cast components such as housings, brackets, and engine parts. Studies have shown that carefully selected FSW parameters can produce joints in die-cast aluminium with strength close to that of the base material [57].

Within the automotive sector, FSW aligns closely with the industry’s long-standing drive towards vehicle lightweighting. Aluminium alloys are central to this goal because of their favourable strength-to-weight ratio, corrosion resistance, and recyclability. Yet the widespread use of aluminium in safety-critical structures demands reliable joining techniques. FSW has therefore emerged as an attractive solution. It is already being used to produce a range of automotive components including engine cradles, suspension arms, and body-in-white structures. For sheet applications, variants such as friction stir spot welding (FSSW) and refill FSSW (RFSSW) allow the production of spot joints suitable for panels, closures, and tailored blanks. These processes provide comparable or superior static and fatigue performance to traditional resistance spot welding in aluminium sheets, while eliminating the need for consumables such as electrodes, shielding gases, or filler wires [58, 59].

A further advantage of FSW for the automotive industry is its compatibility with automation. The process can be readily adapted to robotic systems or integrated into existing production lines, making it attractive for high-volume manufacturing. Its relatively low energy requirements compared with fusion welding, together with reduced distortion and rework rates, contribute to cost savings across large production runs [60]. Moreover, FSW is increasingly being explored for joining dissimilar materials, including aluminium to steel, to enable hybrid lightweight structures that combine the best attributes of each material. This capability is of particular significance for modern vehicles, which must meet increasingly stringent weight and efficiency targets without compromising safety [61].

3 Experimental procedures

This section provides a detailed description of the adhesives selected for the present study, along with the manufacturing processes of the used specimens and testing procedures employed.

3.1 Materials

Two adhesive systems were used along this work: a hot-melt adhesive (HMA) and a modified-silane (MS) polymer adhesive.

The hot-melt adhesive used in this study is a multi-material adhesive (MMA) designated LS-XU, supplied by Zeon® Corporation (Chiyoda-ku, Tokyo, Japan). It is a cyclic olefin-based polymer film with a thickness of 0.4 mm. Curing was carried out by simultaneously applying heat and pressure in a hot press at 159 °C for 45 minutes under a pressure of 3 MPa. The mechanical properties of the adhesive are presented in Table 1. This adhesive was previously characterised by Rodrigues et al. [62] in a related study conducted on the same film with a thickness of 0.1 mm. A study to characterize the 0.4 mm thickness adhesive was performed after.

Table 1: LS-XU mechanical properties [62]

Property	Units	Value
Young's modulus, E	[MPa]	230.18 ± 8.08
Yield strength, σ_y	[MPa]	5.49 ± 0.36
Tensile failure strength, σ_f	[MPa]	10.86 ± 1.48
Tensile failure strain, ε_f	[%]	1066 ± 83
Poisson's ratio, ν	[-]	0.47 ± 0.02
Shear modulus, G	[MPa]	76.67 ± 2.52
Shear failure strength, τ_f	[MPa]	5.09 ± 0.08
Shear failure strain, γ_f	[%]	354 ± 19
Toughness in mode I, J_{Ic}	[N/mm]	0.20 ± 0.05
Toughness in mode II, J_{IIc}	[N/mm]	2.66 ± 0.19

The MS polymer adhesive employed in this study is Teroson®MS 939, supplied by Henkel (Düsseldorf, Germany). Curing occurred through ambient moisture absorption over a period of two weeks, resulting in an elastic and durable product. Table 2 presents the mechanical properties of this MS polymer adhesive.

Table 2: Teroson MS 939 mechanical properties [62]

Property	Units	Value
Young's modulus, E	[MPa]	2.90 ± 0.01
Yield strength, σ_y	[MPa]	8.24
Tensile failure strength, σ_f	[MPa]	3.14 ± 0.03
Tensile failure strain, ε_f	[%]	2.30 ± 0.04
Poisson's ratio, ν	[-]	0.37
Shear modulus, G	[MPa]	0.94 ± 0.02
Shear failure strength, τ_f	[MPa]	2.59 ± 0.07
Shear failure strain, γ_f	[%]	5.68 ± 0.36
Toughness in mode I, J_{Ic}	[N/mm]	5.2 ± 1.8

The die-cast aluminium component studied throughout this project is presented in Figure 10. This part is made of die-cast aluminium $AlSi_{10}Mg$, and is obtained through high pressure die-casting (HPDC). This aluminium component is produced by Wedrone, Portugal, a company that develops products based on aluminum, using die casting technology and machining of parts for the automotive and construction industries. The specimens for all the testing done in the following work were retrieved from this part.



Figure 10: Die-cast aluminium component under study for bonding.

The chemical composition of this aluminium alloy is presented in Table 3.

Table 3: Chemical composition of $AlSi_{10}Mg$ (EN AC-43400) alloy [63]

Si	Fe	Cu	Mn	Mg	Cr	Ni
9.0–11.0	0.45–0.90	0.08	0.55	0.20–0.50	0.15	0.15
Zn	Pb	Sn	Ti	Others (each)	Others (total)	Al
0.15	0.05	0.05	0.20	0.05	0.15	Remainder

The mechanical properties for the aluminium alloy $AlSi_{10}Mg$ are presented in Table 4.

Table 4: Mechanical properties of the aluminium alloy $AlSi_{10}Mg$ (EN AC-43400) [63]

Young's modulus [GPa]	Yield strength [MPa]	Tensile strength [MPa]	Poisson's ratio [-]
70	140	240	0.33

For a more rigorous assessment of the component and of the different joining configurations, it is essential to characterise the mechanical solicitations to which the part is subjected, while also accounting for the environmental conditions of its intended application. For the component shown in Figure 10 previously, its operating conditions are:

- the operating temperature range is between -30°C and 140°C ;
- the operating pressure range is between 0 and 9.7 bar;
- there is an oil in contact with the joint (0W20);
- the most important loading is pressure pulsation, usually between 4.5 and 6 bar.

3.2 Specimen manufacturing

3.2.1 Single lap joints specimens

To assess the performance of both adhesives in joint configurations, single lap joints (SLJs) were manufactured using $AlSi_{10}Mg$ aluminium alloy substrates extracted from the main component, previously shown in Figure 10. The joints were assembled in an aluminium mould. For the LS-XU adhesive, curing was carried out in a hot press, whereas the MS polymer joints were left to cure at room temperature under slight pressure to achieve the desired thickness. When using the MS polymer adhesive, the mould was pre-treated with a release agent spray to facilitate demoulding. The geometry of the SLJ manufacturing is shown in Figure 11.

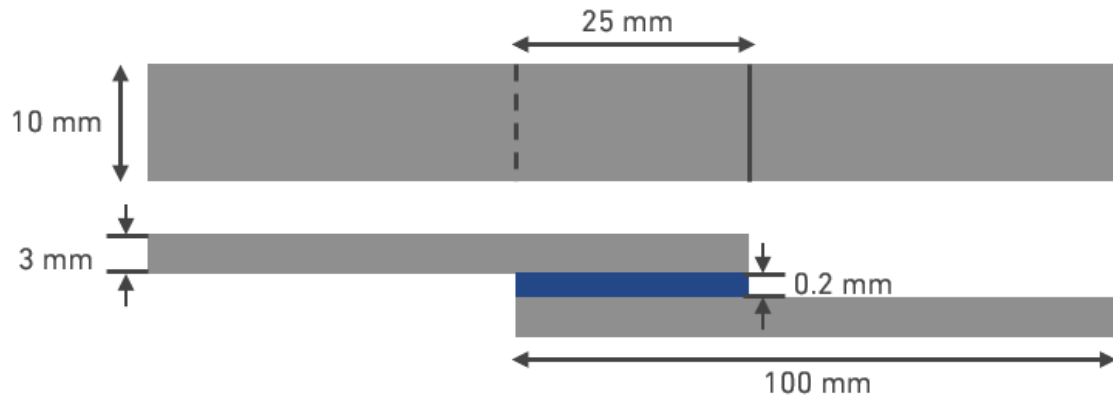


Figure 11: Single lap joint geometry.

It is important to mention that to guarantee the desired adhesive thickness, the SLJs were manufactured with spacers and calibrated tape inside the aluminium mould.

In this study, the specimens were subjected to three different surface treatments: degreasing, sanding, and anodizing. Degreasing was performed using acetone cleaning, sanding was carried out with P600 grit sandpaper, and anodizing was conducted in accordance with ASTM D3933-98 [64]. Figure 12 presents the substrates appearance after the surface treatment.

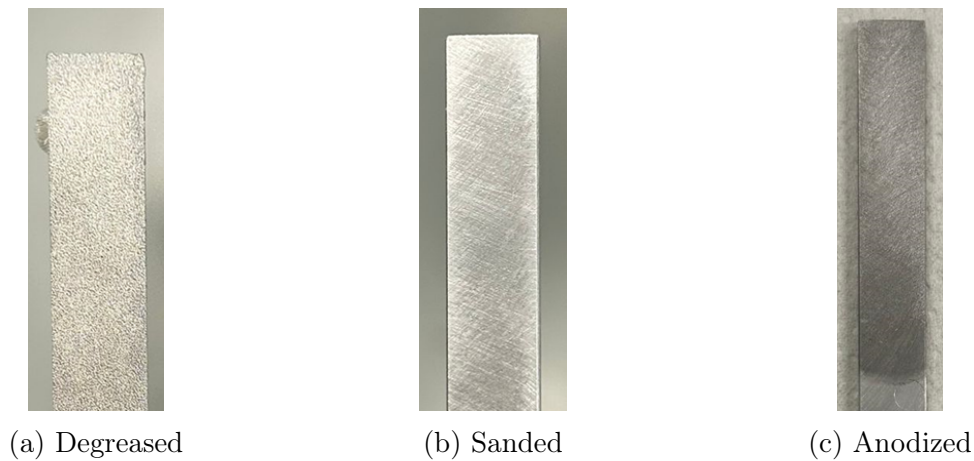


Figure 12: Substrates appearance after the surface treatment.

Regarding the anodization of aluminium–silicon die-cast alloys, it often leads to visual and structural defects that compromise both the appearance and the performance of the oxide film. Figure 13 presents the results of the anodization performed the manufactured specimens. In the specimens, dark, patchy regions and irregular surface contrast were clearly visible after anodizing, consistent with the defects frequently reported in the literature. According to Razzouk, Koncz-Horváth and

Török [65], these anomalies arise primarily from the heterogeneous microstructure inherent to Al-Si alloys. The aluminium matrix oxidizes readily to form a continuous alumina layer, while the silicon-rich regions remain relatively inert, creating zones of thinner or discontinuous oxide. This difference in local oxidation kinetics results in coloured surfaces where lighter regions correspond to thicker anodic films and darker areas correspond to silicon phases or discontinuities in the oxide.

Casting-related defects such as porosity, shrinkage cavities and entrapped gas further accentuate this non-uniformity. When exposed to the anodizing electrolyte, these features disrupt current distribution, producing localised pores, streaks or pits in the oxide film. Surface preparation also plays an important role, as machining marks and variations in roughness can concentrate current at asperities and hinder uniform film growth [65].



Figure 13: Different results of as-cast aluminium substrates anodization.

The sensitivity of Al-Si die-cast alloys to anodizing parameters has also been highlighted in recent reviews. Variations in applied current density, voltage and electrolyte composition can strongly influence film thickness and morphology, and excessive current or local overheating can exacerbate defects by promoting oxide dissolution [65]. Several mitigation strategies have been proposed, including mechanical polishing to remove surface defects, alloy composition optimisation to reduce the amount of deleterious intermetallics such as Fe-rich phases, and process control measures such as operating at lower current densities and lower electrolyte temperatures to improve uniformity [66]. Post-anodization sealing treatments, such as hydrothermal sealing in hot water or nickel acetate, can also help close porosity

and improve both the aesthetic appearance and the corrosion resistance of the oxide film [67].

3.2.2 90° peel test specimens

The 90° peel test specimens for adhesive bonding were prepared using the main component as the rigid adherend and a calibrated tape as the flexible adherend. The tape was bonded to the die-cast $AlSi_{10}Mg$ component in the as-cast condition, without machining, using both adhesives under study. The only surface treatment applied to the adherends was acetone degreasing. Figure 14 shows the configuration of the adhesive-bonded peel test specimens.

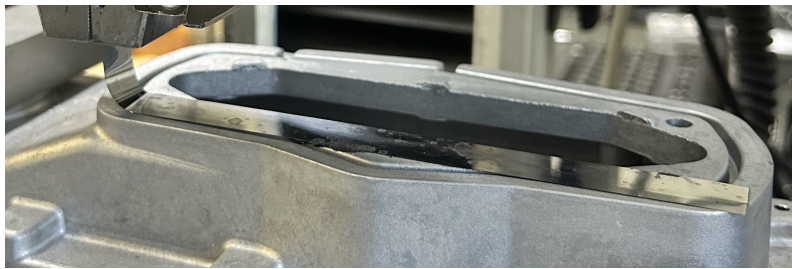


Figure 14: 90° peel test specimen with adhesive bonding.

In addition, 90° peel specimens were produced using friction stir welding (FSW) as the bonding method between the flexible and rigid adherends. In this case, the rigid adherend was the same $AlSi_{10}Mg$ component, while the flexible adherend was manufactured from $AlMg_6$ alloy. The FSW specimens, illustrated in Figure 15, correspond to transverse sections of the main part, prepared to facilitate subsequent testing.



Figure 15: 90° peel test specimen with FSW.

3.2.3 Internal pressure test specimens

Given the intended application of this component in the automotive sector, it was necessary to evaluate the internal pressure resistance that the joints could sustain.

For this purpose, a 1.5 mm thick $AlMg_6$ aluminium alloy lid was bonded to the part, using both adhesives systems, LS-XU and Teroson MS 939, and FSW. Figure 16 illustrates an internal pressure test specimen assembled with the LS-XU adhesive.



Figure 16: Specimen prepared for the internal pressure test with LS-XU adhesive.

For the FSW specimen, the welding parameters used are presented in Table 3.

Table 5: Friction stir welding parameters

Parameter	Value
Rotational speed	1200 rpm
Feed speed	300 mm/min
Plunge depth (Z)	1.6 mm (0.1 mm penetration)

To validate the adequacy of the selected FSW parameters, a metallographic examination was carried out on a transverse cross-section of the weld. The specimen was sectioned perpendicular to the welding direction, mounted, ground, and polished following standard metallographic procedures, and subsequently etched to reveal the microstructural features. Figure 17 shows a high-magnification image of the weld interface at a scale of 100 μm . The micrograph highlights the intermixed region of the aluminium alloys along the bond line, confirming material consolidation and evidence of diffusion and plastic flow within the stir zone.

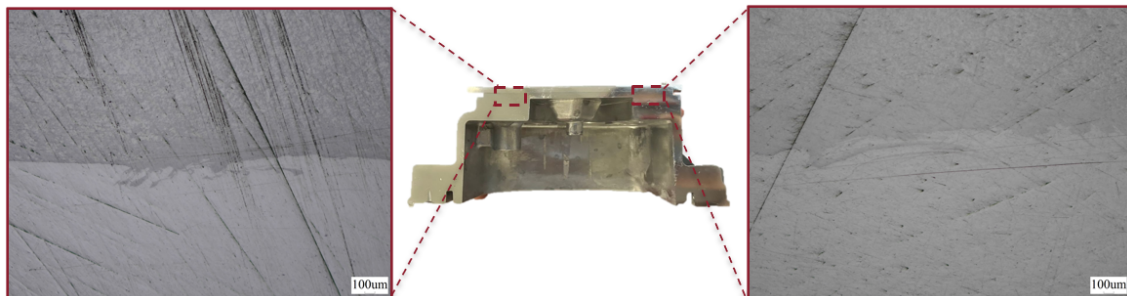


Figure 17: Microstructure of the FSW bond line in a transversal section for the specimen.

3.3 Testing methods

In this section, the testing methodology carried out in this study will be detailed. The tests were performed using a universal testing machine, an INSTRON®3367 equipped with a 30 kN load cell. For each specimen configuration, at least three specimens were tested to ensure consistency, and the resulting data were then processed and analysed.

3.3.1 Single lap joints

The SLJs specimens were tested under quasi-static conditions using a displacement-controlled loading rate of 1 mm/min. This relatively low crosshead speed was selected to minimise inertial and dynamic effects, ensuring that the measured response reflects the intrinsic mechanical behaviour of the adhesive joints rather than strain-rate sensitivity. The applied rate is consistent with standard practices for characterising adhesive joints, allowing reliable comparison of load–displacement behaviour, failure modes, and maximum joint strength across the different surface treatments and adhesives investigated.

3.3.2 Durability test

Durability tests were performed to evaluate the effect of hydraulic oil exposure on the mechanical performance of single lap joints (SLJs). The SLJs specimens were fully immersed in hydraulic oil for 32 days under ambient conditions, simulating long-term contact with lubricants commonly encountered in automotive environments. After the ageing period, the joints were removed, cleaned of surface residues, and tested under standard SLJ conditions at a quasi-static displacement rate of 1 mm/min, ensuring direct comparability with unaged specimens.

3.3.3 90° peel test

The 90° peel tests were conducted in accordance with ASTM D6862-11 [68], a standard method for evaluating the peel resistance of adhesives. In this configuration, the bonded specimen consisted of the $AlSi_{10}Mg$ aluminium alloy substrate as the rigid adherend and a calibrated tape acting as the flexible adherend. During testing, the flexible adherend (peel arm) was clamped vertically in the upper grip of the testing machine, while the rigid adherend was fixed horizontally in the lower grip, ensuring a constant 90° peel angle throughout the procedure. The peel arm was displaced at a crosshead speed of 12 mm/min, progressively separating the bonded interface while the force required for debonding was continuously recorded. The test setup for adhesive-bonded specimens is illustrated in Figure 18 where it is possible to see a pulley system, connected to the crosshead, ensuring the coordinated movement of the rigid adherend, maintaining a constant 90° peel angle throughout the test.

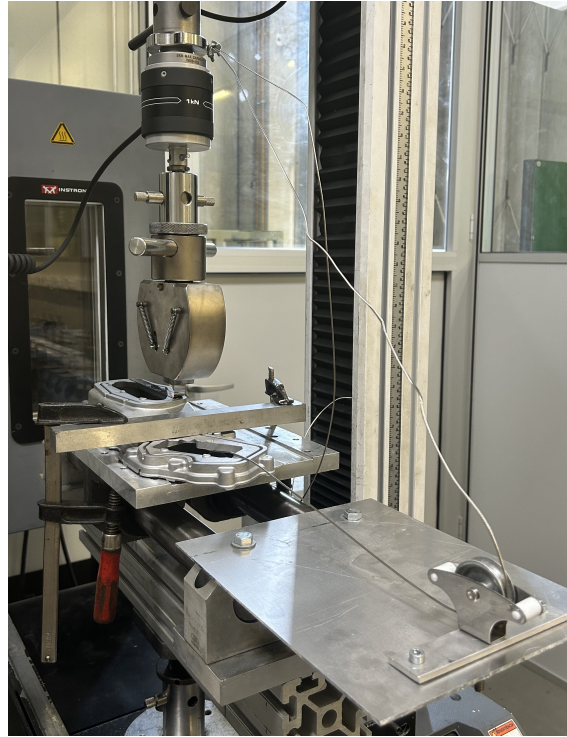


Figure 18: 90° peel test setup for adhesive-bonded joints.

This test not only quantifies the peel strength of the adhesive bond but also provides valuable information on the fracture mechanisms governing debonding, including whether failure occurs cohesively within the adhesive or adhesively at the interface. Furthermore, by plotting the peel force against displacement, it is possible to calculate the critical energy release rate, G , which represents the energy dissipated per unit width of crack propagation and serves as a reliable measure of interfacial toughness. For this study, the adherends were only subjected to acetone degreasing prior to bonding, thereby isolating the effect of the adhesive systems themselves on peel resistance.

A similar procedure was adopted for the FSW specimens, although the test setup differed and is presented in Figure 19.

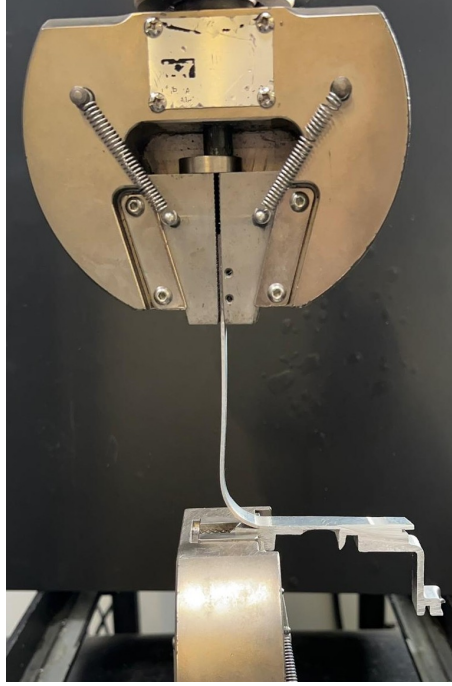


Figure 19: 90° peel test setup for FSW specimens.

The comparative assessment of adhesively bonded and welded configurations provide insight into differences in interfacial toughness and failure mechanisms across the two joining methods, offering valuable guidance for the automotive sector where adhesives are typically preferred for sealing and vibration damping, while welded joints are relied upon for structural integrity.

3.3.4 Internal pressure test

The internal pressure test was designed to evaluate the ability of the bonded joints to withstand pressurisation, simulating service conditions in which components are exposed to internal loads. The test setup is presented in Figure 20. Once assembled, pressure was applied inside the cavity beneath the lid under quasi-static conditions using a displacement at a crosshead speed of 1 mm/min. The pressurisation acted on the bonded joint in a manner analogous to a tensile test, generating stresses perpendicular to the bond line and progressively loading the adhesive layer until failure. By recording the pressure at which leakage or rupture occurred, the resistance of each adhesive system and FSW joint to internal loading could be quantified. This test therefore provided complementary information to lap shear and peel tests, by assessing the joint's capacity to sustain stresses under realistic loading conditions relevant to automotive applications.

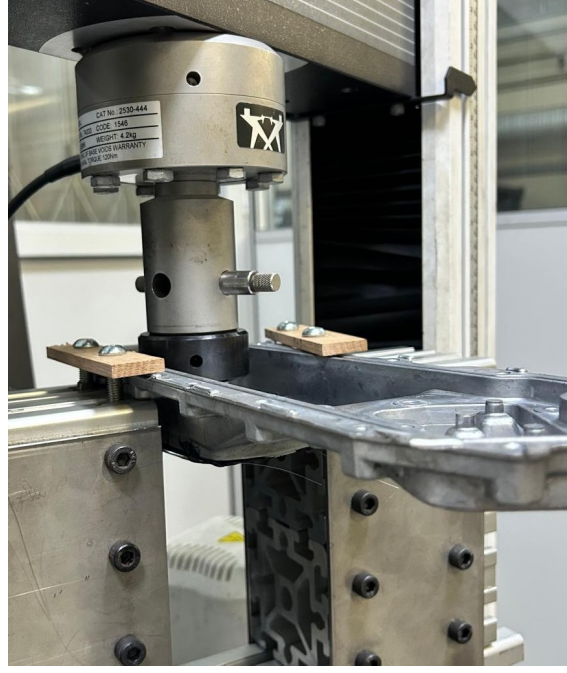


Figure 20: Internal pressure test setup.

3.3.5 Surface energy tests

The surface energy of a substrate is a critical factor governing the quality and durability of adhesive bonds. A high surface energy generally promotes better wetting of the adhesive, thereby increasing the likelihood of achieving strong interfacial adhesion. Conversely, low surface energy surfaces can result in poor wetting, incomplete spreading of the adhesive, and reduced bond strength [20]. For aluminium alloys, particularly those produced by high-pressure die casting, the actual surface energy can deviate considerably from the theoretical values of pure aluminium due to the presence of alloying elements, surface oxides, and contaminants [69].

In this work, surface energy tests were carried out to compare the as-cast and machined surface conditions of the aluminium alloy $AlSi_{10}Mg$ used as adherends. The sessile drop method was employed using a goniometer (OCA 15, DataPhysics, Neurtek Instruments, Spain) to measure contact angles under ambient conditions. Three probe liquids with known surface tension components were selected: distilled water and ethylene glycol (polar liquids), and n-hexadecane (a non-polar liquid). The selection of both polar and non-polar liquids is important for distinguishing between the dispersive and polar contributions to the total surface energy.

The contact angles were measured by depositing small droplets of each liquid on the substrate surface and recording the static contact angle using image analysis software. The results were then processed using the Owens–Wendt–Rabel–Kaelble (OWRK) method, which expresses the total surface energy, γ_s , as the sum of a dispersive component, γ_s^d , and a polar component, γ_s^p :

$$\gamma_s = \gamma_s^d + \gamma_s^p$$

According to the OWRK model, the contact angle θ of a liquid with dispersive (γ_l^d) and polar (γ_l^p) components on a solid surface is given by:

$$\gamma(1 + \cos \theta) = 2 \left(\sqrt{\gamma_s^d \gamma_l^d} + \sqrt{\gamma_s^p \gamma_l^p} \right)$$

By combining contact angle data from at least two liquids of different polarity, the dispersive and polar components of the solid surface energy can be determined. In this study, the inclusion of three liquids increased the robustness of the calculations.

The theoretical surface energy of pure aluminium is reported to be in the range of 500–1000 mJ/m², reflecting the high reactivity of metallic aluminium [69]. However, practical values for passivated aluminium surfaces exposed to air are typically much lower, in the range of 40–60 mJ/m², as a result of the spontaneous formation of a thin oxide layer and the presence of surface contaminants [20]. The surface energy values obtained for the die-cast *AlSi₁₀Mg* substrates in this study are presented in Figure 21, in as-cast and machined conditions. It is possible to see that they were generally lower than those reported for pure aluminium, which is consistent with previous findings that die-cast alloys exhibit reduced surface energies due to high silicon content, intermetallic particles, and casting defects [70].

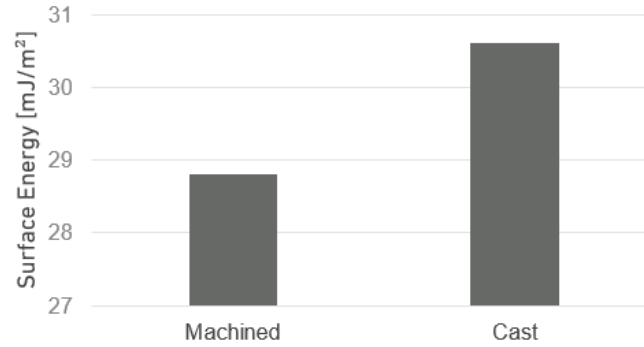


Figure 21: Surface energy of substrates in the as-cast and machined conditions.

4 Results and discussion

This section presents and analyses the experimental and numerical results obtained in this study. The mechanical performance of the single lap joints (SLJs), durability tests, peel tests, and internal pressure tests are examined in detail for both adhesives under different substrate conditions and surface treatments. In addition, peel and internal pressure tests conducted on friction stir welded (FSW) specimens are included to provide a direct comparison between adhesive bonding and welding.

4.1 Single lap joints

A more detailed analysis of these results is presented in Paper A, appended to this thesis. In the present section, the discussion will instead focus on the implications of the findings from an automotive application perspective for the component under study.

Figure 22 presents the load–displacement curves for SLJs with substrates in as-cast condition using the LS-XU adhesive. LS-XU in as-cast condition benefits markedly from anodization, moderately from sanding, and least from degreasing. For automotive use, where repeatability and safety margins are critical, anodized surfaces provide the most robust performance for this film adhesive, while sanding may be acceptable for less demanding joints. Degreasing alone is inadequate for structurally loaded connections.

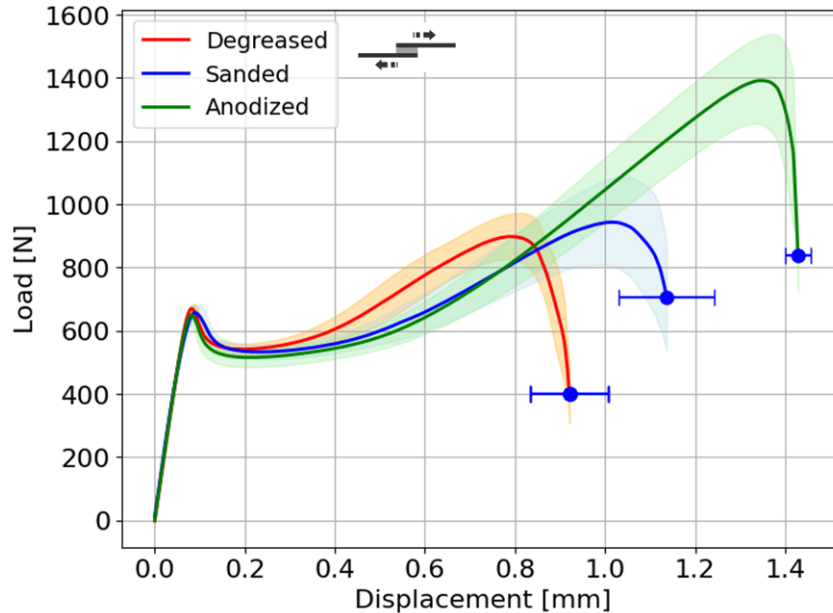


Figure 22: Results of SLJs with substrates in as-cast condition and the LS-XU film adhesive.

Figure 22 shows the failure modes obtained for the three surface treatments used in the SLJs. All joints exhibited adhesive failure, which is consistent with

the load–displacement results of the SLJ tests, where performance was primarily governed by the quality of the substrate surface preparation rather than the bulk properties of the LS-XU film adhesive.

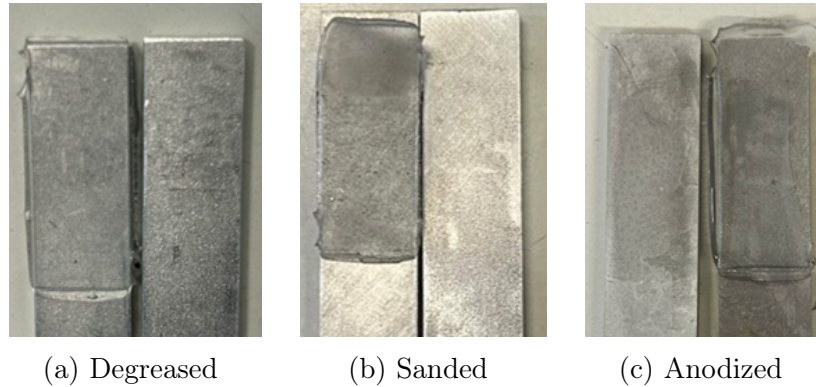


Figure 23: Failure surfaces of the SLJ's with as-cast substrate and the film adhesive.

In the context of automotive applications, adhesive failure in bonded joints presents both advantages and disadvantages. On one hand, adhesive failure can be advantageous because it reflects a clean separation at the interface without extensive damage to either substrate or adhesive bulk. This characteristic can simplify failure analysis, rework, or recycling at end-of-life, which aligns with industry trends towards circularity and sustainable disassembly [26]. However, adhesive failure is generally regarded as undesirable for structural applications, as it indicates insufficient interfacial bonding and limits the load-bearing capacity of the joint. In service, such failure can reduce reliability under fatigue, impact, or environmental exposure, compromising safety and long-term durability [20]. For this reason, adhesive failure may only be tolerable in secondary sealing or non-structural applications.

Figure 24 presents the results for SLJs testing of machined substrates, using the LS-XU adhesive. For machined substrates bonded with LS-XU, anodization delivers the highest and most consistent performance, sanding provides a moderate improvement with some variability, and degreasing offers the weakest interfacial strength. In the context of automotive applications, anodized surfaces stand out as the most reliable option for ensuring structural integrity and reproducibility, while sanding may be suitable for secondary or less demanding joints. Degreasing alone, however, cannot be used for structural applications.

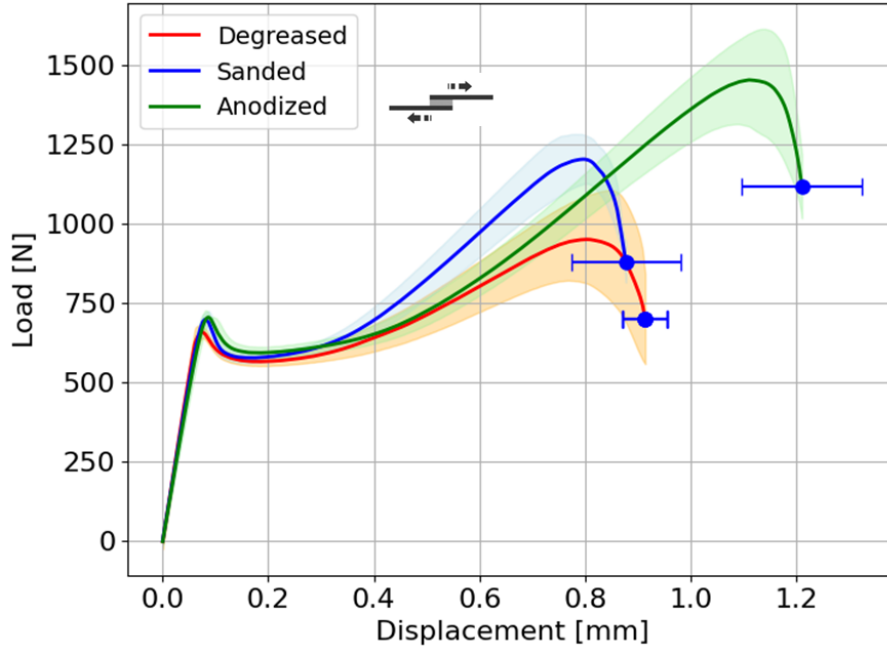


Figure 24: Results of SLJs with substrates in machined condition and the LS-XU film adhesive.

Figure 25 shows the failure mode for the three surface treatments applied to the machined substrates. The adhesive failure in all joints is a repetition of what was seen in the as-cast substrates, which is also consistent with the SLJs testing results.

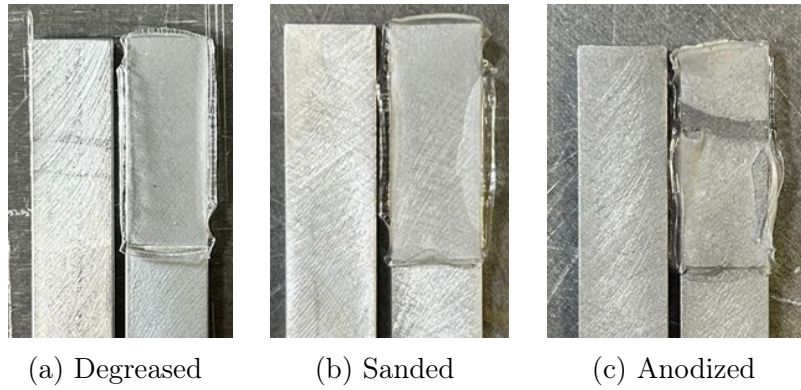


Figure 25: Failure surfaces of the SLJs with machined substrate and the LS-XU film adhesive.

In the automotive sector, the comparison between as-cast and machined substrate conditions carries significant practical and economic implications. If the mechanical performance and durability of adhesively bonded joints in the as-cast state are demonstrated to be sufficient for the functional requirements of the component, the machining step may be omitted from the production sequence. This would represent a substantial advantage, as eliminating machining not only reduces manufacturing time and energy consumption but also lowers costs and simplifies the overall

production chain. Such reductions are particularly valuable in high-volume automotive manufacturing, where even small process optimisations can translate into considerable efficiency gains. Conversely, if machining is shown to deliver markedly superior joint performance, especially in safety-critical or high-stress applications, its retention in the production process can be justified as essential for ensuring long-term reliability. The systematic evaluation of these two substrate conditions is therefore critical to obtain the right balance between performance, cost-effectiveness, and sustainability, aligning with the industry's ongoing efforts to optimise lightweight design strategies while meeting safety and quality standards.

Figure 26 presents the comparison between substrates' surface condition when applying degreasing as surface treatment to them, using the LS-XU adhesive to create the bond. The difference between the two substrate conditions is modest: machined joints exhibit slightly higher peak loads and marginally greater displacement before failure, while the as-cast joints show slightly lower but comparable performance. This indicates that in the absence of additional surface treatments, machining contributes only a limited improvement to interfacial bonding. The small differences between as-cast and machined substrates also highlight that machining, without further surface modification, does not justify the additional manufacturing cost and energy demand in this configuration.

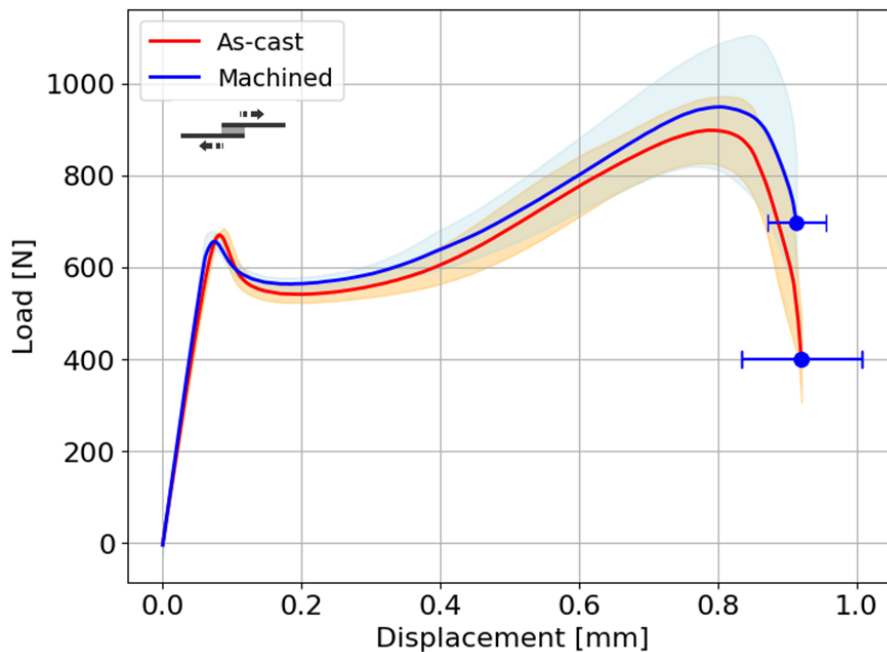


Figure 26: Comparison between substrates' surface condition when degreased, using the LS-XU film adhesive.

Figure 27 presents the comparison between substrates' surface condition when sanded as surface treatment, bonded with the LS-XU adhesive. The results highlight a clearer distinction between the as-cast and machined substrates compared with the

degreased case, the balance between strength and displacement differs depending on the substrate condition.

The as-cast sanded joints reached a lower peak load, but they sustained a slightly greater displacement to failure. This suggests that although the as-cast surface, even after sanding, does not achieve the same interfacial strength as the machined condition, it allows for somewhat greater deformation before failure. By contrast, the machined sanded joints achieved higher peak load, but failed at a lower displacement.

Sanding after machining produces the highest and most reproducible strength levels, making it a more robust option for applications where load-bearing capacity is critical. On the other hand, sanding as-cast surfaces, while resulting in lower strength, may still provide acceptable performance in cases where greater tolerance for displacement is advantageous. In the automotive context, this trade-off highlights the need to balance peak strength against ductility, with the choice of substrate condition depending on the functional requirements of the joint.

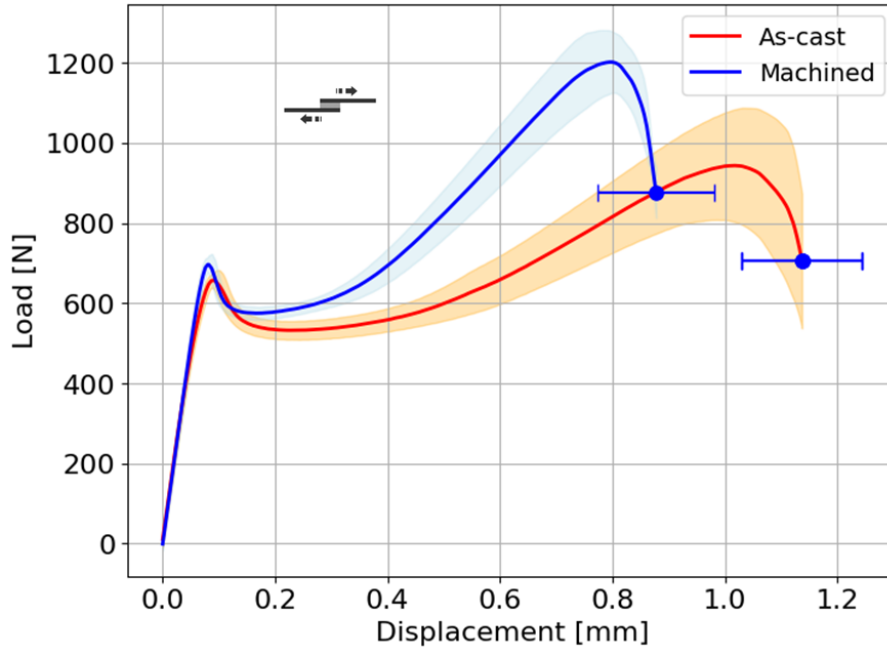


Figure 27: Comparison between substrates' surface condition when sanded, using the LS-XU film adhesive.

Figure 28 presents the comparison between substrates' surface condition when anodized as surface treatment, bonded with the LS-XU adhesive. The anodized condition exhibits the best overall performance for joints bonded with the LS-XU film adhesive, highlighting the beneficial role of anodization in activating the aluminium surface. Both the as-cast and machined specimens show higher peak loads and improved stability compared to degreased and sanded counterparts, but with some clear differences between the two substrate conditions.

The machined anodized joints achieved the highest performance, with higher

peak load. This demonstrates that machining followed by anodization creates a surface with both high mechanical strength and good consistency, as reflected by the narrow scatter. The as-cast anodized joints, while reaching slightly lower peak load, sustained a larger displacement before failure. This suggests that the residual morphology of the as-cast substrate, once anodized, promotes greater deformation capacity, even though ultimate strength is somewhat lower than that of the machined condition.

From an automotive perspective, this makes anodization the most reliable preparation route for ensuring the performance and durability of film-adhesive joints in structural applications, with machining offering an additional gain in strength, while the as-cast anodized condition retains higher ductility.

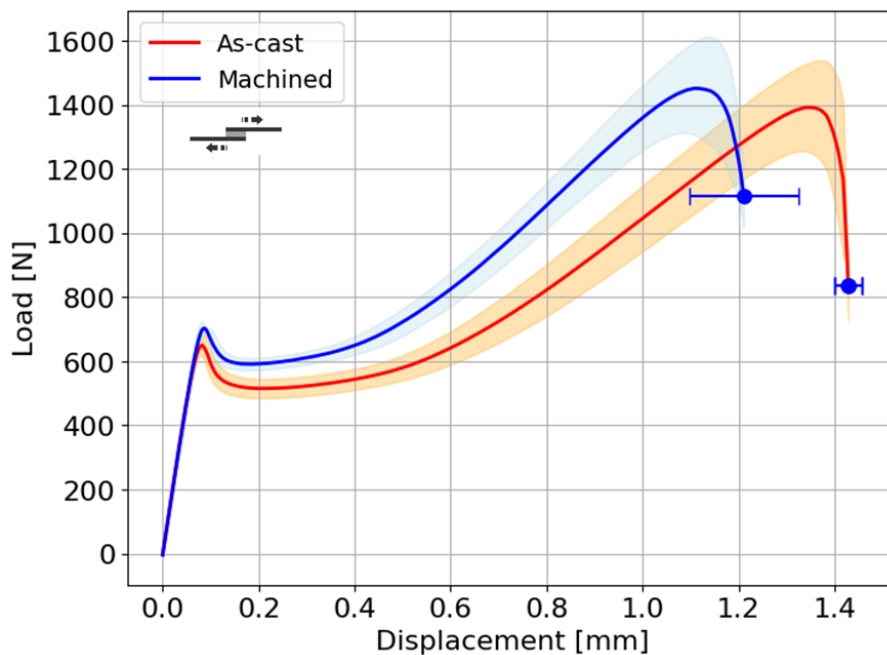


Figure 28: Comparison between substrates' surface condition when anodized, using the LS-XU film adhesive.

Moving forward to the study of the Teroson MS 939 polymer adhesive, the same discussion will be performed, with focus in the application of this adhesive in the automotive context. Figure 29 shows the results of SLJs testing with substrates in as-cast condition, using the MS polymer adhesive.

The load-displacement curves for the MS polymer adhesive exhibit a smoother, more ductile response with a relatively linear increase in load up to failure. This reflects the viscoelastic nature of the MS polymer, which allows it to deform significantly while distributing stresses across the bonded area. Peak loads varied significantly with surface treatment: degreased joints reached the lowest strength, sanded joints improved performance, and anodized joints achieved the highest values. Importantly, despite the differences in peak load, all conditions reached displacements

close to 1.8–2.0 mm, confirming that the MS polymer can sustain large deformations irrespective of surface preparation. This combination of moderate strength and high ductility suggests that MS polymer joints are well suited for absorbing energy under service conditions, a desirable feature in automotive applications requiring vibration damping and crash resistance.

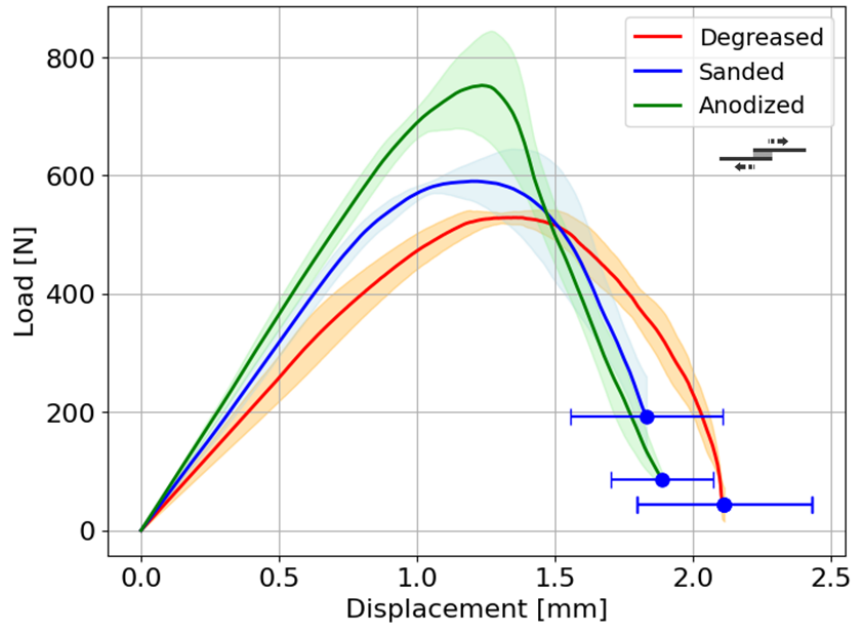


Figure 29: Results of SLJs with substrates in as-cast condition and the Teroson MS 939 adhesive.

Figure 30 shows the failure mode for the SLJs in as-cast condition, for the three surface treatments applied, using the Teroson MS 939 adhesive.

Failure analysis revealed a clear progression with surface treatment. Degreased joints showed mixed but mainly adhesive failure, reflecting poor interfacial activation in the as-cast state. Sanded joints exhibited a higher proportion of cohesive failure, consistent with improved roughness and better mechanical interlocking. Anodized joints failed predominantly cohesively, the most desirable outcome, as it indicates that interfacial strength exceeded the bulk strength of the MS polymer. This transition from adhesive to cohesive-dominated failure highlights the decisive influence of surface preparation, with anodization providing the most reliable bonding, sanding offering an intermediate improvement, and degreasing proving insufficient for structural performance.

In automotive applications, adhesive failure, as observed in degreased joints, is undesirable since it limits load transfer and risks premature debonding. The higher cohesive contribution in sanded joints improves energy absorption under dynamic stresses, while the predominantly cohesive failure of anodized joints ensures stronger, more durable bonds, critical for safety-relevant components.

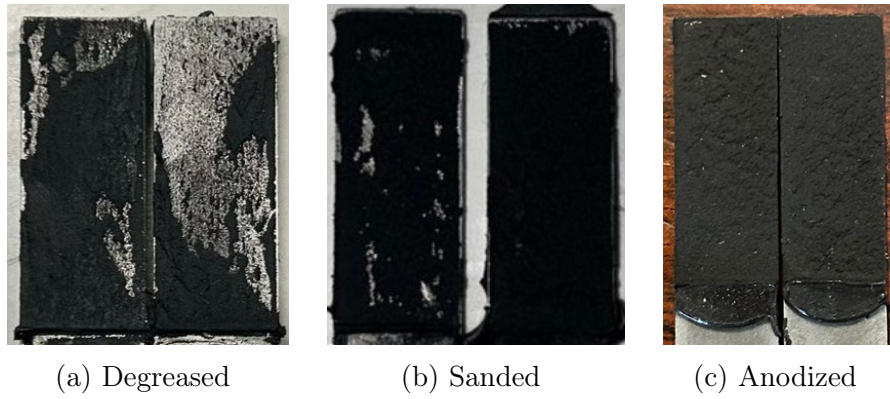


Figure 30: Failure surfaces of the SLJs with as-cast substrate and the Teroson MS 939 adhesive.

Figure 31 shows the results of SLJs testing with substrates in machined condition, using the MS polymer adhesive. The behaviour of the adhesive was similar to the as-cast SLJs previously presented. Strength again varied with surface preparation. Degreased joints performed the weakest joints, anodized joints achieved the highest peak loads, and sanded joints followed closely.

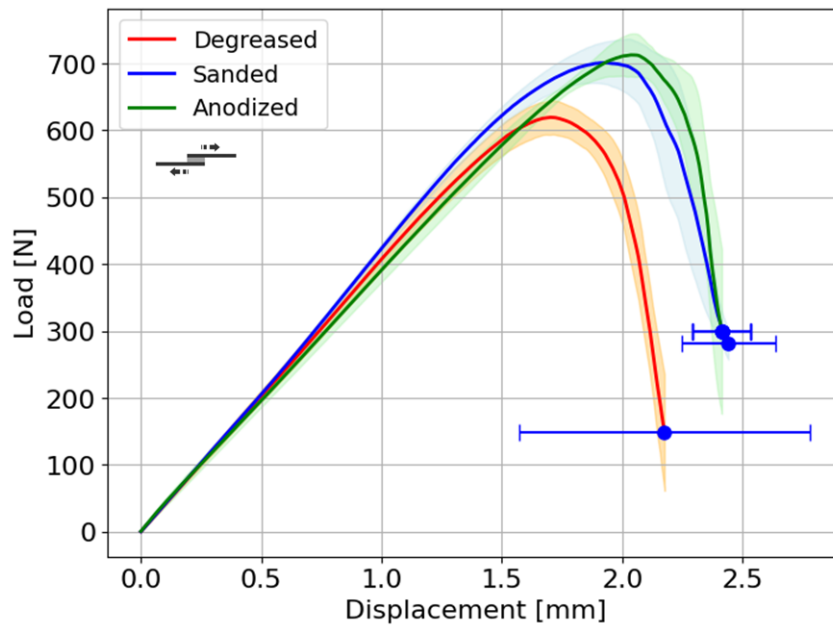


Figure 31: Results of SLJs with substrates in machined condition and the Teroson MS 939 adhesive.

Figure 32 shows the failure mode for the SLJs in machined condition, for the three surface treatments applied, using the Teroson MS 939 adhesive. Failure modes also evolved with surface treatment. Degreased joints exhibited mostly adhesive failure with limited cohesive contribution, while sanding promoted a higher proportion of cohesive failure, consistent with their higher strength. Anodized joints showed mixed-to-cohesive failure, but with more stable behaviour than in the as-cast state.

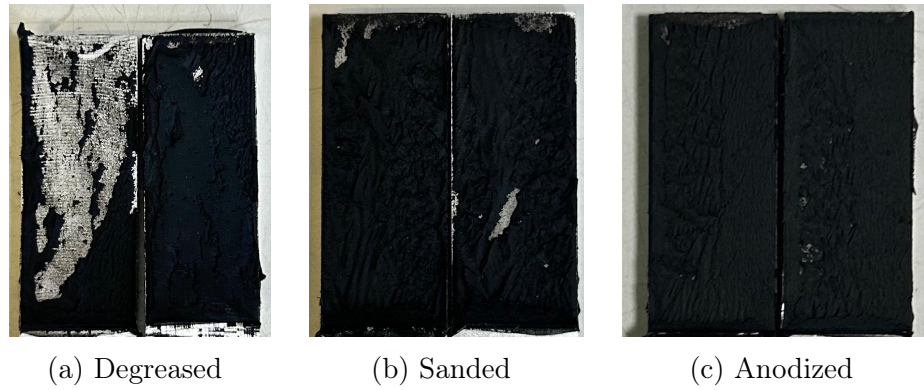


Figure 32: Failure surfaces of the SLJs with machined substrate and the Teroson MS 939 adhesive.

As was done for the LS-XU adhesive, a comparison between the as-cast and machined substrate conditions was also performed for the MS polymer adhesive. Figure 33 presents the comparison between substrates' surface condition when degreased, using the Teroson MS 939 adhesive.

For degreased substrates bonded with the Teroson MS 939 polymer adhesive, machined specimens show a clear but modest advantage over as-cast ones, they reach higher peak loads and sustain slightly larger displacements, while both exhibit mixed but predominantly adhesive failure. This indicates that machining improves interfacial cleanliness and uniformity, even without additional treatment, yielding a small gain in strength and consistency, but it does not change the fact that the interface remains the limiting base.

From an automotive standpoint, this trade-off matters operationally. Where the joint's role is primarily sealing/energy absorption and loads are moderate, the as-cast + degrease route may be acceptable and removes a machining step, reducing cycle time, energy use, and cost. For safety-relevant or higher-load attachments, the machined + degrease condition offers a useful (though limited) strength margin and better repeatability, but still falls short of structural requirements—meaning additional surface activation (e.g., sanding or anodizing) would be recommended if structural reliability is needed.

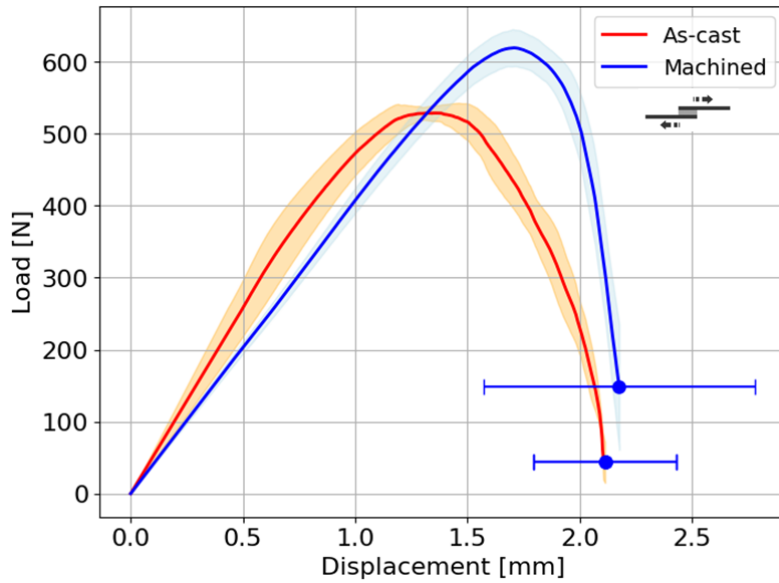


Figure 33: Comparison between substrates' surface condition when degreased, using the Teroson MS 939 adhesive.

Figure 34 presents the comparison between substrates' surface condition when sanded, using the Teroson MS 939 adhesive. For sanded specimens bonded with the MS polymer adhesive, the effect of machining becomes more evident than in the degreased condition. The machined joints clearly outperform the as-cast ones in terms of load capacity and larger displacements, demonstrating the combined benefit of machining (surface uniformity) and sanding (mechanical roughening).

From an automotive perspective, this distinction is significant. Machined and sanded joints offer both higher strength and greater ductility, a combination highly desirable for joints exposed to dynamic loads, vibration, and impact. This makes machined-sanded MS polymer joints a more robust choice for applications where structural integrity and energy absorption must be balanced, while as-cast-sanded joints may be restricted to less critical roles.

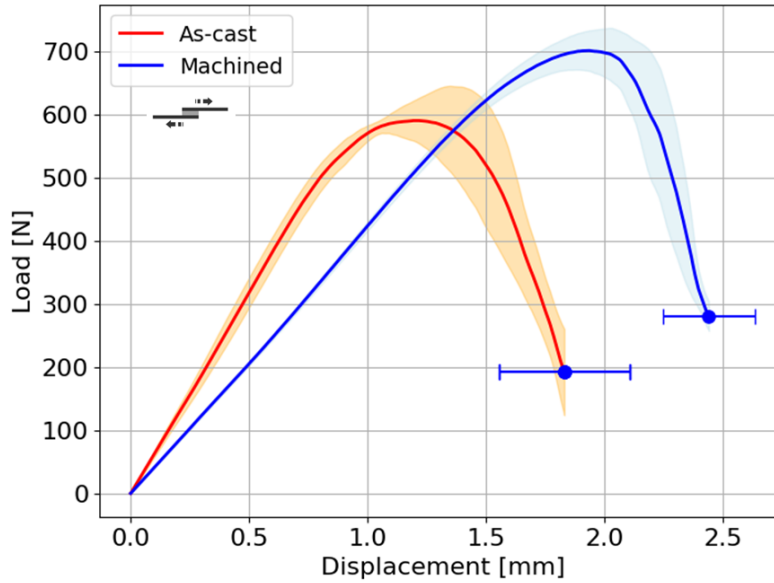


Figure 34: Comparison between substrates' surface condition when sanded, using the Teroson MS 939 adhesive.

Figure 35 presents the comparison between substrates' surface condition when anodized, using the Teroson MS 939 adhesive. The results obtained for the anodized specimens bonded with the MS polymer adhesive show a clear difference between the as-cast and machined surface conditions. The as-cast anodized substrates exhibit a higher peak load, but failure occurs at lower displacements. In contrast, the machined anodized specimens reach a slightly lower maximum load, yet they sustain deformation up to 2.5 mm before failure. This contrast highlights a trade-off between strength and ductility, with the as-cast anodized joints providing superior load-bearing capacity while the machined anodized joints display improved tolerance to displacement.

From an automotive perspective, this behaviour is highly relevant to the design of bonded structures. In applications where peak strength is a priority, such as rigid structural reinforcements, as-cast anodized substrates may offer a more suitable solution. However, in regions of the vehicle where joints are subjected to crash loads, vibrations, or cyclic stresses, the capacity of machined anodized substrates to accommodate greater deformation without immediate failure could prove advantageous.

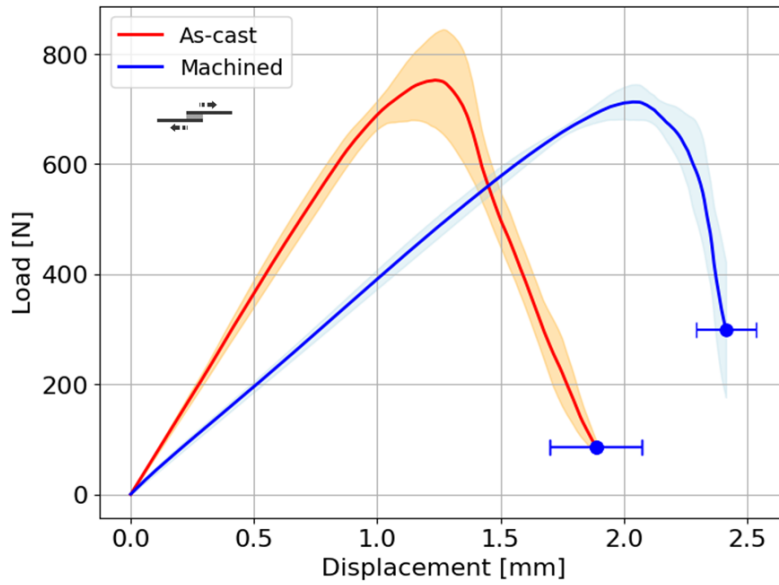


Figure 35: Comparison between substrates' surface condition when anodized, using the Teroson MS 939 adhesive.

4.2 Durability tests

In this section, the results of the durability tests performed on both adhesives will be presented and discussed, giving an automotive perspective of them, regarding the application of the component being studied.

Figure 36 presents the results of the durability tests performed on LS-XU adhesive, for four different combinations between surface treatments and substrates conditions, the most relevant for this context.

The durability results of the LS-XU adhesive after immersion in hydraulic oil for 32 days reveal a strong dependence on both the substrate condition and the surface treatment. These findings highlight that machining combined with either sanding or anodizing provides the most durable joints with LS-XU adhesive under aggressive conditions, although their failure occurs at relatively limited displacements, indicating that strength is retained but ductility is compromised after ageing. As-cast anodized surfaces are the least reliable, suggesting that anodizing in combination with the as-cast surface is particularly vulnerable to degradation in this environment.

In an automotive context, where joints are often exposed to oils, fuels, and lubricants, these results underline the importance of selecting not only the appropriate adhesive but also the optimal surface treatment to ensure long-term reliability of bonded aluminium structures.

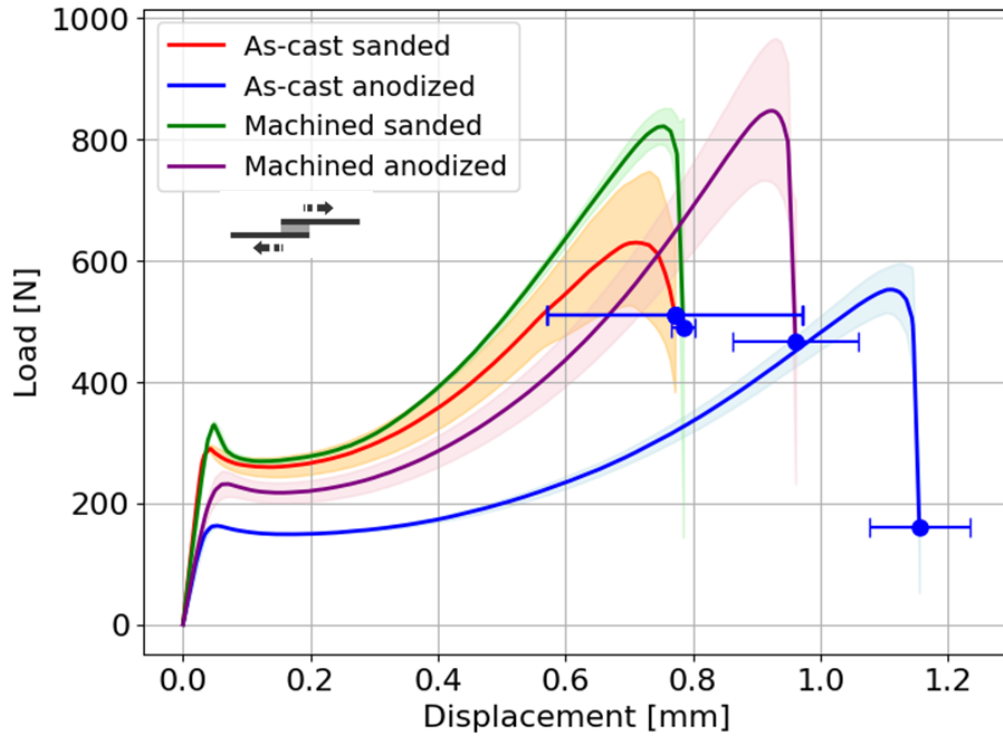


Figure 36: Durability test results for the LS-XU adhesive.

Figure 37 shows the failure modes for the previous results. All SLJs exhibited adhesive failure, consistent with the behaviour observed in the non-aged joints. Nevertheless, prolonged exposure to hydraulic oil introduced a notable effect, as the adhesive layer underwent shrinkage, a phenomenon that will be examined in the subsequent discussion.

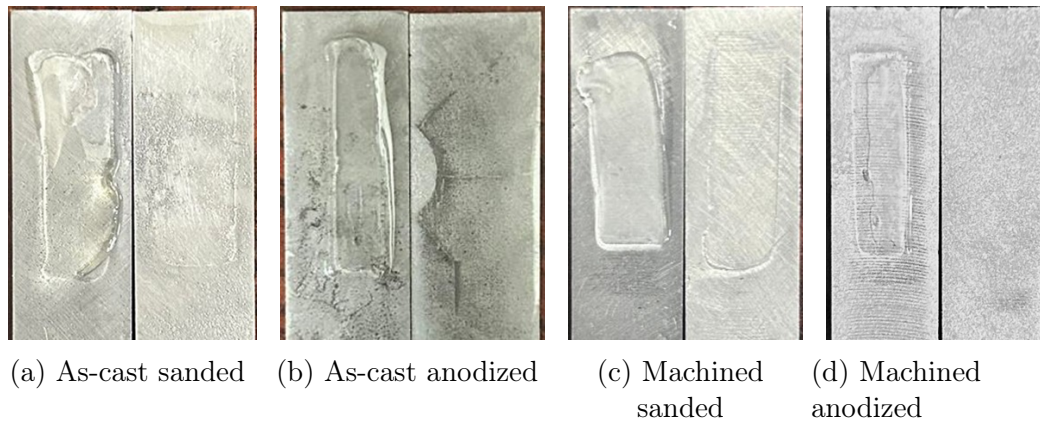


Figure 37: Failure surfaces of the SLJs in durability tests for the LS-XU adhesive.

The shrinkage of the LS-XU adhesive layer after immersion in hydraulic oil can be explained by the chemical nature of the adhesive, which is based on a cyclic olefin polymer. Cyclic olefin copolymers (COCs) and cyclic olefin polymers (COPs) are generally characterized by their low polarity and high glass transition temperature, properties that make them attractive for barrier and structural applications [49,71].

However, their hydrophobic backbone also renders them susceptible to interaction with non-polar environments such as hydrocarbons and oils. When exposed to hydraulic oil for prolonged periods, low-molecular-weight oil components can diffuse into the polymer network, leading to plasticization and leaching of unreacted oligomers or additives. This process alters the equilibrium state of the polymer matrix, often resulting in volumetric contraction as the absorbed oil modifies chain packing and accelerates physical ageing [72].

Additionally, hydrocarbon oils are known to act as solvents or swelling agents in non-polar polymers, depending on compatibility and molecular size. For cyclic olefin-based systems, which lack strong intermolecular interactions, oil absorption can disrupt the free volume distribution. Upon desorption or redistribution of these molecules, the adhesive may undergo densification and dimensional shrinkage [73]. This mechanism provides a plausible explanation for the observed reduction in adhesive layer thickness after 32 days of immersion.

In the context of adhesive joints, such shrinkage is particularly critical as it not only changes the stress distribution within the bondline but may also accelerate adhesive failure under mechanical loading. These findings align with previous reports on the environmental degradation of hydrocarbon-based adhesives, where oil immersion led to microstructural changes, embrittlement, and loss of interfacial integrity [23].

Figure 38 illustrates a critical condition of the adhesive within the SLJ, at which spontaneous debonding of the joint occurs.

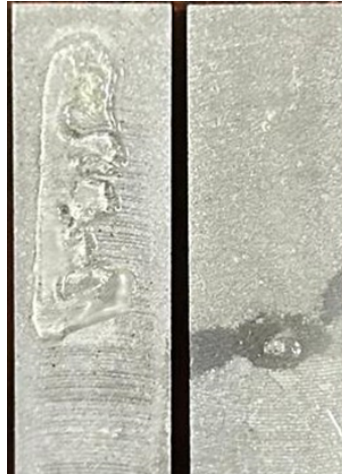


Figure 38: LS-XU adhesive shrinkage after contact with hydraulic oil.

Figures 39, 40, 41 and 42 present the comparisons between the aged and non-aged SLJs for each combination of surface treatment and substrate condition, for the LS-XU adhesive.

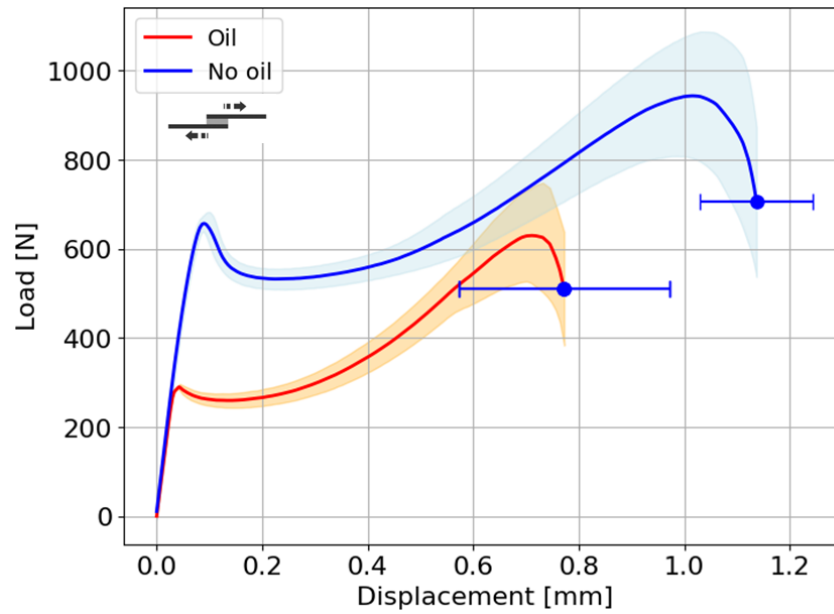


Figure 39: Comparison of as-cast sanded SLJs bonded with the LS-XU adhesive under normal and durability testing.

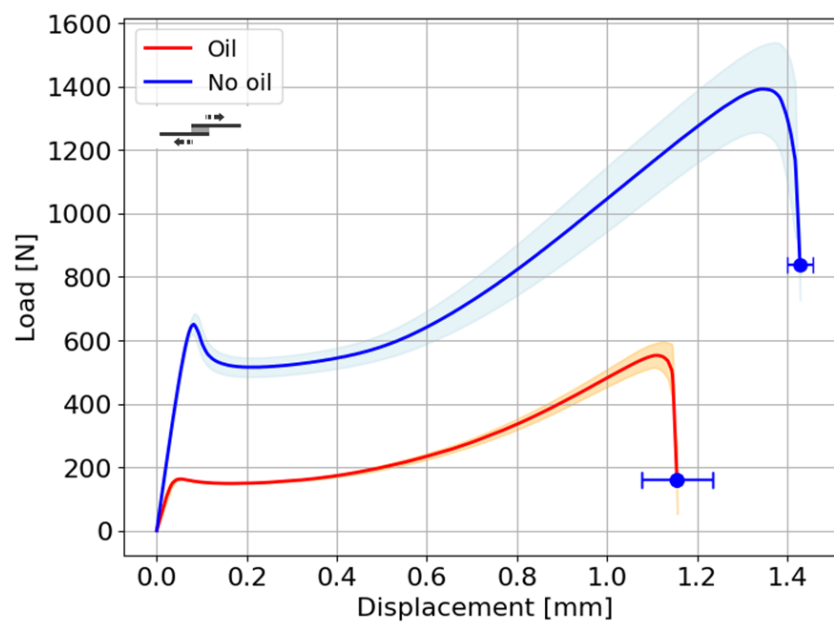


Figure 40: Comparison of as-cast anodized SLJs bonded with the LS-XU adhesive under normal and durability testing.

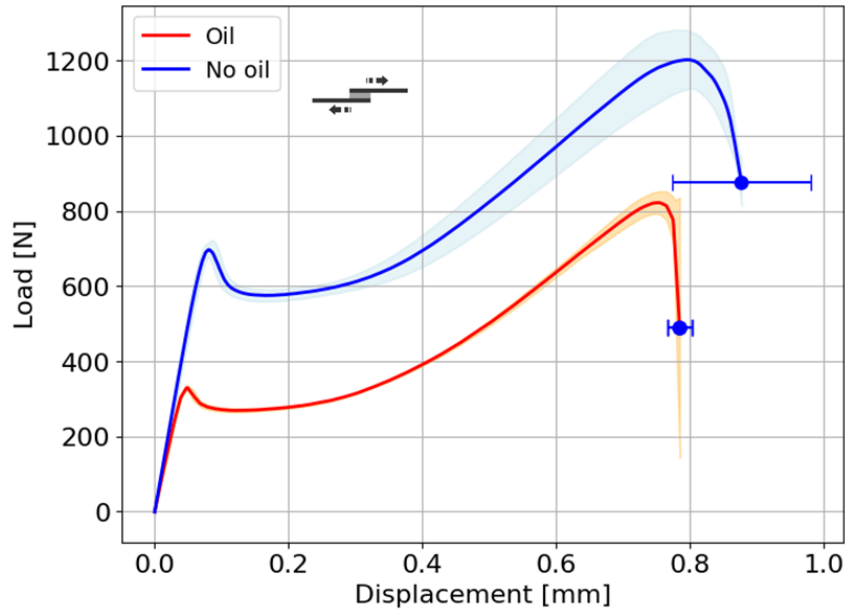


Figure 41: Comparison of machined sanded SLJs bonded with the LS-XU adhesive under normal and durability testing.

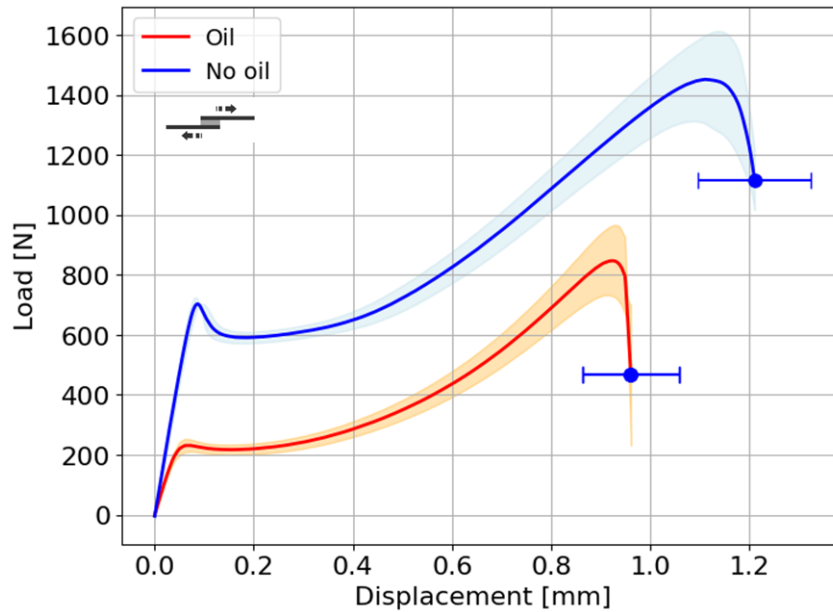


Figure 42: Comparison of machined anodized SLJs bonded with the LS-XU adhesive under normal and durability testing.

The durability tests of the LS-XU adhesive reveal a consistent detrimental effect of hydraulic oil on the performance of SLJs, regardless of the substrate condition or surface treatment. In all cases, the oil-aged specimens show a substantial reduction in both maximum load and displacement when compared to the unaged counterparts, confirming that long-term oil exposure weakens the adhesive layer and accelerates failure. This degradation is most evident in the as-cast anodized joints, which present the lowest mechanical resistance after ageing, dropping to nearly one third

of the strength of the unaged condition. The marked loss of performance in this case highlights a particularly poor compatibility between anodized as-cast surfaces and the LS-XU adhesive in oil-rich environments.

From an engineering standpoint, this behaviour has direct relevance for automotive applications where bonded structures may be exposed to oils and lubricants during service. The results underline that cyclic olefin-based adhesives such as LS-XU are particularly vulnerable and should be avoided in oil-exposed environments, as it compromises long-term reliability of the joints.

Figure 43 presents the results of the durability tests performed on Teroson MS 939 polymer adhesive, for four different combinations between surface treatments and substrates conditions, the same ones performed for the LS-XU adhesive.

The aged SLJs bonded with the MS polymer adhesive reveal that the machined anodized specimens reach the highest peak loads, demonstrating that anodizing in combination with machining enhances interfacial performance and provides greater resistance to ageing effects. The sanded specimens, both as-cast and machined, exhibit similar load levels, with peak values slightly below the anodized condition, but they fail at lower displacements, suggesting a more brittle response.

A distinct characteristic of the as-cast anodized specimens is their ability to sustain larger displacements, extending up to 3.5 mm, despite a lower ultimate load compared to the machined anodized condition. This indicates that while they are not the strongest, they possess improved deformability, which could be beneficial in applications requiring greater energy absorption. Overall, the results confirm that MS polymer adhesives retain bonding capability after ageing, but their performance remains highly dependent on surface treatment. Anodizing, particularly on machined substrates, appears to offer the best balance between strength and durability, while sanding provides intermediate behaviour with a tendency toward earlier failure.

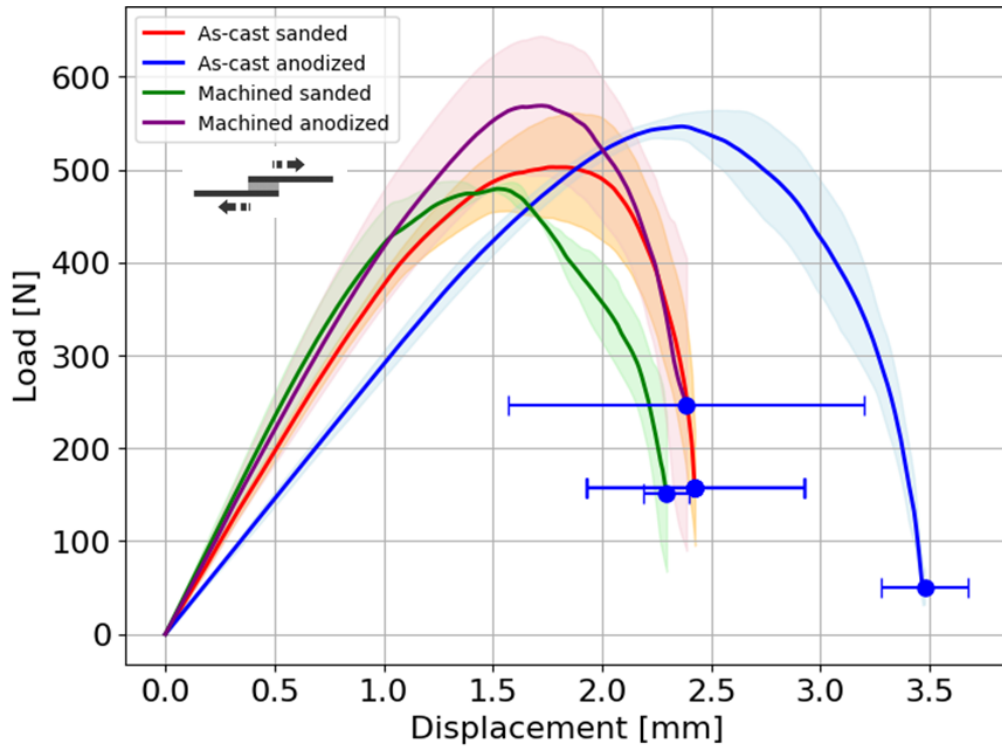


Figure 43: Durability test results for the Teroson MS 939 polymer adhesive.

Figure 44 illustrates the failure modes for the SLJs tested. The as-cast sanded and machined sanded specimens (a and c) display extensive regions of adhesive failure, with large areas of exposed substrate visible. This suggests a weaker interfacial adhesion in sanded surfaces under ageing conditions, likely due to the combined effects of oil absorption and reduced surface stability, which promote debonding at the interface. In contrast, the anodized specimens (b and d) show a more uniform adhesive layer remaining on the substrate, with less extensive exposed regions. This indicates a stronger interfacial bond compared to sanded surfaces, though still accompanied by adhesive failure. This reflects the beneficial role of anodizing in enhancing surface roughness and chemical compatibility, thereby improving the durability of the joint and resistance to oil-induced degradation.

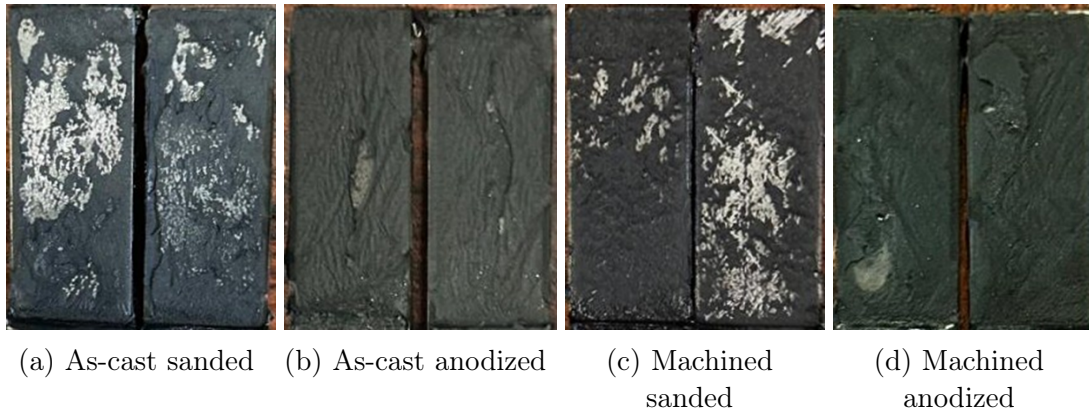


Figure 44: Failure surfaces of the SLJs in durability tests for the Teroson MS 939 adhesive.

Figures 45, 46, 47 and 48 present the comparisons between the aged and non-aged SLJs for each combination of surface treatment and substrate condition, for the Teroson MS 939 polymer adhesive.

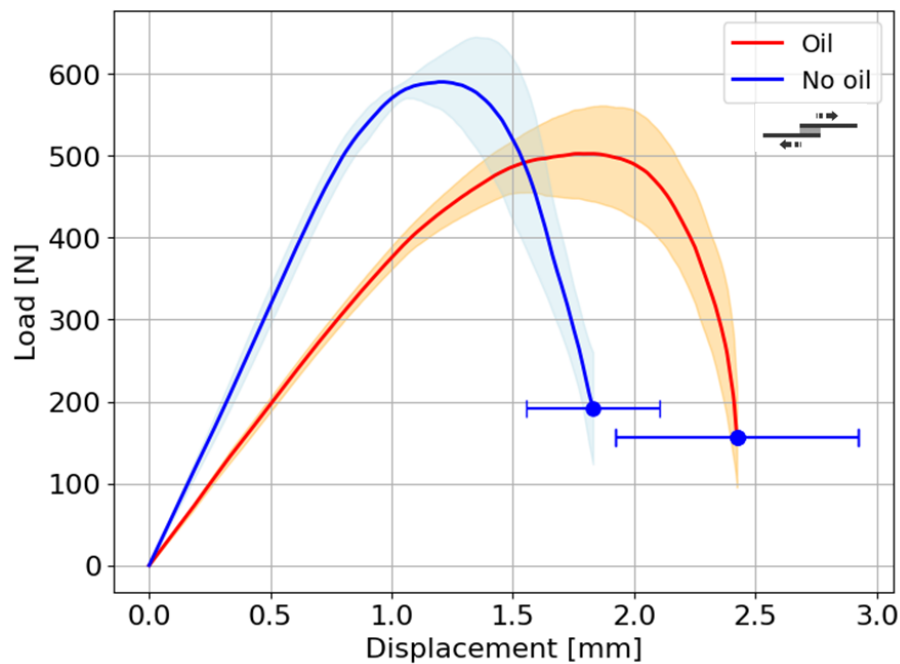


Figure 45: Comparison of as-cast sanded SLJs bonded with the Teroson MS 939 adhesive under normal and durability testing.

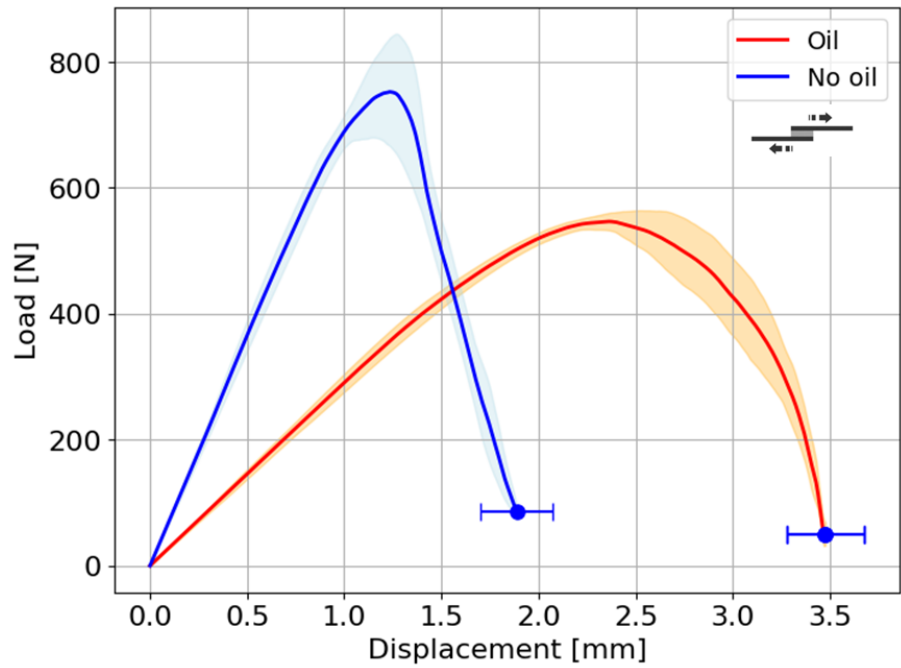


Figure 46: Comparison of as-cast anodized SLJs bonded with the Teroson MS 939 adhesive under normal and durability testing.

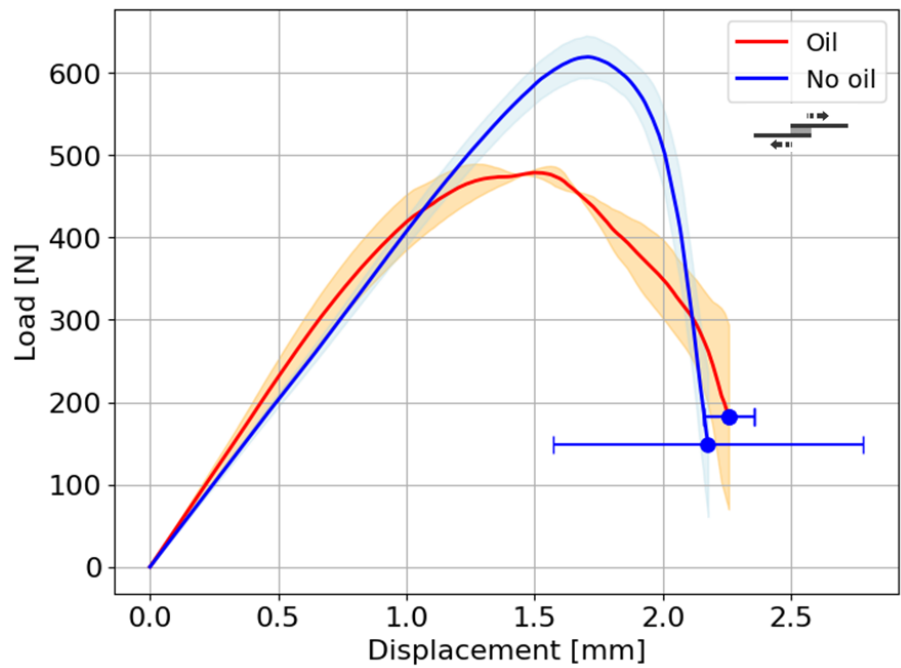


Figure 47: Comparison of machined sanded SLJs bonded with the Teroson MS 939 adhesive under normal and durability testing.

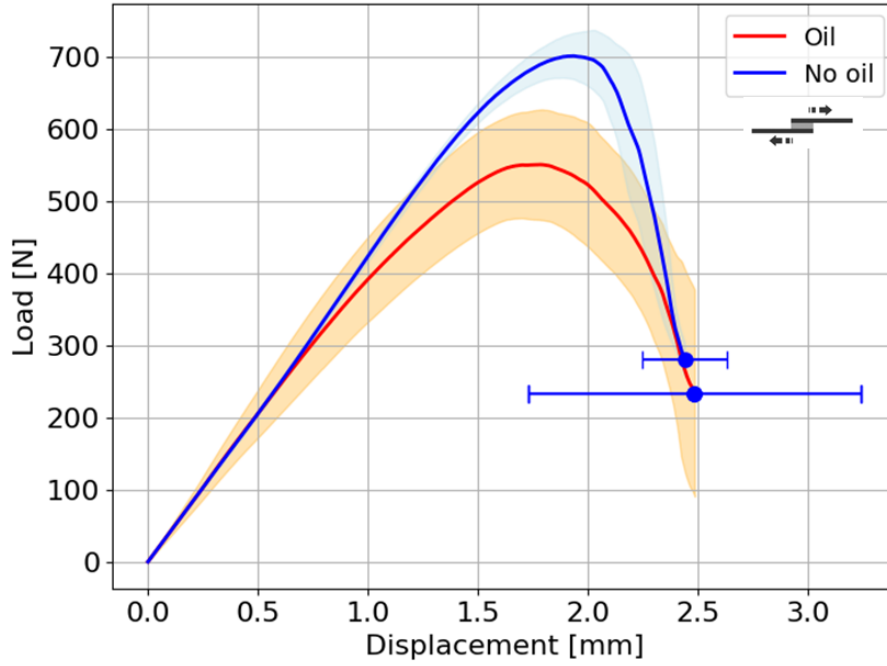


Figure 48: Comparison of machined anodized SLJs bonded with the Teroson MS 939 adhesive under normal and durability testing.

The durability results of the MS polymer adhesive under oil ageing conditions demonstrate a consistent reduction in mechanical performance across all surface treatments and substrate conditions. In general, the oil-aged SLJs show lower maximum loads and reduced stiffness compared to the unaged counterparts, confirming that prolonged exposure to oil negatively affects the adhesive bondline. Despite this overall trend, the severity of the degradation varies with surface treatment.

The most critical behaviour is observed in the as-cast anodized specimens, as well noticed in the LS-XU adhesive, which experience the sharpest decline in strength after oil exposure. Their load-bearing capacity drops markedly, and the curves show premature failure with limited ability to sustain load beyond 2 mm of displacement.

From an engineering perspective, these results emphasize that while MS polymer adhesives can provide acceptable bonding performance under standard conditions, their durability in oil-rich environments is strongly dependent on surface preparation. In particular, as-cast anodized substrates should be avoided in automotive applications where contact with lubricants and hydraulic fluids is expected, as they present the least reliable long-term behaviour.

4.3 90° peel test

In this section, the discussion will be more focused on an automotive perspective of the results. A more detailed analysis of these results is presented in Paper A, appended to this thesis.

Figure 49 presents the load vs displacement curve for the peel test of the LS-XU

adhesive. Importantly, peel tests primarily assess the adhesion of the adhesive to the substrate rather than its cohesive strength, meaning that the results here reflect the interfacial quality of the LS-XU bondline. The steady plateau suggest that the adhesive maintains reliable adhesion with no abrupt failures under peel loading.

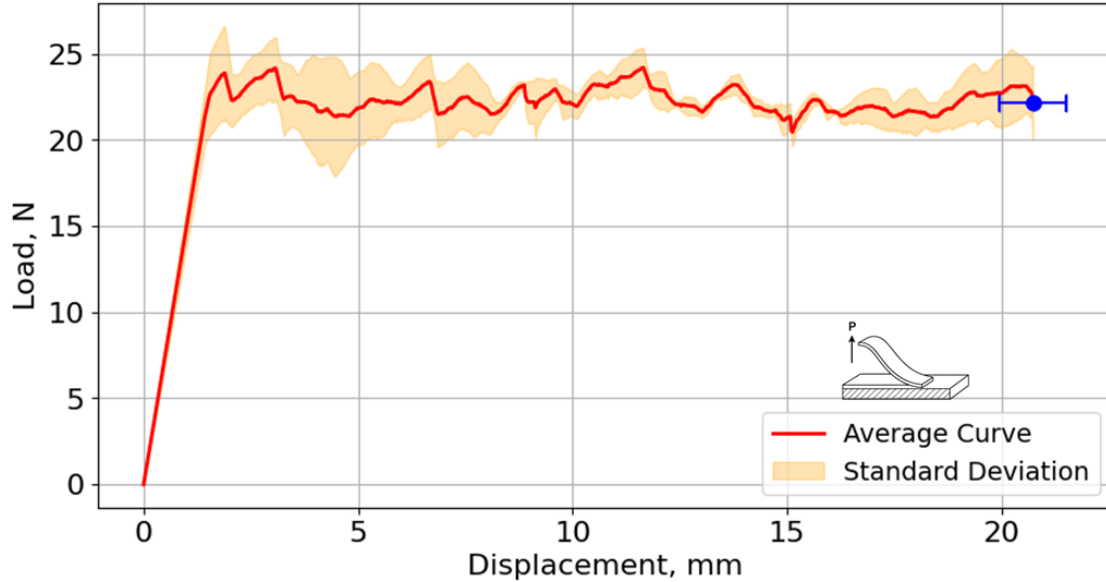


Figure 49: Results of the peel test of the LS-XU film adhesive.

The peel strength is measured by G , in N/mm, where $G = \frac{P}{b}$, being P the peel load and b the adhesive width. This result is presented in Figure 50. When compared with values reported in the literature, the performance of the LS-XU adhesive film is within a realistic range for polymer-based adhesives. Typical peel strengths for structural epoxies lie between 2–6 N/mm depending on substrate and surface treatment [23,74], while pressure-sensitive adhesives and elastomeric systems often range between 1–3 N/mm [28]. The peel strength of ~ 3.2 N/mm obtained here therefore places LS-XU within the lower spectrum of structural adhesives but higher than many flexible sealants, indicating it can provide durable adhesion in conditions where peel stresses are inevitable.

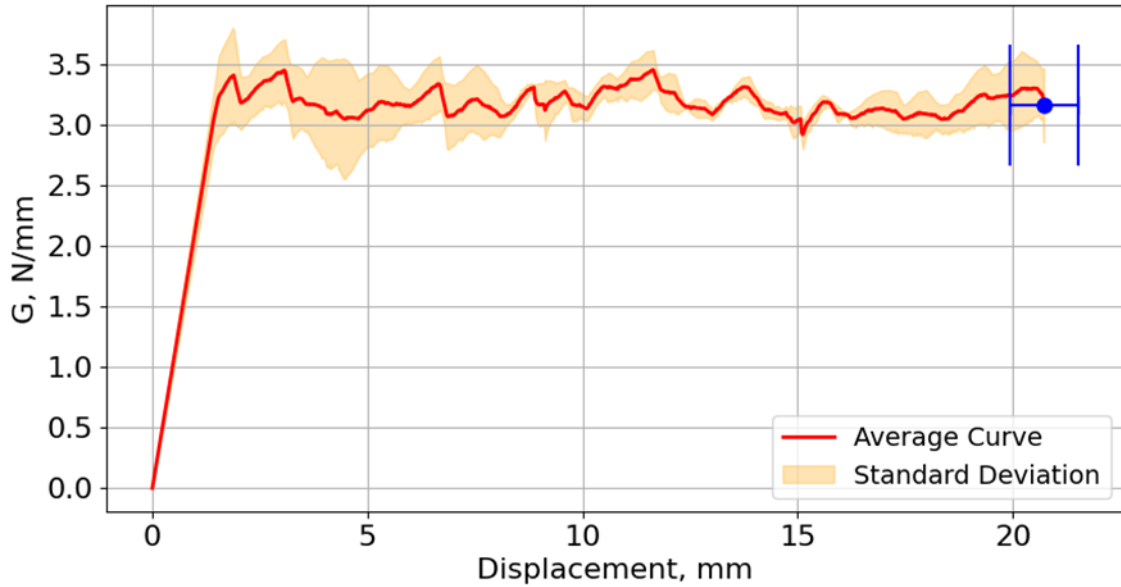


Figure 50: Peel strength, G , for the LS-XU film adhesive.

In the automotive sector, peel stresses are particularly relevant in joints where prying, bending, or out-of-plane forces occur, such as trim attachments, seals, weatherstrips, or layered panels prone to edge lifting. The relatively stable response of LS-XU under these conditions suggests that it could be used effectively in semi-structural or secondary applications, where peel resistance and adhesion reliability are more critical than ultimate shear strength. However, given its moderate performance compared to high-strength epoxies, its use should be limited to areas where peel loading is unavoidable but not excessive, ensuring long-term reliability of bonded automotive assemblies.

Figure 51 presents the load vs displacement curve for the peel test of the Teroson MS 939 adhesive. These results suggest that the MS polymer adhesive provides more robust surface interaction than LS-XU under peel stresses, due to the higher load values.

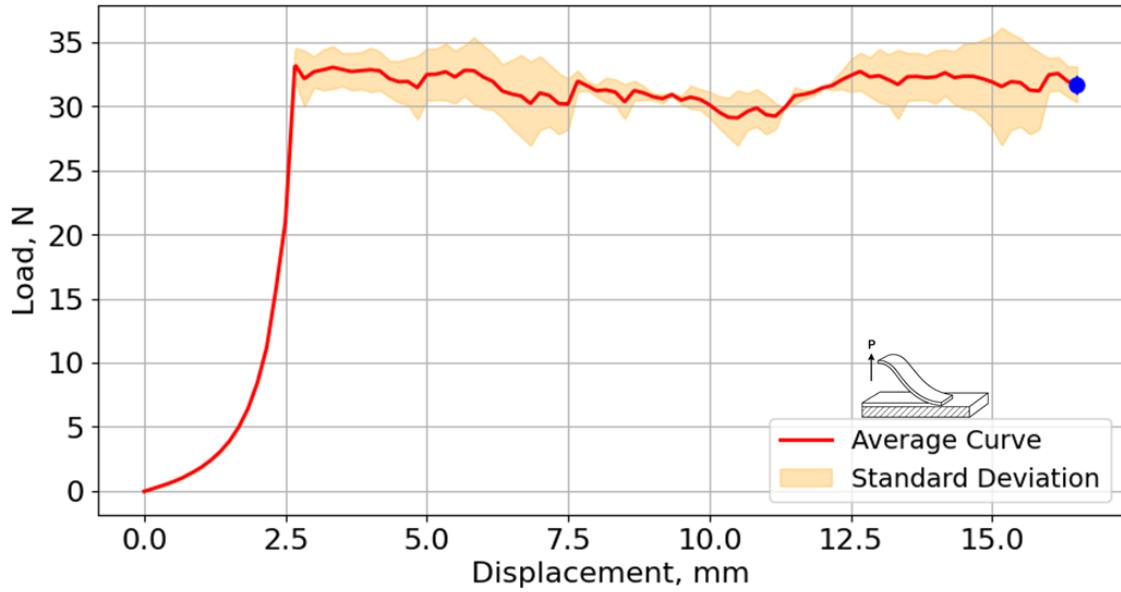


Figure 51: Results of the peel test of the Teroson MS 939 adhesive.

Regarding peel strength, the results for the Teroson MS 939 adhesive is given in Figure 28. Literature values for flexible adhesives, such as polyurethanes and MS polymers, can exhibit peel energies between 3–5 N/mm [31]. The value measured here of ~ 4.4 N/mm therefore position the MS polymer adhesive at the higher end of flexible systems and close to the lower spectrum of structural adhesives.

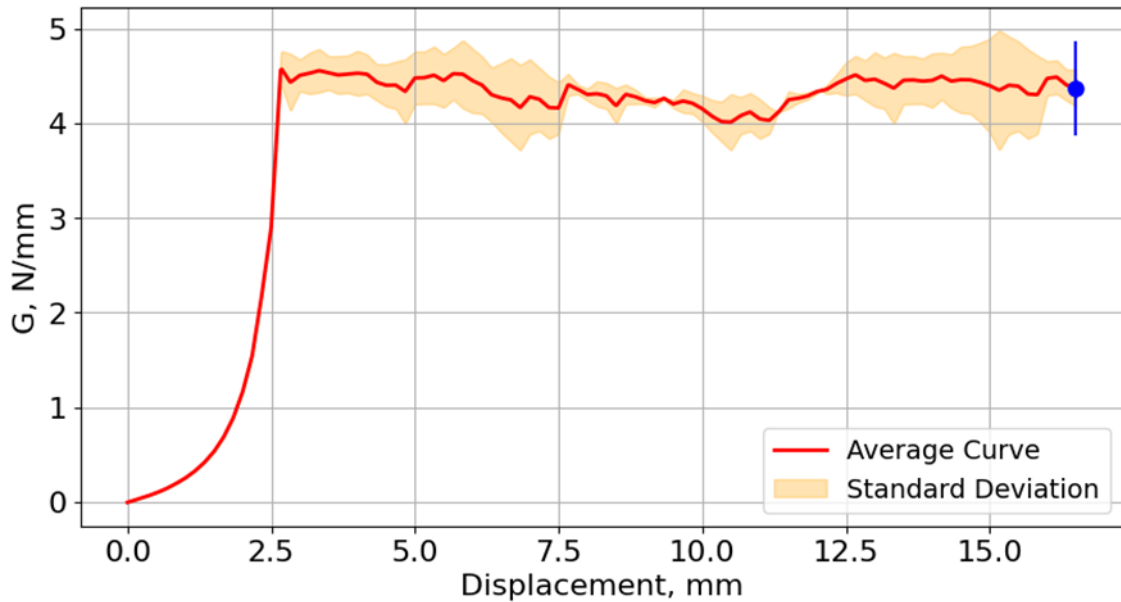


Figure 52: Peel strength, G , for the Teroson MS 939 adhesive.

From an automotive perspective, the higher and more stable peel resistance of the MS polymer adhesive compared to typical flexible sealants suggests that it could provide durable adhesion in such applications, reducing the risk of premature debonding under service conditions. Its ability to maintain adhesion under

peel stresses makes it particularly relevant for non-structural and semi-structural automotive components where exposure to peel loads is unavoidable.

Moving forward to the FSW bonded specimens for the peel test, the load vs displacement curve is presented in Figure 53 and the peel strength, G , result is presented in Figure 54. The peel test results for the FSW joints show a markedly different behaviour compared to the adhesive films, with both the load and peel strength increasing almost linearly up to failure. The specimens reached a maximum load of around 800 N and a corresponding peel strength, G , close to 80 N/mm before catastrophic failure occurred. Unlike the adhesive joints, where a plateau region and oscillations were observed after crack initiation, the FSW specimens display a single monotonic rise, reflecting the metallic continuity and plastic deformation capability of the welded interface rather than interfacial debonding.

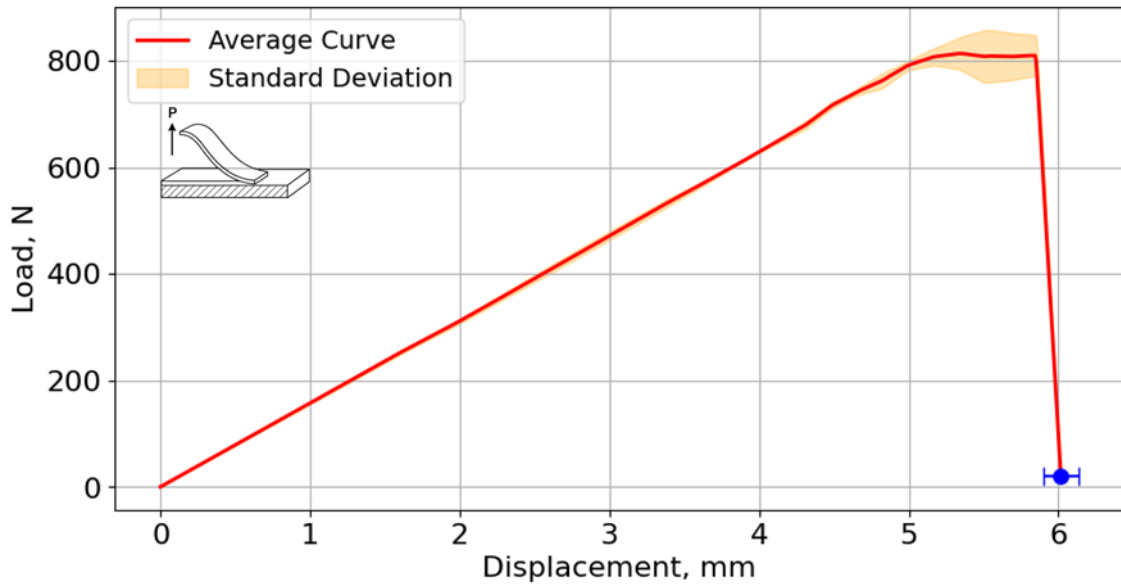


Figure 53: Results of the peel test of the FSW specimens.

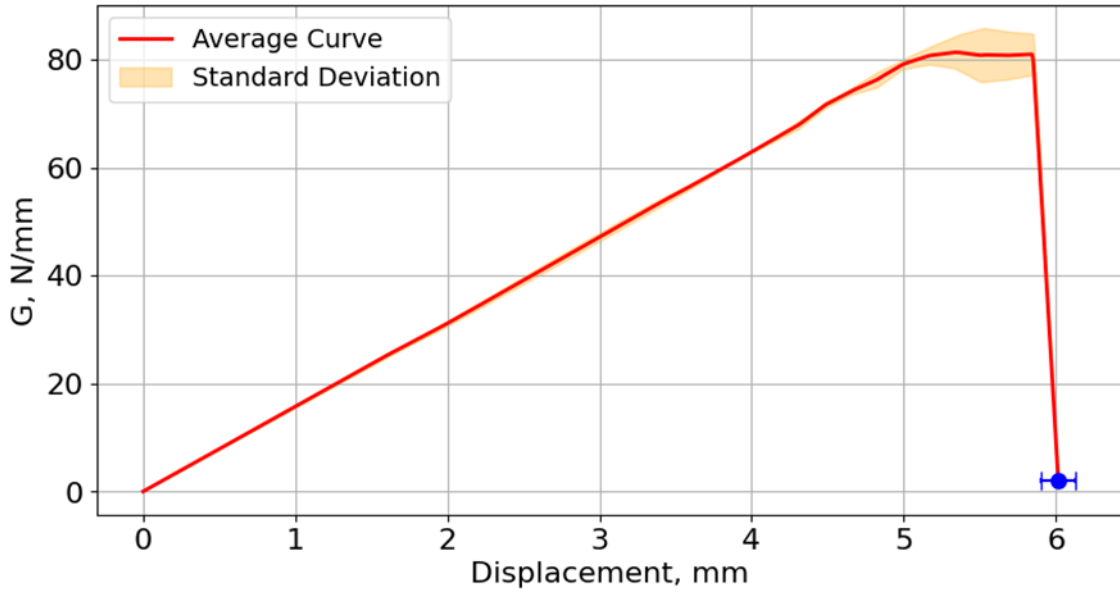


Figure 54: Peel strength, G , for the FSW specimens.

This performance indicates that under peel stresses, FSW joints provide substantially higher resistance, maintaining integrity up to very high forces without progressive interfacial degradation. From an automotive perspective, this is highly relevant for structural components subject to prying or opening forces, such as closures, battery housings, or safety-critical crash structures. The high peel resistance of FSW ensures that joints can withstand extreme conditions without premature failure, offering a level of robustness well beyond that achievable with polymer-based adhesives. However, it is also important to note that while adhesives can provide flexibility, vibration damping, and corrosion protection, FSW offers rigid, metallurgical bonding at the cost of reduced compliance.

Thus, while FSW is advantageous for primary structural joints exposed to peel stresses, adhesives remain better suited to semi-structural or secondary applications where flexibility and energy absorption are more desirable. The complementary use of both techniques in automotive design can therefore provide a balance between strength, durability, and functional performance.

4.4 Internal pressure testing

This section is where internal pressure tests results will be provided and discussed, while connecting them to the automotive context, where the studied aluminium component is included.

Figure 55 compares the results from both adhesives, LS-XU and Teroson MS 939, and the FSW specimens.

For the adhesives, the load–displacement response was tracked only to the first-failure plateau, which marks the onset of stable, local debonding rather than global

separation. The results highlight a clear difference in performance between the LS-XU and Teroson MS 939 adhesives. The LS-XU specimens exhibit a steeper initial slope, reaching their peak load capacity of approximately 2.2 kN at a displacement of less than 1 mm, after which failure occurs abruptly. This behaviour indicates a relatively stiff but brittle response under internal pressure loading, with limited capacity for energy absorption once the peak load is reached. By contrast, the Teroson MS 939 adhesive shows a more progressive load–displacement response, sustaining loads beyond 4 kN with displacements exceeding 3 mm before failure. This indicates not only a higher ultimate strength but also significantly greater ductility compared to LS-XU. The extended plateau region near the maximum load suggests that there was plastic deformation of the lid, while the adhesive accommodated pressure-induced deformations without immediate failure, providing both strength and tolerance to structural compliance.

For the FSW specimens the load–displacement curve is almost a straight line up to the maximum load, which shows a stiff, largely elastic–plastic response controlled by global bending and membrane stretching of the aluminium lid. There is no clear plateau before failure, instead, the curve drops suddenly at the peak, indicating the rapid formation of a leak rather than slow damage growth. The peak load for this specimens is around 13.3 kN, in a displacement superior than 5 mm.

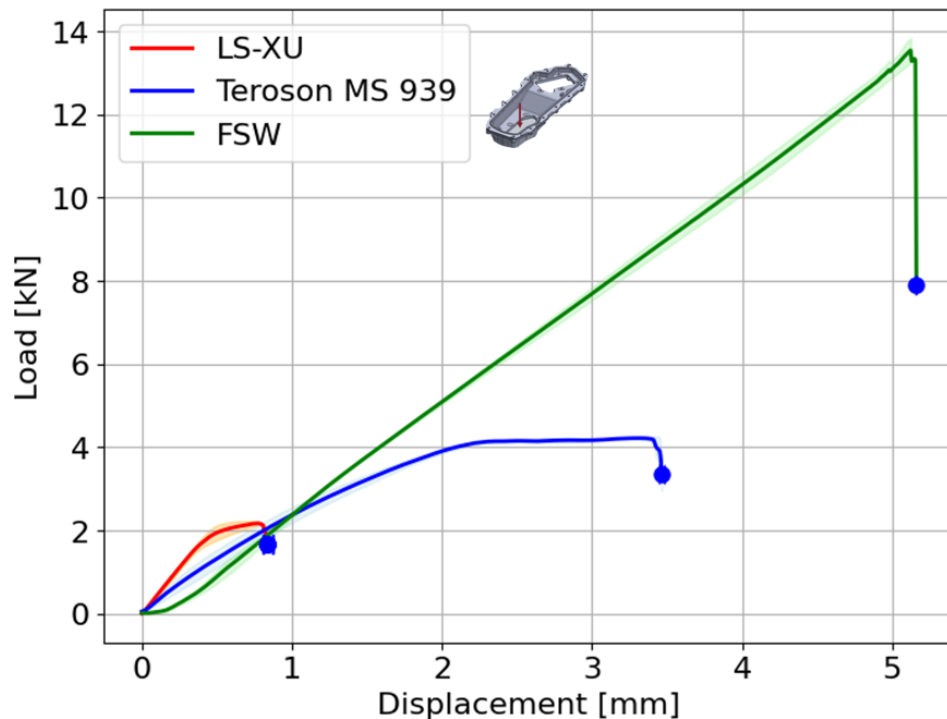


Figure 55: Internal pressure test results for both adhesives, LS-XU and Teroson MS 939.

From an automotive perspective, these findings are particularly relevant for bonded structures that may be subjected to internal pressurisation, such as battery

housings, sealed enclosures, or fluid-containing assemblies. While LS-XU provides adequate stiffness and strength for low-deformation scenarios, its brittle behaviour limits its suitability for applications where joints must withstand pressure fluctuations or impact-induced stresses. Teroson MS 939, with its higher strength and superior deformation capacity, appears far more suitable for such conditions, ensuring both structural integrity and leak-proof performance under service-relevant internal pressures. FSW offers very high stiffness and burst strength for pressurised enclosures, making it appropriate where minimal deformation under internal pressure is essential. However, because failure can be abrupt once a leak initiates at the seam, its use should be paired with tight process control and, where needed, a secondary seal to maintain leak-tight performance.

Figure 56 shows the failure mode of the LS-XU adhesive. As seen previously in SLJs testing, the failure is consistently adhesive. After the first-failure plateau, the LS-XU adhesive deformed locally but didn't fully separate, so when the specimen was depressurized and unloaded, the adhesive recovered enough to re-seat the joint, so the lid did not come off.



Figure 56: Failure mode of the LS-XU adhesive in internal pressure testing.

Regarding Teroson MS 939 failure mode, illustrated in Figure 57, it is clearly mixed failure, with both adhesive and cohesive zones. Since the substrates were only acetone degreased, this failure mode is also consistent with the SLJs failure modes previously presented. For this case, the specimen was fully separated in the testing machine, for a full vision of the failure mode.



Figure 57: Failure mode of the Teroson MS 939 adhesive in internal pressure testing.

Finally, Figure 58 shows the failure of the FSW specimen under internal pressure testing. The aluminium lid noticeably domed by internal pressure and a narrow opening along the weld line. The doming explains the near-linear rise in the curve, while the local opening provides a leak path that causes a sharp pressure loss and the abrupt load drop at failure. The fracture appearance therefore matches the mechanical record from the FSW test.



Figure 58: Failure mode of the FSW specimen in internal pressure testing.

Regarding the operating conditions of the studied component mentioned in section 3.1, when benchmarking both adhesive systems against them, they present important limitations. From the internal pressure tests, LS-XU achieved an equivalent pressure capacity of only ~ 3 bar, which is below the pulsation band (4.5 - 6 bar) and far from the maximum operating requirement of 9.7 bar. Teroson MS 939, in contrast, reached ~ 6.5 bar, providing sufficient resistance to pulsation but remaining marginal for the static pressure limit. When the thermal envelope is considered, LS-XU is further restricted by its reported softening temperature of 87.7°C , which is well below the specified 140°C limit, disqualifying it from service under elevated temperatures. Teroson MS 939 shows broader thermal compliance, retaining functionality down to -30°C and up to $\sim 120^\circ\text{C}$. However, this still falls short of the full operating range, with expected property loss beyond its thermal ceiling.

Oil durability further reinforces these distinctions. LS-XU, as a cyclic olefin copolymer, exhibits poor chemical resistance and cannot maintain adhesive performance in direct oil contact, eliminating it as a candidate for this application. Teroson MS 939 demonstrates superior compatibility, with experimental evidence indicating that while some reduction in mechanical properties occurs after oil exposure, the adhesive remains cohesive and serviceable, especially under pulsating pressure loads.

Overall, LS-XU is unsuitable across all boundary conditions, being limited in pressure, temperature, and oil resistance. Teroson MS 939 performs comparatively better, particularly with respect to pulsation resistance and oil compatibility, yet it still fails to cover the full pressure and thermal operating requirements. Under the combined constraints of 9.7 bar maximum pressure, -30 to 140°C operating temperature, and oil exposure, neither adhesive can be regarded as fully compliant for reliable long-term service, highlighting the need to consider alternative high temperature, chemically resistant structural adhesives in future evaluations.

5 Numerical analysis

5.1 Single lap joints

The adhesive joints tested experimentally were reproduced numerically in ABAQUS®FE in order to evaluate their mechanical behaviour under tensile shear loading and to provide a direct comparison with experimental results. A two-dimensional finite element model was developed to represent the single lap joint (SLJ) configuration, balancing computational efficiency with sufficient accuracy to capture the main stress distributions and failure mechanisms. This SLJ configuration is illustrated in Figure 59.

Under quasi-static conditions, the adherends and adhesive were modelled using 2D plane stress elements with reduced integration (CPS4R). This choice was made because the joint thickness is small relative to its length and width, making plane stress assumptions appropriate for capturing in-plane stress states. Reduced integration was employed to avoid volumetric locking and to improve computational efficiency, with hourglass control activated to mitigate potential element distortions.

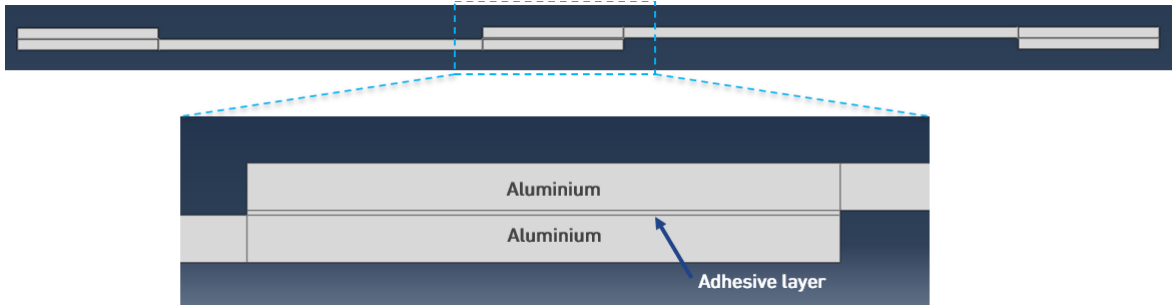


Figure 59: 2D static model of the SLJ in ABAQUS®FE.

The boundary conditions were established according to the experimental tests of single lap joints. One end of the joint was fully constrained in all directions ($U1=U2=U3=0$), while the opposite end was subjected to a prescribed displacement in the axial direction ($U1$), replicating the conditions of the tensile test. Out-of-plane degrees of freedom were restrained to enforce the 2D assumption. The loading was applied incrementally under static general analysis steps, allowing for the capture of nonlinear material and damage behaviour. Figure 60 presents the boundary conditions applied to the SLJ.



Figure 60: Boundary conditions applied to the SLJ in ABAQUS®FE.

Regarding the mesh applied to the model, it was refined in the overlap region

where high stress gradients are expected, particularly near the free edges of the adhesive layer where peel and shear stresses concentrate. A coarser mesh was applied to the adherends outside the overlap to reduce computational cost while maintaining accuracy in the critical region. Mesh convergence studies were performed to ensure that further refinement in the adhesive layer did not significantly alter the predicted load–displacement response. As illustrated in Figure 61, mesh refinement is evident in the overlap regions.



Figure 61: Mesh applied to the SLJ in ABAQUS®FE.

Teroson MS 939 model

When modelling the Teroson MS 939 MS polymer adhesive, the adhesive layer was characterized with hyperelastic properties. To represent the observed cohesive failure, the adhesive layer was partitioned through its thickness into two equal sub-layers, and a cohesive zone was inserted mid-thickness between the hyperelastic bulk material, that uses a 4-node two-dimensional cohesive element, COH2D4. Figure 62 presents the schematic representation of the Teroson MS 939 single lap joint in ABAQUS®FE.

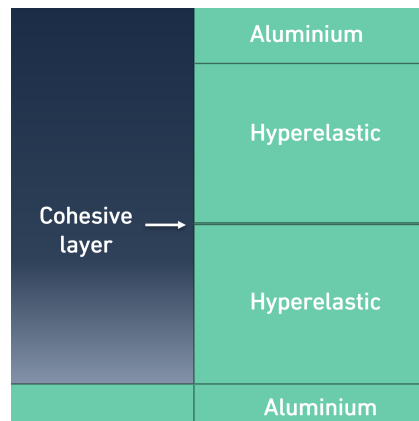


Figure 62: Schematic representation of Teroson MS 939 single lap joint model as constructed in ABAQUS®FE.

The hyperelastic model used was Marlow Model. This model is a data-driven formulation that requires only a single set of experimental test data, such as a uniaxial tension curve, to define the strain energy potential. Unlike polynomial or Ogden-type hyperelastic models, the Marlow model does not rely on an assumed analytical expression. Instead, it directly interpolates the supplied data, ensuring that the predicted stress–strain response under primary loading exactly follows the experimental input. This feature makes the Marlow model particularly suitable

when reliable uniaxial test data are available but multiaxial datasets are limited or not feasible to obtain.

For this study, the stress–strain curve measured from bulk tensile tests of Teroson MS 939 was used as the input dataset for the Marlow formulation. The curve, shown in Figure 63, was therefore reproduced precisely by the numerical model during uniaxial loading. This allowed the adhesive layer in the single lap joint simulations to reflect the experimentally observed nonlinear elastic behaviour of the MS polymer, while avoiding the need for assumptions about the material’s response beyond the test range. By relying on direct experimental data, the model provides a robust representation of the adhesive’s load–deformation characteristics under the conditions most relevant to the joint configuration studied.

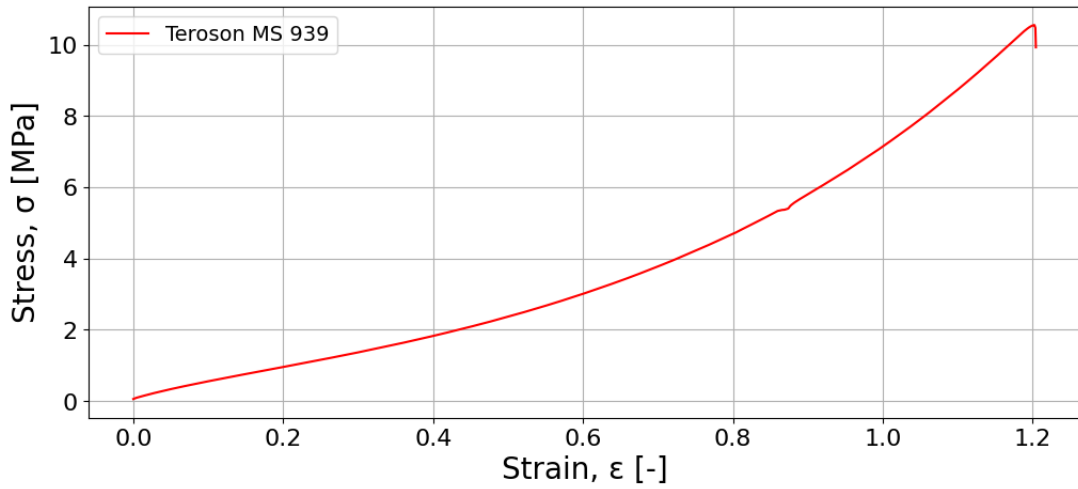


Figure 63: Stress vs strain curve for Teroson MS 939 obtained from bulk testing.

It is important to note that MS polymers such as Teroson MS 939 are, in reality, viscoelastic materials. Their molecular architecture, combining a flexible polyether backbone with siloxane crosslinks, gives rise to time-dependent behaviours including creep, stress relaxation, and rate sensitivity. A more physically complete model would therefore ideally combine a hyperelastic formulation with a viscoelastic representation (e.g., a Prony series) to capture both instantaneous nonlinear elasticity and long-term time-dependent effects. However, the present study focused on monotonic, quasi-static tests, for which time-dependent contributions are comparatively minor. Furthermore, the experimental dataset available for calibration consisted only of bulk uniaxial tension results, which are sufficient for defining an elastic law but not for identifying viscoelastic parameters. For these reasons, the Marlow hyperelastic model was adopted as a pragmatic choice, providing an accurate description of the nonlinear load–displacement behaviour under the conditions examined, while acknowledging that viscoelastic phenomena may become relevant under cyclic or long-term service conditions.

In the cohesive layer, the cohesive elements (COH2D4) were assigned elastic properties consistent with those of the bulk adhesive in order to ensure realistic stiffness prior to damage initiation. Damage initiation was governed by the quadratic nominal stress criterion (QUADS) implemented in ABAQUS®FE, which accounts for the combined effect of normal and shear stresses acting on the cohesive plane. Once the initiation threshold was reached, damage evolution was described through an energy-based softening law, in which the area under the traction–separation curve corresponds to the fracture energy. Mode-I and mode-II fracture energies were calibrated against experimental lap shear data, and a mixed-mode interaction law was applied to capture the combined influence of opening and shear. This formulation allowed progressive stiffness degradation of the cohesive layer, leading to crack propagation through the adhesive thickness and enabling the model to reproduce the experimentally observed cohesive fracture surfaces.

LS-XU model

Regarding the modelling of the film adhesive LS-XU, the the bulk adhesive layer was characterized with elastic and plastic properties. The elastic data was obtained from bulk tensile testing and the plastic data from a reverse engineering process, obtaining the stress vs strain curve.

To model the failure of the SLJ, which is adhesive, the debonding is captured with surface-to-surface contact interactions, in each interface adherend-adhesive in the joint, provided with cohesive behaviour. The cohesive properties were inputted as a contact property defined with traction-separation elastic stiffness and damage initiation following the quadratic nominal stress criterion (QUADS) in ABAQUS®. For damage evolution Benzeggagh–Kenane (BK) law was chosen due to the fact that its coefficient, η , controls how the effective fracture energy increases with shear content. This matches the experimentally observed rise in toughness for hot-melt adhesives under mode-II-dominated loading in single-lap joints. Figure 10 presents the schematic representation of the film adhesive LS-XU single lap joint.

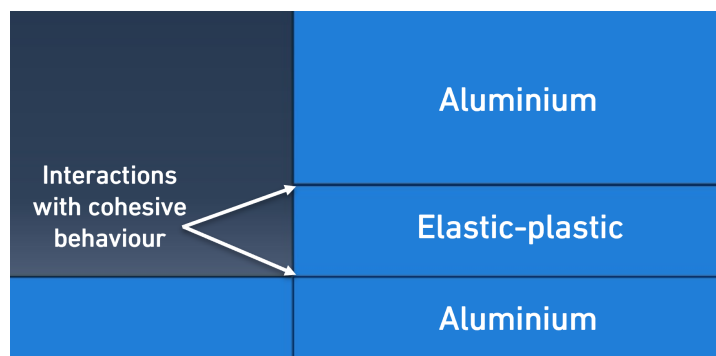


Figure 64: Schematic representation of LS-XU single lap joint in ABAQUS®.

5.2 Internal pressure test

Numerical modelling was undertaken to complement the experimental investigation of the internal pressure performance of the bonded joints. In line with the boundary condition requirements defined for the component, the analysis focused exclusively on the MS polymer adhesive, Teroson MS 939. The hot-melt LS-XU was excluded from further study, as its mechanical response under pressure, thermal stability, and oil durability all fell below the operational thresholds, rendering it unsuitable for application. By concentrating on Teroson MS 939, which demonstrated conditional compliance in the pulsation regime and retained functional cohesion under oil exposure, the modelling effort aims to replicate its load–displacement response and to assess its behaviour under simulated service conditions. This approach provides a means of validating the experimental findings, exploring stress distributions at the bond interface, and identifying potential failure mechanisms that may not be directly observable in laboratory testing.

To facilitate computation, the numerical model was developed using a simplified representation of the bonded area, rather than the full component geometry. This reduction in complexity allowed for greater efficiency in solving the problem, while still capturing the critical stress–strain behaviour within the adhesive layer. Figure 65 illustrates the three parts created in ABAQUS®, that consist of a simplified part that represents the die-cast aluminium component, only for the bonded area, the adhesive layer and the lid.

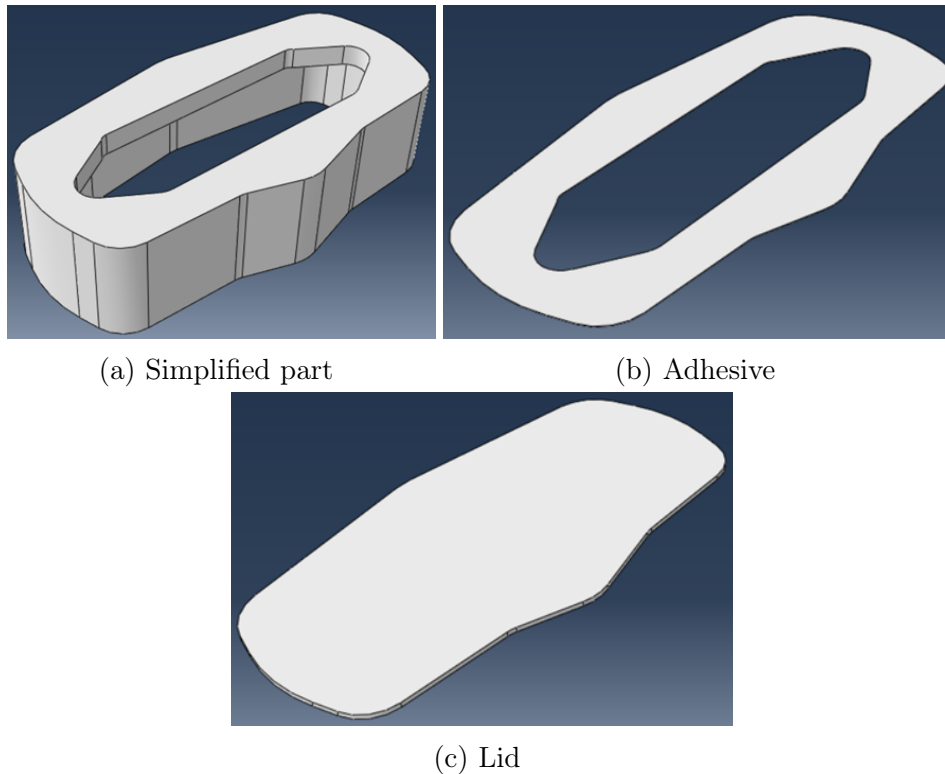


Figure 65: Parts created in ABAQUS® to model the internal pressure test.

After assembling the three parts, the boundary conditions (BCs) were defined to match the experimental test set-up. To apply BCs to the model there was the need of creating two reference points. The first reference point, RF1, presented in Figure 66, is coupled to the area where the load of the machined is applied. A continuum distributing coupling was selected to ensure the applied displacement was transferred uniformly across the surface, preventing local stress concentrations and providing a more realistic representation of the experimental loading conditions.

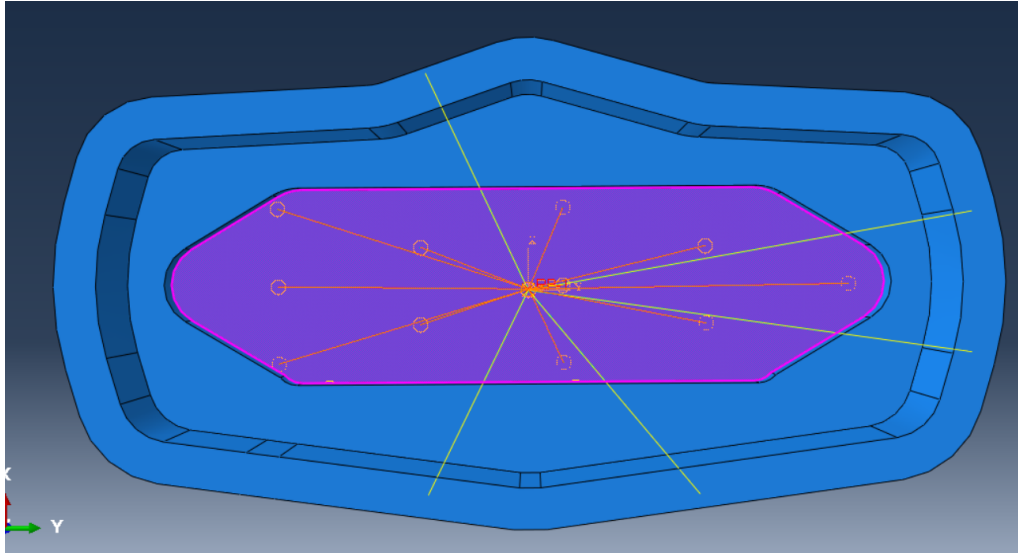


Figure 66: Reference point 1 creation to apply a boundary condition.

The displacement (U3) boundary condition is then applied to that reference point, RF1, as shown in Figure 67.

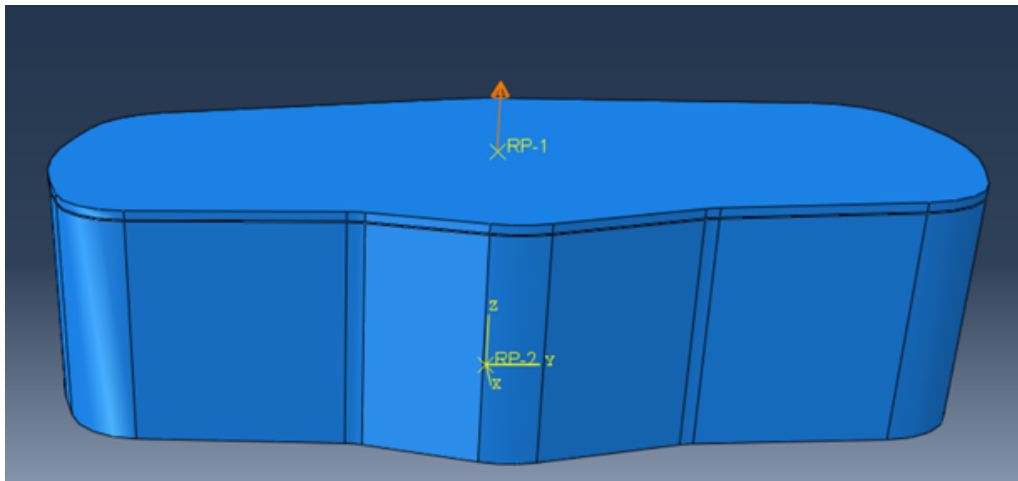


Figure 67: Displacement (U3) applied to RP1.

The second reference point, RF2, was coupled to the bottom area of the simplified part, as can be seen in Figure 68, using a kinematic coupling. This ensured that the boundary condition, defined as a full constraint of the specimen, was applied

consistently across the surface, reproducing the way the joint was rigidly fixed in the testing machine.

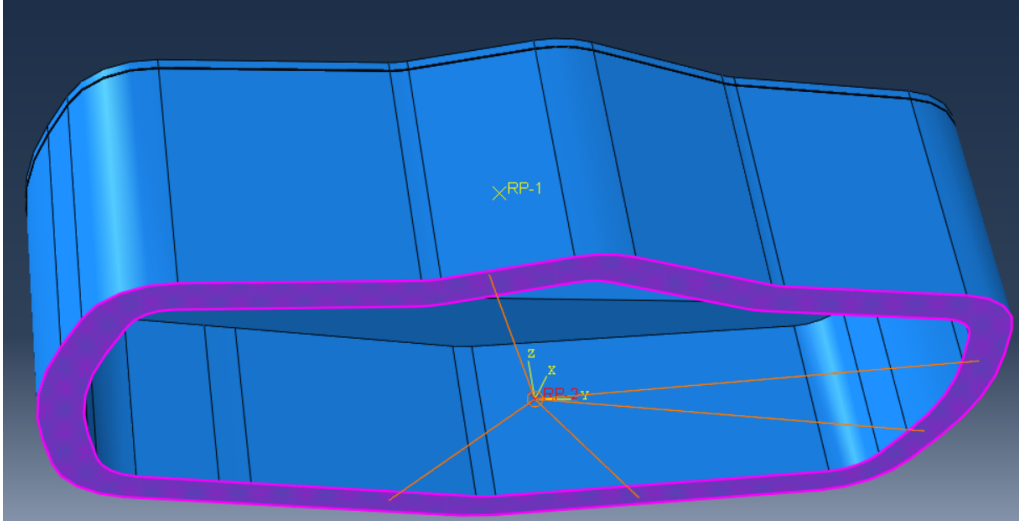


Figure 68: Reference point 2 creation to apply a boundary condition.

The displacement ($U1=U2=U3=UR1=UR2=UR3=0$) boundary condition is then applied to that reference point, RF2, as shown in Figure 67.

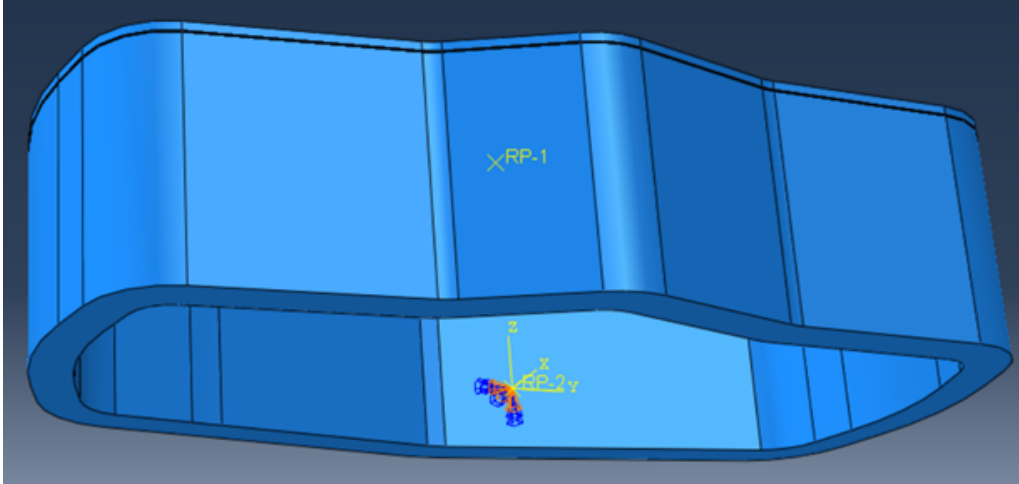


Figure 69: Displacement ($U1=U2=U3=UR1=UR2=UR3=0$) applied to RP2.

Both adherends, the simplified part and the lid, were defined with elastic and plastic properties, for each aluminium alloy ($AlSi_{10}Mg$ and $AlMg_6$ respectively). The simplified part has a complex, non-sweepable geometry and is therefore discretized with free-tetrahedral C3D10 quadratic elements, which are preferred over linear tets for their superior stiffness and curvature representation. Local mesh refinement is applied adjacent to the adhesive to ensure compatible tie constraints and smooth stress transfer. The lid is meshed with C3D8R reduced-integration hexahedra where the geometry is sweepable, providing an efficient, non-locking solid for linear-elastic metal and good accuracy in bending with built-in hourglass control.

The MS polymer adhesive layer was discretised hyperelastic properties, with the Marlow model previously described for the modelling of single lap joints in section 5.1. To model cohesive failure, a traction–separation cohesive law was implemented in a layer in the middle of the bulk adhesive, with properties calibrated against the experimental load vs displacement curve. The bulk adhesive is modelled with structured C3D8H hybrid hexahedra. The hybrid formulation prevents volumetric locking in this near-incompressible material and the swept hex mesh gives a clean through-thickness stress/strain resolution needed to capture joint stiffness. The cohesive layer embedded at mid-thickness is represented by COH3D8 cohesive elements, where elastic stiffness in the normal and shear directions quadratic nominal-stress initiation and energy-based evolution are defined. Figure 70 presents the meshed assembly for the internal pressure test.

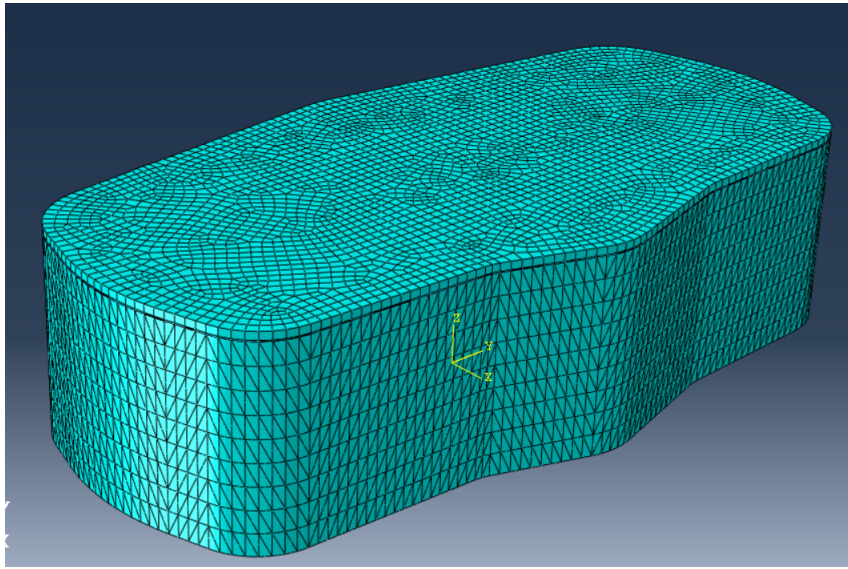


Figure 70: Meshed assembly of the internal pressure test specimen.

Because the experimentally observed (and intended) failure mode is cohesive within the adhesive, the two adhesive–adherend interfaces are modelled as perfectly bonded using surface-based tie constraints. Ties eliminate interfacial slip/separation, remove penalty-contact compliance, and ensure load transfers directly from the adherends into the bulk adhesive and then to the mid-thickness cohesive zone, where damage initiates and propagates. Mesh densities are matched across the tied faces to promote smooth stress transfer. No contact is defined at these interfaces, preventing competing failure paths and keeping the response governed by the adhesive and its cohesive law.

This modelling framework enables evaluation of stress distributions within the adhesive layer, prediction of crack initiation sites, and assessment of progressive damage under service-like conditions, thereby extending the experimental observations with detailed insight into the mechanics of joint performance.

5.3 Numerical validation

5.3.1 Single lap joints

The accuracy of the numerical models developed for both adhesives was assessed by comparing the predicted responses of single lap joints with the corresponding experimental load–displacement curves. Validation focused on evaluating the ability of the models to reproduce not only the peak load but also the overall stiffness and post-peak behaviour observed in the tests.

Figure 29 shows the comparison between the experimental curve for the LS-XU adhesive film, considering SLJs with anodized substrates and the numerical model. The numerical simulations were able to replicate closely the experimental load–displacement curves, particularly the initial linear stiffness, the subsequent plastic hardening of the adhesive, and the abrupt load drop linked to interfacial debonding, thereby capturing the adhesive failure mode observed in the joints.

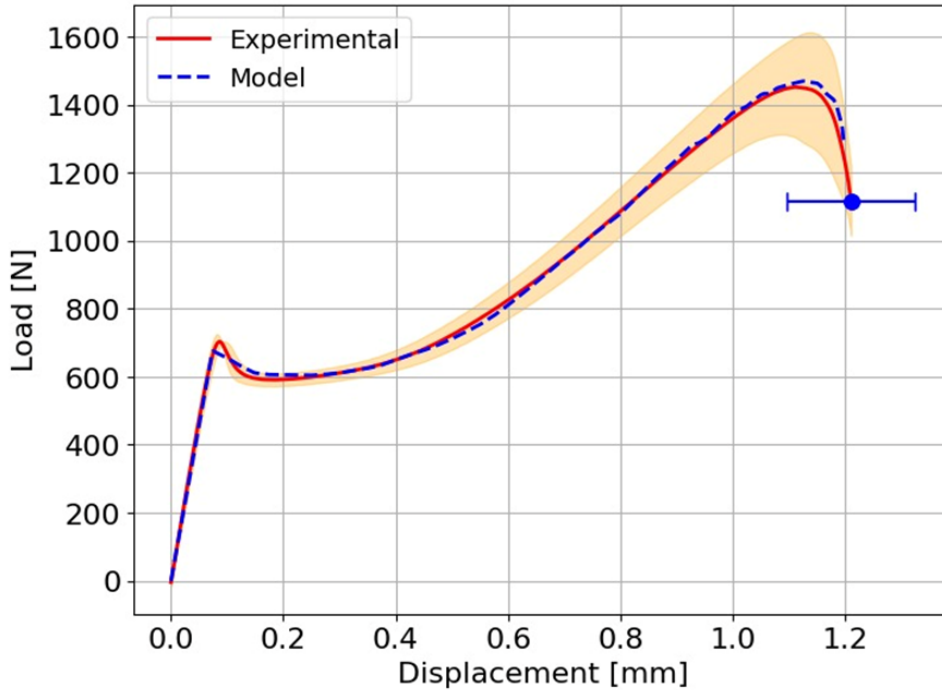


Figure 71: Comparison between experimental and numerical curves for the LS-XU adhesive film.

Initial simulations using only the tensile-derived plasticity data underestimated the plastic contribution of the adhesive in the lap joint configuration. To improve correlation, a reverse engineering process was performed: the plastic stress–strain curve was iteratively adjusted until the simulated load–displacement response aligned with the experimental results. This refinement ensured that both stiffness and peak load were reproduced with reasonable accuracy. The adjusted stress–strain curve used in this model is presented in Figure 72.

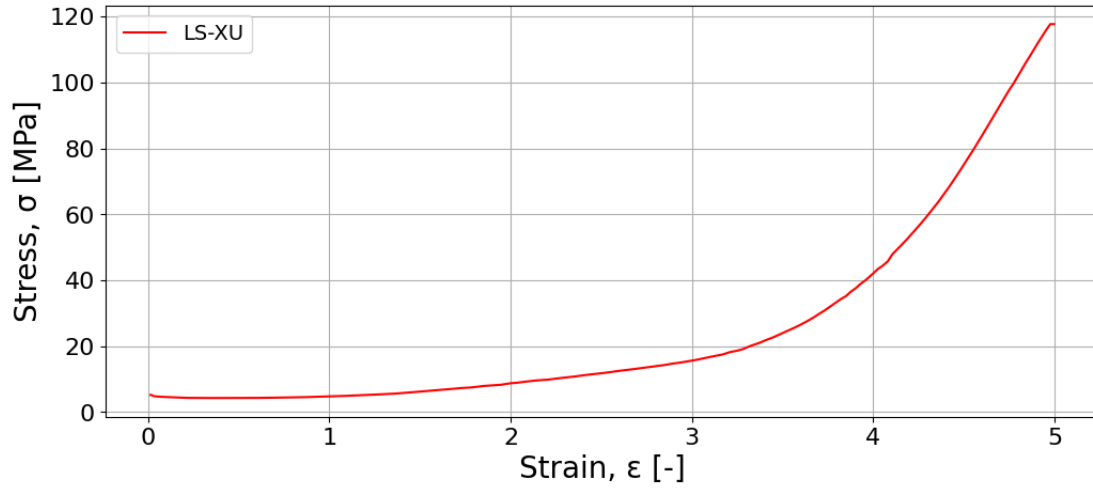


Figure 72: Adapted stress vs strain curve for the modelling of the LS-XU adhesive.

Figure 73 shows the comparison between the experimental curve for SLJs bonded with the Teroson MS 939 adhesive and anodized substrates where the failure was totally cohesive, and the numerical model. Numerical predictions showed good agreement with the experimental load–displacement curves, particularly in terms of initial stiffness and the progressive softening that occurred prior to failure. The inclusion of a cohesive zone within the adhesive was essential to reproduce the observed damage process, as models without this feature exhibited unrealistically high ductility and did not capture the failure point accurately. Minor differences between experimental and numerical curves at large displacements are attributed to the fact that the Marlow model, based solely on monotonic tension data, does not account for unloading or rate-dependent effects. Nevertheless, the model was deemed capable of accurately describing the joint behaviour under the quasi-static conditions studied.

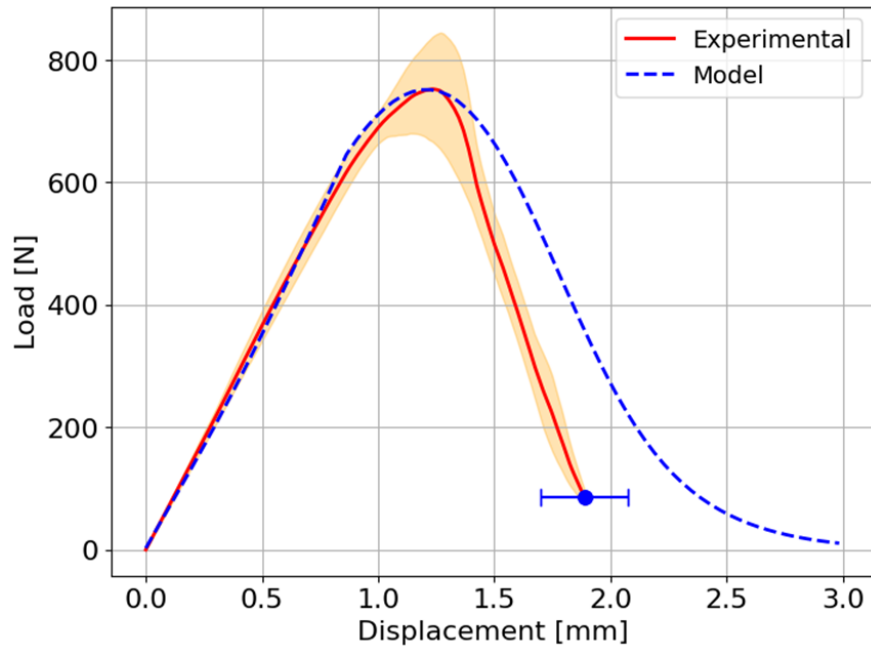


Figure 73: Comparison between experimental and numerical curves for the Teroson MS 939 adhesive.

5.3.2 Internal pressure test

The numerical results were first examined by comparing stress fields against experimentally observed failure patterns, providing a direct means of validation. Figure 74, which illustrates the von Mises stress distribution in the aluminium lid under internal pressurisation, highlights two distinct zones: a low-stress dome over the central wetted region and a circumferential ridge of elevated stress around the bonded land. This stress ridge arises from bending effects in the thin lid, where the transition between the supported and pressurised regions generates a ring of concentrated tensile and shear stresses. Within this ridge, the internal corners and geometric curvature transitions act as amplifiers of stress, as load is channelled through the shortest mechanical paths into the joint. This localisation is significant because it coincides with the areas where experimental failures were consistently initiated. The agreement between predicted stress concentrations and observed failure sites confirms that the boundary conditions and meshing strategy accurately replicated the physical test configuration.

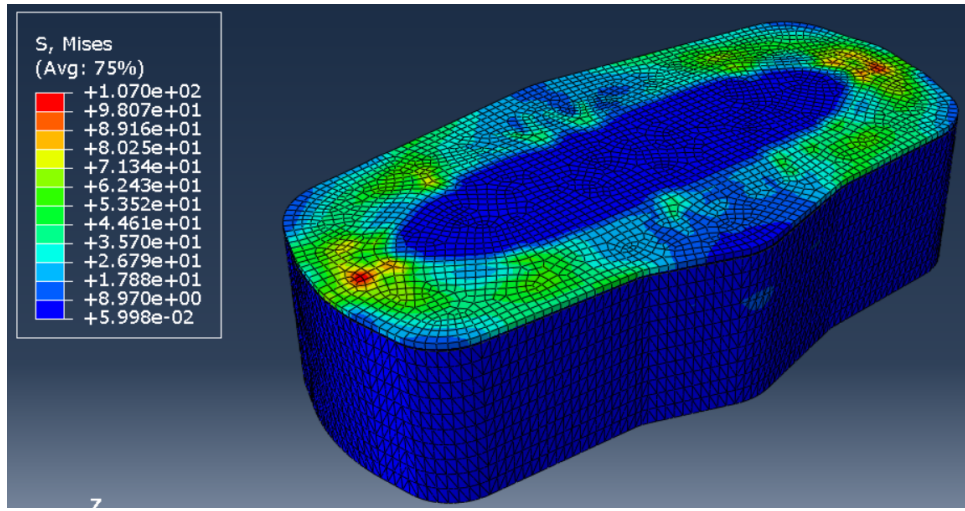


Figure 74: Von Mises stress in the lid under internal pressure.

Subsequent analysis focused on the adhesive layer itself, since this region governs joint integrity. The von Mises stress field within the MS polymer adhesive at a specific step time, in Figure 75, showed peak stresses of approximately 3.09 MPa. This value is just below the tensile strength of the adhesive (3.14 MPa), indicating that, at this point, the joint is at the precise stage immediately preceding damage onset. The distribution of stresses within the adhesive was not uniform, instead, stresses intensified near the internal corners of the bonded land, again matching the initiation sites observed experimentally. This reinforces the conclusion that corner regions are the dominant locations for crack initiation under internal pressure.

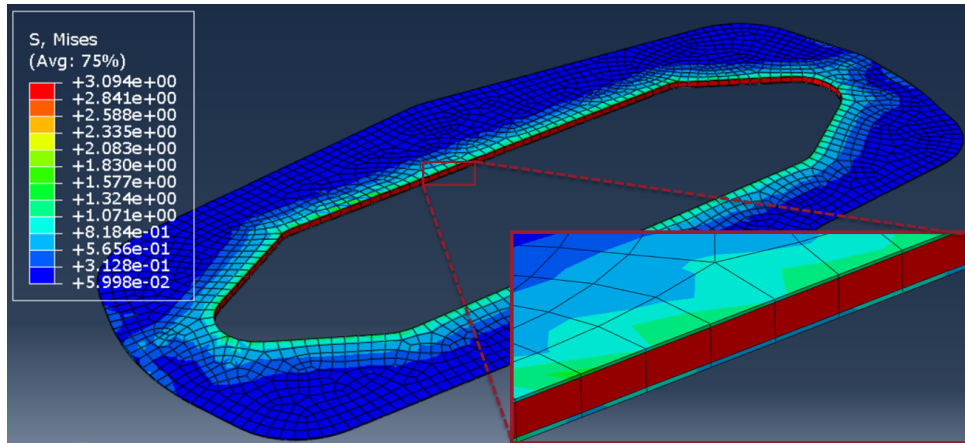


Figure 75: Pre-damage von Mises stress in the bulk MS polymer adhesive under internal pressure.

A more conservative evaluation was obtained by analysing the through-thickness normal stress component, S_{33} , in the adhesive layer, shown in Figure 76. This parameter isolates the peel (Mode I) stresses that develop as the pressurised lid attempts to separate from the substrate. In the same step time as the von Mises stresses previously shown, the results revealed peak S_{33} values of approximately

3.75 MPa, which exceed the measured tensile strength of the adhesive. In contrast to the von Mises criterion, which represents the deviatoric component of stress, the normal stress criterion directly captures opening stresses that drive interfacial or cohesive debonding. By predicting failure initiation earlier than the von Mises approach, it highlights the role of peel-dominated stresses in governing adhesive performance under pressurisation. This insight is particularly important in the design of bonded pressure-retaining structures, as it shows that localised out-of-plane stresses at geometric transitions can trigger premature failure even when global stress levels appear to remain below bulk material limits.

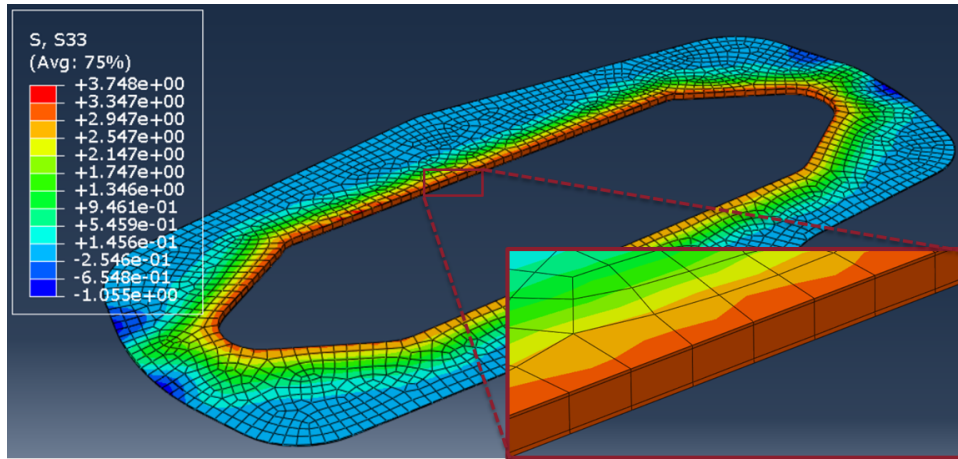


Figure 76: Normal stress field in the bulk MS polymer adhesive under internal pressure.

Overall, the numerical model provided a richer picture of the local stress environment within the joint. Experimental testing could confirm global strength and observe macroscopic failure, but only the finite element analysis revealed how stresses were distributed, how local peaks developed, and why cracks initiated in the observed regions. By demonstrating that cohesive debonding initiates at the internal corners under mixed-mode stress conditions, shear from circumferential loading combined with peel from out-of-plane bending—the model directly supports the experimental conclusion that Teroson MS 939 joints fail progressively through a combination of adhesive and cohesive mechanisms.

This validation significantly strengthens confidence in the model’s predictive capability. Beyond reproducing observed behaviour, it provides a framework for parametric exploration, such as varying adhesive thickness, altering joint geometry, or testing different surface treatments, all of which can be investigated virtually to optimise design. In this way, the numerical study not only corroborates the experimental campaign but also extends it, offering predictive power for future design and application of adhesive joints in pressurised aluminium components.

6 Summary of the appended papers

Paper A - Adhesive bonding of cast aluminium for automotive applications: a comparative study

This study evaluates the adhesive bonding of die-cast aluminium alloy $AlSi_{10}Mg$ for automotive applications using two adhesives: a hot melt (LS-XU) and a silane-modified polymer (Teroson MS 939). Single lap joints with different substrate conditions and surface treatments, supported by peel tests, were experimentally assessed and numerically modelled in ABAQUS®FE. Results showed that adhesive type and surface treatment strongly influenced strength and failure mode: LS-XU promoted adhesive failure with best performance under anodization, while Teroson MS 939 achieved cohesive failure, higher strength, and greater energy absorption. Overall, Teroson MS 939 demonstrated superior performance, underscoring the importance of adhesive and surface preparation choice for lightweight automotive structures.

Paper B - Durability and internal pressure performance of adhesive and welded joints in die-cast aluminium components

This work compares two adhesive systems, a cyclic olefin hot-melt adhesive (LS-XU) and a silane-modified polymer (Teroson MS 939), with friction stir welding (FSW) for joining die-cast aluminium $AlSi_{10}Mg$. Single lap joints were tested after hydraulic oil ageing, and internal pressure tests assessed strength and sealing. LS-XU degraded significantly under ageing and failed abruptly under pressure, while Teroson MS 939 retained ductility and cohesive behaviour, offering better durability. FSW joints provided the highest strength but lacked sealing capability, failing by leakage at the weld seam. Numerical modelling with ABAQUS®FE confirmed the experimental trends, identifying stress concentrations in the adhesive layer. The results show that joining method selection must consider both strength and sealing: MS polymers are best for sealing and durability, FSW ensures structural capacity, and hybrid approaches combining both may offer optimal solutions for lightweight automotive and aerospace applications.

7 Conclusion

7.1 Conclusions

This thesis evaluated the performance of innovative bonding methods for die-cast aluminium components, focusing on adhesive bonding with a hot-melt cyclic olefin film (LS-XU) and a silane-modified polymer (Teroson MS 939), as well as comparisons with friction stir welding (FSW). Experimental testing included single lap joints, durability assessments, peel tests, and internal pressure tests, supported by finite element modelling.

The results confirmed that joint performance is strongly dependent on both adhesive type and surface preparation. LS-XU exhibited exclusively adhesive failure across all conditions, with anodization producing the best results, while degreased surfaces consistently underperformed. By contrast, Teroson MS 939 demonstrated more favourable cohesive or mixed failures, with anodized joints showing the highest reliability and energy absorption capacity. These differences underline the importance of surface activation in ensuring durable bonding of die-cast aluminium.

Durability testing under oil ageing conditions revealed that LS-XU is highly susceptible to degradation, suffering shrinkage and loss of strength, which limits its applicability in oil-rich automotive environments. The MS polymer adhesive showed comparatively better retention of performance, although as-cast anodized joints proved particularly vulnerable. Peel tests further highlighted the superior viscoelastic dissipation of Teroson MS 939 (~ 4.4 N/mm), compared with LS-XU (~ 3.2 N/mm). Internal pressure testing confirmed the higher strength and ductility of MS polymer joints, which sustained pressures above 4 kN, while LS-XU exhibited brittle failure below 2.5 kN. FSW, on the other hand, delivered significantly higher resistance to peel and internal pressure, positioning it as the most robust option for safety-critical structural applications.

Numerical modelling in ABAQUS®FE successfully reproduced the experimental single lap joints load-displacement curves for both adhesives. The hyperelastic-cohesive model accurately captured the cohesive behaviour of the MS polymer, while the traction-separation contact formulation, calibrated with BK law, described the adhesive debonding of LS-XU. This demonstrates that cohesive zone modelling provides an effective tool for predicting the mechanical behaviour of adhesively bonded aluminium joints.

Overall, the study demonstrates that while friction stir welding remains the most suitable choice for primary structural joints, it creates a permanent, non-reversible bond that limits serviceability. By contrast, Teroson MS 939 provides a debondable adhesive route for semi-structural and sealing applications. These adhesive joints can be reopened and re-bonded to enable repair, part replacement, or end-of-life

disassembly. LS-XU, despite some advantages in stiffness and dimensional stability, is not suitable for environments involving long-term oil exposure. The findings contribute to ongoing lightweighting strategies in automotive design, balancing performance, cost, maintainability, and sustainability.

7.2 Future work

Further research is needed to consolidate the industrial applicability of the findings. Recommended directions include:

- Extending durability studies to encompass temperature cycling, humidity, and salt spray exposure, reflecting real automotive service conditions, and also quantify the oil absorption for each adhesive.
- Exploring alternative environmentally friendly surface treatments beyond phosphoric acid anodization, such as plasma or silane-based conversion coatings.
- Investigating hybrid joining strategies that combine adhesive bonding with mechanical fastening or local FSW, to exploit complementary benefits.
- Refining numerical models to include fatigue loading, impact resistance, and multiphysics effects such as thermal ageing.
- Evaluating recyclability and end-of-life disassembly of adhesively bonded components, aligning with circular economy requirements.

These developments would enable a deeper understanding of the long-term reliability of bonded aluminium assemblies and support the transition to more sustainable, high-performance automotive structures.

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Appendices

A Paper A

Adhesive bonding of cast aluminium for automotive applications: a comparative study

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This study investigates the adhesive bonding performance of die-cast aluminium alloy $AlSi_{10}Mg$, focusing on its application in the automotive industry. Two adhesive systems were evaluated: a cyclic olefin-based hot melt adhesive (LS-XU) and a silane-modified polymer adhesive (Teroson MS 939). Single lap joints (SLJs) were manufactured under two substrate conditions (as-cast and machined) and three surface treatments (degreased, sanded, anodized), while 90° peel tests were carried out to complement the mechanical evaluation. Numerical models in ABAQUS®FE were developed to replicate the experimental tests and validate the observed behaviours.

The results show that adhesive type and surface treatment strongly affect joint strength and failure modes. LS-XU joints consistently failed adhesively, with anodization producing the best performance, whereas Teroson MS 939 promoted cohesive failure under sanding and anodization, resulting in higher strength and energy absorption. Peel tests confirmed the superior viscoelastic dissipation of Teroson MS 939, with higher critical energy release rates (~ 4.4 N/mm) compared to LS-XU (~ 3.2 N/mm). These findings highlight the importance of selecting appropriate adhesive systems and surface preparation strategies for cast aluminium in automotive structures, where balancing strength, ductility, and durability is critical to meet lightweighting and performance requirements.

A.1 Introduction

Die-cast aluminium alloys, particularly Al–Si–Mg systems such as $AlSi_{10}Mg$, are widely employed in the automotive industry due to their low density, high specific strength, good corrosion resistance, and excellent castability for complex geometries [1, 2]. Their use supports industry-wide lightweighting initiatives aimed at reducing fuel consumption and greenhouse gas emissions. However, joining die-cast aluminium components presents significant challenges compared to wrought alloys. The die-casting process often produces a heterogeneous surface layer containing entrapped oxides, silicon-rich eutectic phases, porosity, and residual release agents. These features reduce surface wettability, hinder the formation of durable adhesive bonds, and may promote interfacial defects under service conditions [3].

Surface preparation is therefore a critical step in achieving reliable bonding performance. Mechanical treatments such as abrasion, sanding, or grit blasting are commonly used to increase surface roughness and promote mechanical interlocking. Chemical treatments, including alkaline cleaning, acid etching, or chromate conversion coatings, are effective in removing contaminants and modifying surface chemistry. More advanced approaches, such as anodizing and plasma treatment aim to increase surface energy and introduce chemically active sites, thereby improving adhesive–substrate interaction and long-term durability [4, 5]. The selection of an appropriate treatment must balance performance benefits with manufacturing feasibility, environmental regulations, and compatibility with downstream processes.

The application of structural adhesive bonding to die-cast aluminium in automotive body-in-white (BIW) assembly remains a relatively recent development compared to its extensive use with sheet-formed aluminium and steel panels. Historically, the complex surface morphology, high silicon content, and susceptibility to casting defects made die-cast aluminium less attractive for adhesive bonding, leading manufacturers to rely on mechanical fastening methods such as riveting, bolting, and self-piercing rivets, which add weight, manufacturing cost and constrain design flexibility [6]. The growing adoption of high-performance surface treatments and tailored adhesive formulations has now made it feasible to achieve durable, high-strength bonds in die-cast components, enabling engineers to replace heavy or intrusive fasteners with bonded joints. This shift represents a significant innovation pathway in automotive lightweighting, offering manufacturing advantages, including reduced part count and simplified assembly processes [7].

In this study, the bonding performance of die-cast aluminium $AlSi_{10}Mg$ was evaluated using two adhesive systems: a silane-modified polymer (SMP) sealant and a thermoplastic hot melt adhesive (HMA) cycloolefin-based film. SMPs, also referred to as silyl-modified or MS polymers, are hybrid adhesives combining elasticity, durability, and environmental resistance. According to Henkel [8], SMPs undergo one-component, moisture-curing that yields elastomeric bonds free of solvents, iso-

cyanates, silicones, and PVC, with excellent UV and weather resistance and strong adhesion to diverse substrates, even without primers. This sealant imparts high initial adhesion, excellent sag resistance, and long-term flexibility, characteristics that make SMPs particularly suited to automotive applications requiring durable elastic sealing, vibration damping, and structural bonding of body components [9].

HMA films, on the other hand, soften when heated and solidify on cooling, enabling rapid assembly, consistent bondline thickness, and minimal curing time [10]. They provide high initial tack, good gap filling, and reliable adhesion to various substrates, which suits high-volume automotive manufacturing where process speed and reproducibility are critical [11]. The comparative assessment of these two adhesive systems on $AlSi_{10}Mg$ substrates provides insight into the influence of adhesive type on joint performance and the suitability of each for structural and sealing applications in the automotive sector.

In the automotive sector, adhesive bonding of die-cast aluminium is gaining strategic importance as manufacturers transition toward multi-material body architectures and reduced mechanical fastening. Furthermore, the rise of the megacasting type of structures for body construction reinforces the move away from conventional sheet metal and its associated conventional joining methods, such as bolting, riveting, clinching [12]. In these cases, this imposes strict design constraints, including the need for overlapping flanges, local stress concentrations, added mass, and reduced fatigue life. Adhesive bonding offers unique advantages: it enables uniform load transfer over a large area, seals joints against corrosion, eliminates stress risers, and allows for joining thin or dissimilar materials without introducing heat distortion. These attributes are essential for modern vehicle structures, where weight reduction, crash performance, and production efficiency must be achieved simultaneously. Effective bonding of die-cast aluminium is thus not only a materials engineering challenge but also a key enabler for the next generation of lightweight and sustainable automotive designs [3].

As shown, there is limited information on how to join cast aluminium using adhesive bonding, although the importance of this technique is growing. In this work, experimental and numerical steps were carried out to identify suitable procedures for bonding these materials. In more detail, single lap joints (SLJs) employing die-cast aluminium $AlSi_{10}Mg$ adherends were manufactured using two distinct adhesives: Zeon’s hot melt adhesive LS-XU and Henkel’s MS polymer Teroson MS 939 adhesive. The adherends underwent three different surface preparation methods - degreasing, sanding, and anodizing — to evaluate their influence on joint performance, with particular attention to failure modes and adhesion characteristics. Additionally, the aluminium substrates were tested in two surface conditions, as-cast and machined, to assess the impact of machining operations on surface properties and adhesion. 90° peel tests were conducted to determine the peel strength of both

adhesives under the aforementioned surface preparation and substrate condition scenarios. Complementary numerical models were developed in ABAQUS[®]FE using geometries replicating those of the experimental specimens, thereby enabling direct correlation between the experimental and numerical results.

A.2 Experimental details

A.2.1 Materials

A multi-material film adhesive was used, with the commercial reference LS-XU, with 0.4 mm thickness and cyclic olefin-based polymer produced by Zeon[®] Corporation (Chiyoda-ku, Tokyo, Japan). It was cured by using a hot press, under 159 °C during 45 minutes. Rodrigues et al. [13] characterised this adhesive at a thickness of 0.1 mm, and a subsequent study on the 0.4 mm variant provided the mechanical properties listed in Table 1.

Table 1: LS-XU mechanical properties

Property	Units	Value
Young's modulus, E	[MPa]	230.18 ± 8.08
Yield strength, σ_y	[MPa]	5.49 ± 0.36
Tensile failure strength, σ_f	[MPa]	10.86 ± 1.48
Tensile failure strain, ε_f	[%]	1066 ± 83
Poisson's ratio, ν	[-]	0.47 ± 0.02
Shear modulus, G	[MPa]	76.67 ± 2.52
Shear failure strength, τ_f	[MPa]	5.09 ± 0.08
Shear failure strain, γ_f	[%]	354 ± 19
Toughness in mode I, J_{Ic}	[N/mm]	0.20 ± 0.05
Toughness in mode II, J_{IIc}	[N/mm]	2.66 ± 0.19

TEROSON[®] MS 939 is an adhesive/sealant based on modified silane polymers, provided by Henkel (Düsseldorf, Germany). It was cured by absorbing ambient humidity, during two weeks, forming an elastic product. Table 2 presents the mechanical properties of this MS polymer adhesive.

Table 2: Teroson MS 939 mechanical properties

Property	Units	Value
Young's modulus, E	[MPa]	2.90 ± 0.01
Yield strength, σ_y	[MPa]	8.24
Tensile failure strength, σ_f	[MPa]	3.14 ± 0.03
Tensile failure strain, ε_f	[%]	2.30 ± 0.04
Poisson's ratio, ν	[-]	0.37
Shear modulus, G	[MPa]	0.94 ± 0.02
Shear failure strength, τ_f	[MPa]	2.59 ± 0.07
Shear failure strain, γ_f	[%]	5.68 ± 0.36
Toughness in mode I, J_{Ic}	[N/mm]	5.2 ± 1.8

The substrates are made of the aluminium alloy $AlSi_{10}Mg$, extracted from a high pressure die-cast automotive part, and, therefore in the cast state. The Young's modulus, E , considered is of 70 GPa and a Poisson's ratio, ν , of 0.33.

A.2.2 Specimen manufacturing

Four types of single lap joints were manufactured for the purpose of studying their joint behaviour, with two different adhesives and two different substrates. The substrates of $AlSi_{10}Mg$ were machined to obtain the dimensions 10 x 100 x 3 mm, and were considered in the as-cast and machined state. All joints have an overlap of 25 mm and 0.2 mm of adhesive thickness. Figure 1 presents the dimensions of the single lap joints.

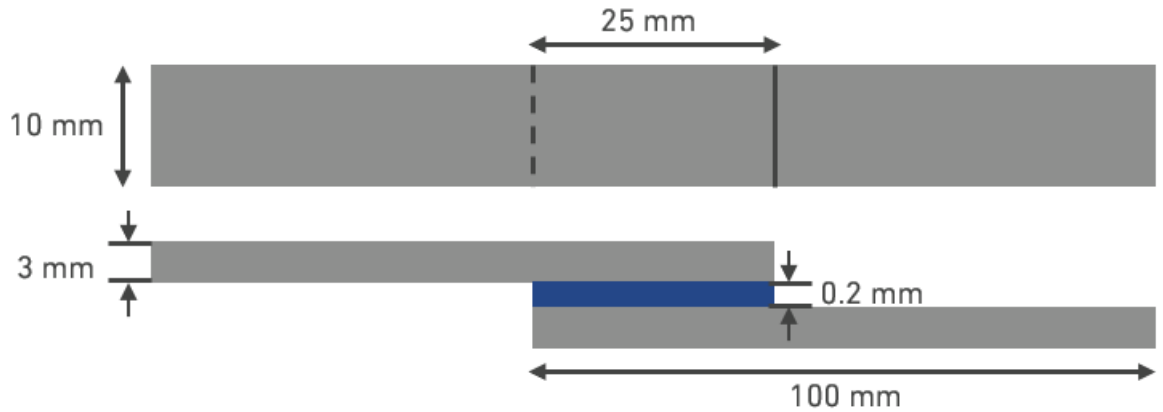


Figure 1: Single lap joint geometry used.

A.2.3 Surface energy and surface preparation

As a preliminary test, the surface energy was measured to understand how properties like adhesion, wettability, and coating compatibility behave in these substrates, as cast and machined. The test consists in the direct measurement of the contact angle of different fluids using a OCA 15 goniometer (DataPhysics, Neurtek Instruments, Eibar, Spain) under ambient conditions, using three different liquids: water (polar liquid), ethylene glycol 55% (polar liquid) and n-hexadecane (nonpolar). The surface energy is obtained by combining the Owens-Wendt-Rabel-Kaelble (OWRK) method and the measured contact angles. In Figure 2 are presented the results of this measurement.

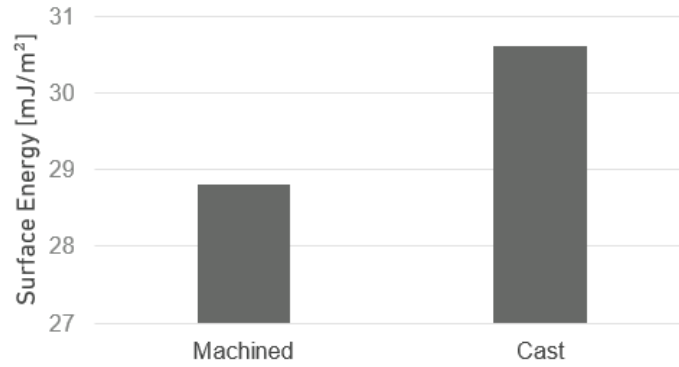


Figure 2: Surface energy of substrates in the as-cast and machined states.

The theoretical surface energy of aluminium lies around 500 to 1000 mJ/m^2 , whereas real (passivated) surfaces range from 40 to 60 mJ/m^2 , depending on the surface roughness, cleaning procedure and alloy constituents [14]. The results presented are lower than the ones found in the literature, which can be attributed to the fact that the material in study is die-cast aluminium, rather than pure aluminium with implications on the surface topography and the eventual presence of contaminants which are not fully removed by an acetone pre-cleaning.

Regarding the surface preparation, three different treatment surfaces were considered. The substrates were degreased with acetone, then they were sanded with a p600 sandpaper and lastly anodized with phosphoric acid anodization. Figure 3 presents the appearance of the substrates after surface treatments.

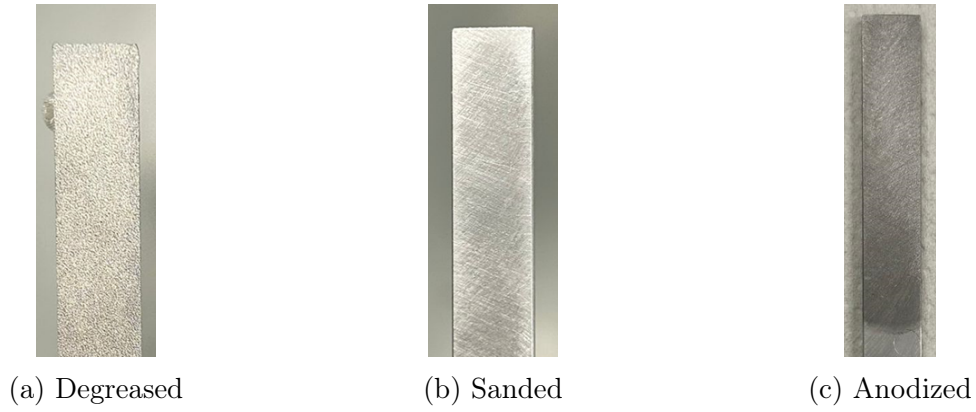


Figure 3: Substrates appearance after the surface treatment.

As cast aluminium anodization

Anodizing as-cast aluminium presents significant challenges due to the surface characteristics and alloy composition of the material. In contrast to wrought aluminium, as-cast alloys frequently exhibit elevated levels of silicon and other alloying elements, resulting in a rough, porous, and heterogeneous surface. The irregular surface of the material in question has been shown to interfere with the formation of a uniform and adherent anodic oxide layer. This has been shown to result in poor corrosion resistance, inconsistent colouring, and reduced aesthetic quality. Intermetallic particles and casting defects disrupt the anodizing process, making it difficult to achieve reliable, high-quality finishes on aluminium parts [15]. In Figure 4 are presented different results of anodized as-cast aluminium substrates, that were anodized under the same conditions, at the same time.



Figure 4: Different results of the anodization of as-cast aluminium substrates.

A.2.4 Testing procedures

Single lap joints

The single lap joints were tested at the rate of 1 mm/min (quasi-static), to avoid inertial and dynamic effects, like acceleration, vibrations, or strain-rate sensitivity. The tests were performed on the testing machine INSTRON® 3367 universal (Illinois ToolWorks, Hopkinton, MA, USA).

90° peel test

The 90° peel test was performed as described in ASTM D6862-11 [16], in the testing machine INSTRON® 3367 universal (Illinois ToolWorks, Hopkinton, MA, USA) and it is a method used to evaluate the adhesive strength between two bonded materials, in this case the aluminium alloy $AlSi_{10}Mg$ and the both adhesives. In this test, one adherent, the peel arm, which is considered the flexible adherend, was clamped vertically in the upper grip. The other adherent, which is considered the rigid adherend, was fixed horizontally in the lower grip to maintain a 90° peel angle during testing. The peel arm is pulled at a right angle (90°) at 12 mm/min to the bonded interface while the other remains fixed, allowing the measurement of the force required to progressively separate the layers. This test provides insight into the adhesion performance and failure characteristics of the adhesive.

For this test, the only surface treatment applied to the adherends was acetone degreasing.

A.3 Numerical details

To simulate the behaviour of the joints with the LS-XU film adhesive and the Teroson MS 939 MS polymer, the software ABAQUS®FE was used to model single lap joints. For both models, it was developed a 2D static model, that is shown in Figure 5. Under quasi-static conditions, the single lap joints testing procedures were modelled using ABAQUS® CPS4R plane stress elements.

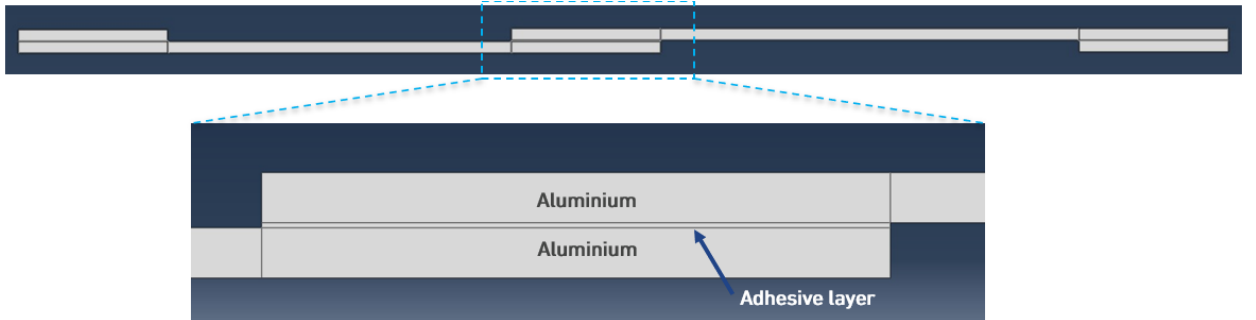


Figure 5: 2D static model of the SLJ in ABAQUS®FE.

The boundary conditions were established according to the experimental tests of single lap joints. The left end of the joint was pinned ($U_1=U_2=U_3=0$) and a displacement (U_1) was applied to the right end of the joint, as shown in Figure 6.



Figure 6: Boundary conditions applied to the SLJ in ABAQUS®FE.

Regarding the mesh applied to the model, it is refined in the regions with higher stress concentrations, in the proximity of the overlap edges. The overlap area is characterised by the presence of two distinct element sizes: smaller elements positioned at the periphery and larger elements situated within the central region. Then, until both end sides of the SLJ, the mesh increases again. This approach ensures computational efficiency by avoiding over-meshing the part. As illustrated in Figure 7, mesh refinement is evident in the overlap regions.



Figure 7: Mesh applied to the SLJ in ABAQUS®FE.

A.3.1 MS polymer adhesive model

When modelling the Teroson MS 939 MS polymer adhesive, the adhesive layer was characterized with hyperelastic properties. To model the ideal single lap joint failure, which is cohesive, a cohesive layer was introduced between the hyperelastic bulk material, that uses a 4-node two-dimensional cohesive element, COH2D4. Figure 8 presents the schematic representation of the Teroson MS 939 single lap joint model in ABAQUS®.

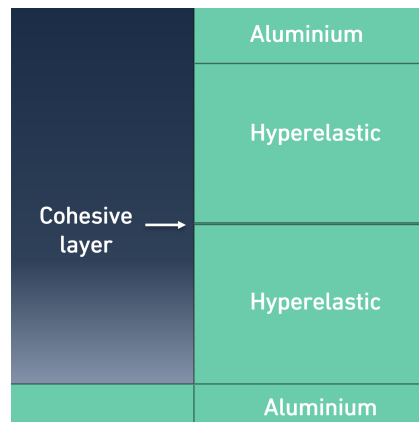


Figure 8: Schematic representation of Teroson MS 939 single lap joint model as constructed in ABAQUS®FE.

The hyperelastic model used was Marlow Model, where only one set of test data is provided (e.g uniaxial tension), and the model follows the provided data exactly. For this case, the stress vs strain curve obtained from bulk testing was used as the provided test data. The stress vs strain curve is presented in Figure 9. The cohesive layer has the elastic properties of the adhesive and the damage initiation followed the quadratic nominal stress criterion (QUADS) in ABAQUS®.

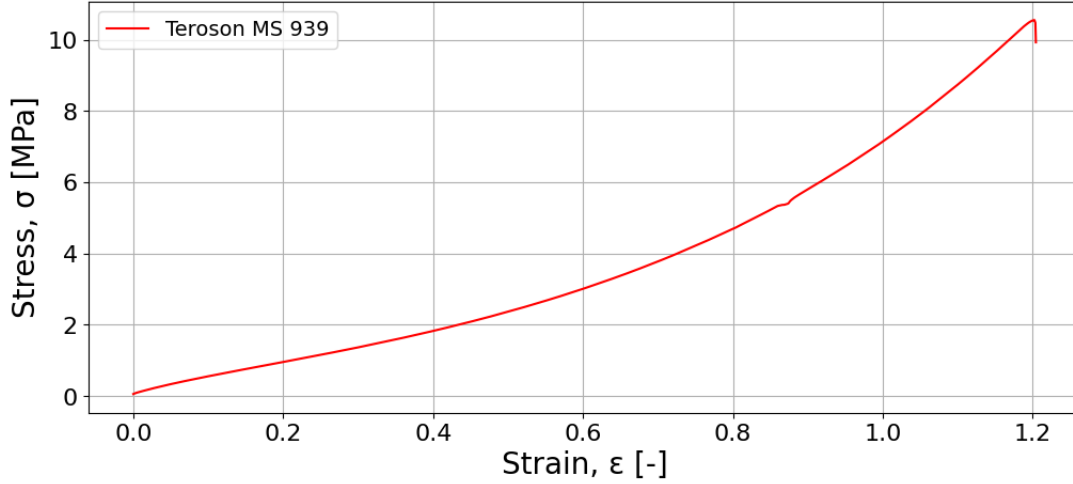


Figure 9: Stress vs strain curve for Teroson MS 939 obtained from bulk testing.

A.3.2 Film adhesive model

The LS-XU adhesive was characterised as an elastic–plastic material to describe its bulk response. The elastic properties, Young’s modulus and Poisson’s ratio, were obtained directly from bulk tensile testing, while the plastic behaviour was established through a reverse engineering process. This procedure allowed to obtain stress–strain curve to be implemented in ABAQUS®FE for the adhesive material.

Since LS-XU failed predominantly by adhesive debonding, failure was introduced at the interfaces with the adherends. To model this, surface-to-surface contact interactions were defined at both adherend–adhesive interfaces in the single lap joint. These interactions were assigned cohesive properties via a traction–separation law, representing the initiation and progression of interfacial cracks. The elastic stiffness of the cohesive contact was calibrated to be consistent with the adhesive bulk stiffness, ensuring that the interface remained initially rigid and only softened upon damage initiation.

Damage initiation was defined using the quadratic nominal stress (QUADS) criterion, which considers the combined contribution of normal and shear stresses acting at the interface. Once the initiation threshold was reached, damage evolution was controlled using the Benzeggagh–Kenane (BK) mixed-mode law. This criterion was selected because its parameter, η , allows the effective fracture energy to vary with the relative contribution of shear loading. For hot-melt adhesives such as LS-

XU, this is particularly relevant, as experiments on single lap joints have shown an increase in apparent toughness under mode II-dominated loading. By implementing the BK law, the model was able to reflect this experimentally observed behaviour more realistically than a simpler linear mixed-mode law.

Figure 10 presents the schematic representation of the film adhesive LS-XU single lap joint.

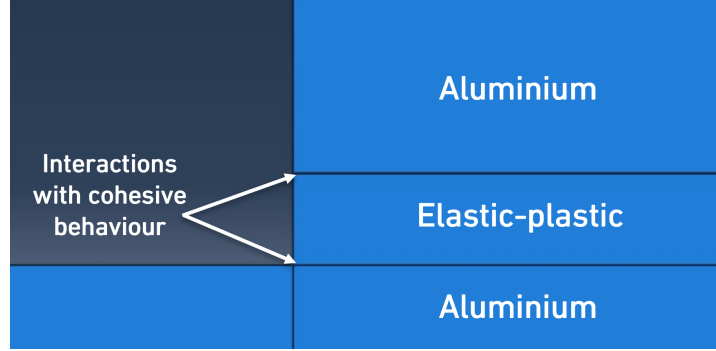


Figure 10: Schematic representation of LS-XU single lap joint in ABAQUS®.

A.4 Experimental results

A.4.1 Single lap joints

For the SLJs testing, at least three specimens were considered in the presented results. Figure 11 shows the results of the tested SLJs with the adherends in as-cast condition, treated with the three different surface treatments previously mentioned, and the adhesive film LS-XU. These results highlight the significant influence of surface preparation on joint strength, with anodizing providing the most favourable mechanical performance, reaching the highest ultimate load of around 1400 N at ~ 1.35 mm of displacement. Then, it is followed by sanding, that achieves around 950 N of highest load at ~ 1.05 mm of displacement. Finally, degreasing produced the weakest joints, only reaching 900 N at ~ 0.80 mm of displacement.

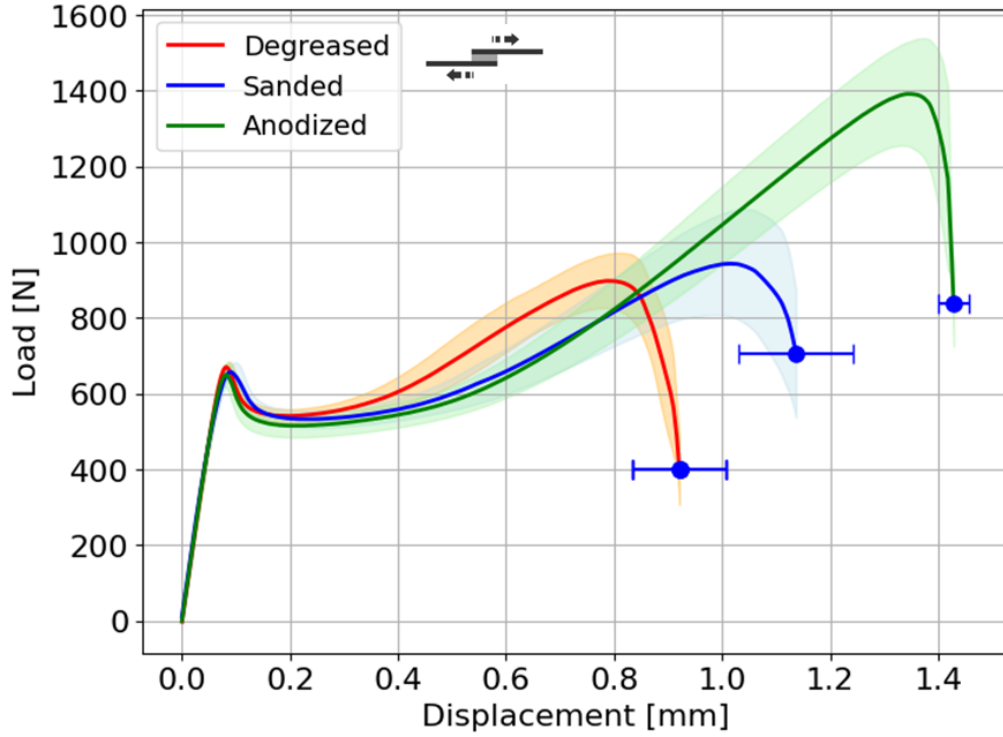


Figure 11: Results of SLJs with substrates in as-cast condition and the LS-XU film adhesive.

Figure 12 shows that all tested SLJs failed by adhesive failure, meaning the fracture occurred at the interface between the adhesive and the substrate. In this failure mode, the adhesive cleanly detaches from one adherend, leaving little or no residue, indicating that interfacial adhesion was the limiting factor, rather than the adhesive's internal strength or the substrate's strength.

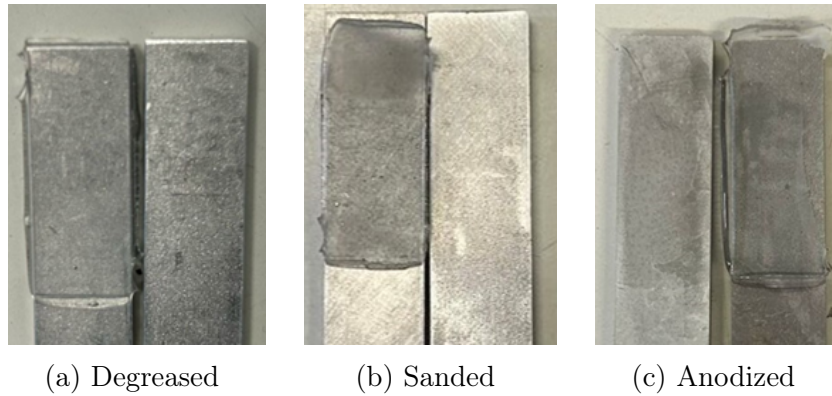


Figure 12: Failure surfaces of the SLJ's with as-cast substrate and the film adhesive.

For the substrates in the machined condition, Figure 13 shows the results for SLJs tested with the same film adhesive LS-XU, and the same surface treatments. The anodized SLJs exhibited the highest ultimate load, attaining approximately 1450 N at a displacement of ~ 1.10 mm. In contrast, both sanded and degreased SLJs failed at a similar displacement of ~ 0.80 mm, however, the sanded specimens

achieved a substantially higher peak load of about 1200 N, whereas the degreased specimens reached only around 950 N.

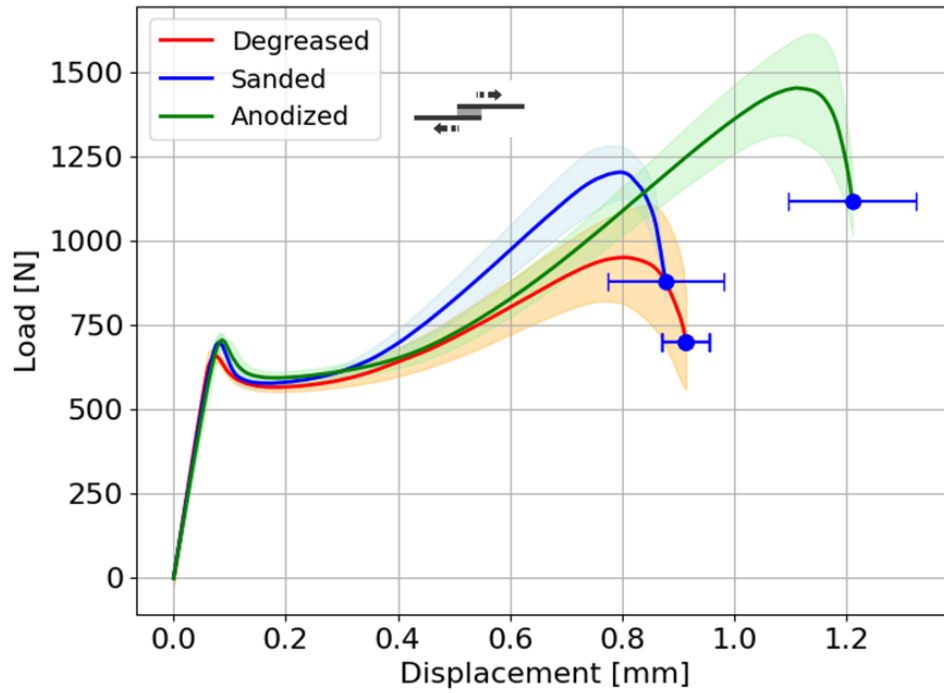


Figure 13: Results of SLJs with substrates in machined condition and the LS-XU film adhesive.

Figure 14 shows the type of failure that occurred in the joint, it was adhesive failure in all of them, as for the as-cast condition previously presented.

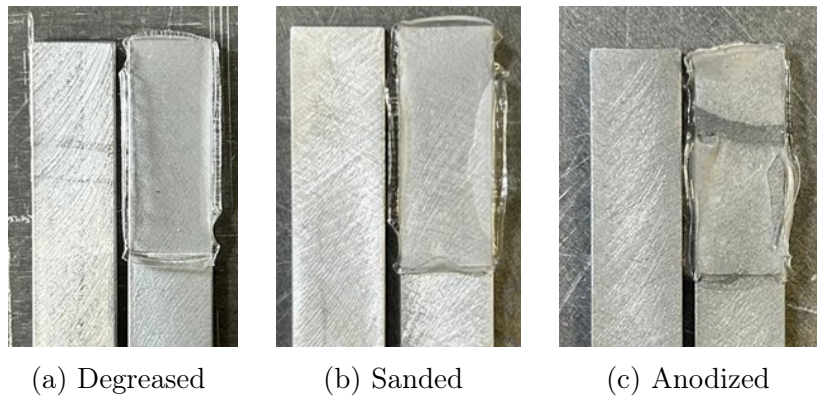


Figure 14: Failure surfaces of the SLJs with machined substrate and the LS-XU film adhesive.

After testing both specimens conditions, as-cast and machined, with three surface treatments, it is possible to compare both conditions for the same surface treatment. This comparison between as-cast and machined substrates highlights the influence of surface condition on the mechanical performance and failure behaviour of SLJs.

Figure 15 presents the comparison between substrates' surface conditions as-cast and machined when degreased with acetone, using the LS-XU film adhesive. Both substrates' conditions exhibit very similar behaviour, with peak loads approaching 900–950 N and failure occurring at comparable displacements ~ 0.80 mm. The close overlap between the curves suggests that machining offers no significant benefit when the failure mechanism is dominated by interfacial debonding. The reduced effectiveness of surface preparation in this case can be explained by the limiting factor that is the adhesive–substrate interface rather than the bulk adhesive properties.

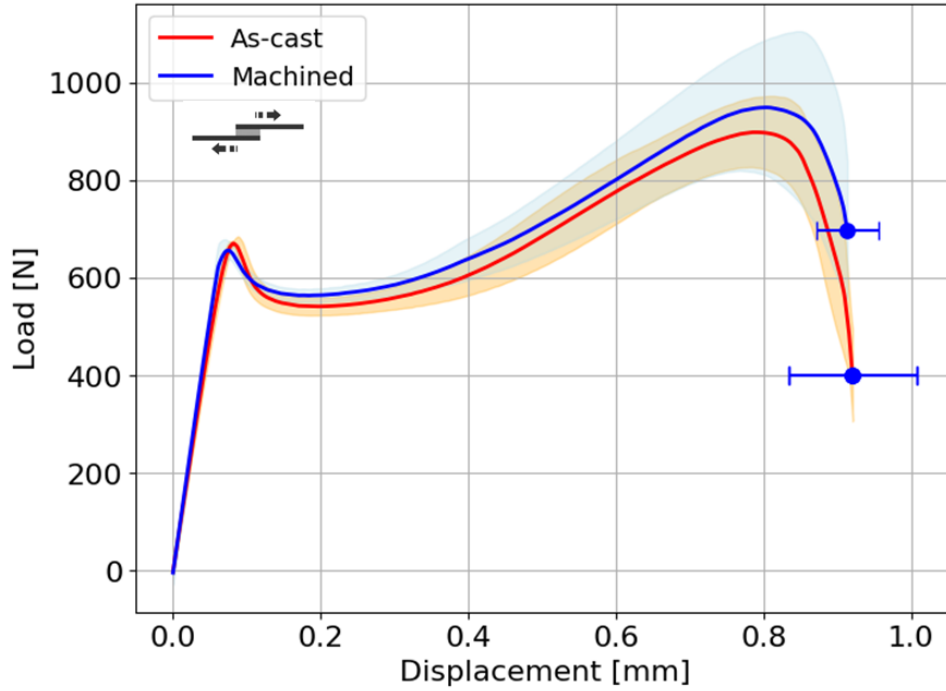


Figure 15: Comparison between substrates' surface condition when degreased, using the LS-XU film adhesive.

Regarding sanding as surface treatment, Figure 16 presents the comparison between as-cast and machined conditions for the adhesive film LS-XU. For this surface treatment there is a stronger difference in the results, whereas the machined substrates achieve a much higher peak load around 1200 N, at a lower displacement of ~ 0.80 mm, than the as-cast substrates that only reach around 950 N, at ~ 1.05 mm of displacement. This improvement can be attributed to the combined effect of sanding and machining, which reduces surface irregularities while increasing effective contact area, thereby promoting stronger interfacial adhesion. In contrast, the as-cast specimens, despite the sanding treatment, may be affected by residual surface defects that continue to act as stress concentrators.

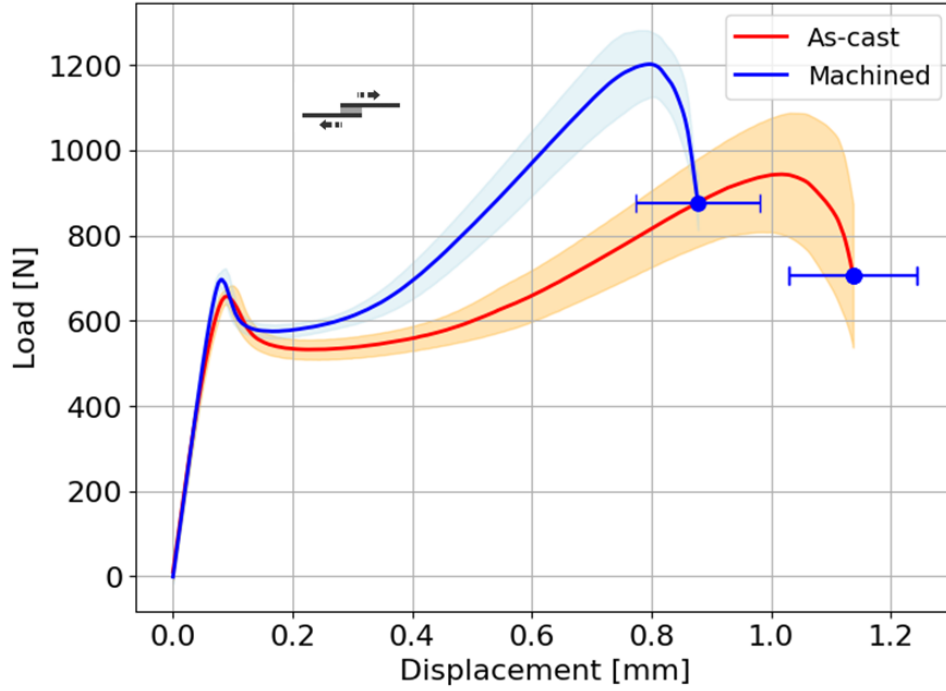


Figure 16: Comparison between substrates' surface condition when sanded, using the LS-XU film adhesive.

Finally, for the anodized specimens, Figure 17 presents the comparison between as-cast and machined conditions for the adhesive film LS-XU. The machined specimens achieve the highest peak strength, exceeding 1400 N, whereas the as-cast specimens reach slightly lower values. However, the as-cast anodized joints sustain greater displacements before failure, extending beyond 1.4 mm compared to approximately 1.1 mm for the machined condition. This suggests a trade-off between strength and ductility: machining prior to anodization enhances maximum load capacity, likely due to improved surface uniformity and oxide layer quality, but the as-cast surface retains features that promote slightly greater deformation before interfacial debonding. Overall, anodization provides the most effective treatment, with the as-cast and machined variants favouring ductility and strength, respectively.

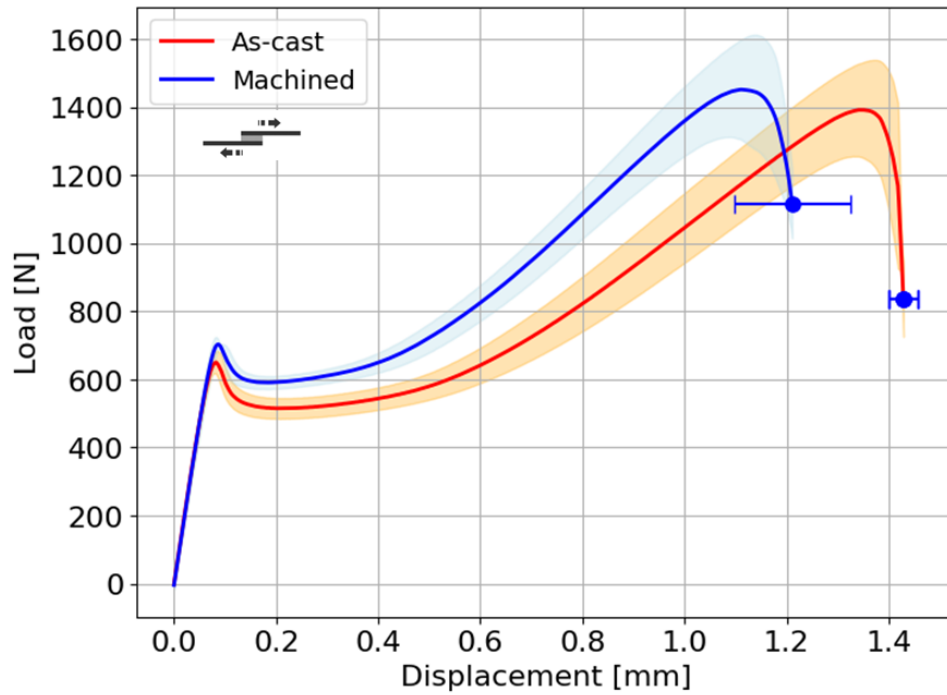


Figure 17: Comparison between substrates' surface condition when anodized, using the LS-XU film adhesive.

Figure 18 shows the results of the tested single lap joints with substrates in as-cast condition and with MS polymer adhesive Teroson MS 939. It can be seen that the surface treatment clearly influences the maximum load reached in the SLJs, being the anodized specimens the ones with better outcome.

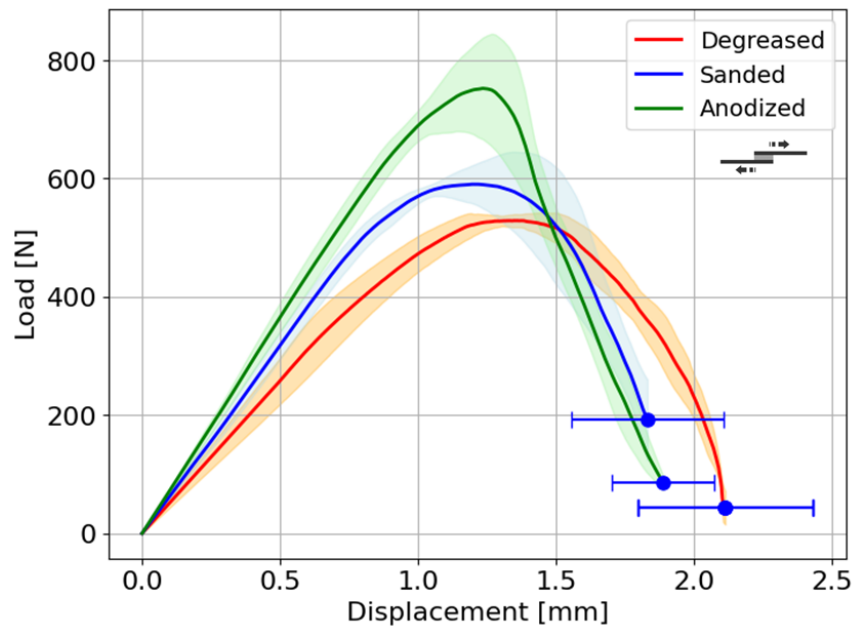


Figure 18: Results of SLJs with substrates in as cast condition and the Teroson MS 939 adhesive.

Figure 19 illustrates the failure mechanisms observed for each surface treatment.

In the case of the degreased specimens, a mixed mode failure was identified, with adhesive failure being predominant. This behaviour accounts for the comparatively lower load-bearing capacity of the degreased SLJs. For the sanded specimens, mixed failure was also observed, however, cohesive failure was more prevalent. This results in a higher peak load than the degreased specimens. The anodized specimens predominantly exhibited cohesive failure, which represents the most favourable outcome for MS polymer SLJs and is consistent with their superior maximum load capacity.

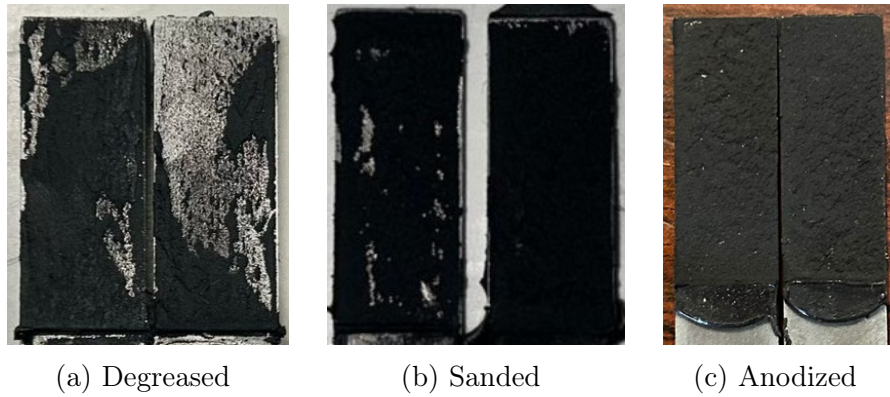


Figure 19: Failure surfaces of the SLJs with as cast substrate and the Teroson MS 939 adhesive.

Figure 20 shows the results of the tested single lap joints with substrates in machined condition and with the Teroson MS 939 adhesive. As observed in the results for the as-cast condition, the surface treatment significantly affects the maximum load attained by the SLJs. Among the treatments, anodized specimens demonstrate the highest performance, although sanded specimens achieve comparably close values.

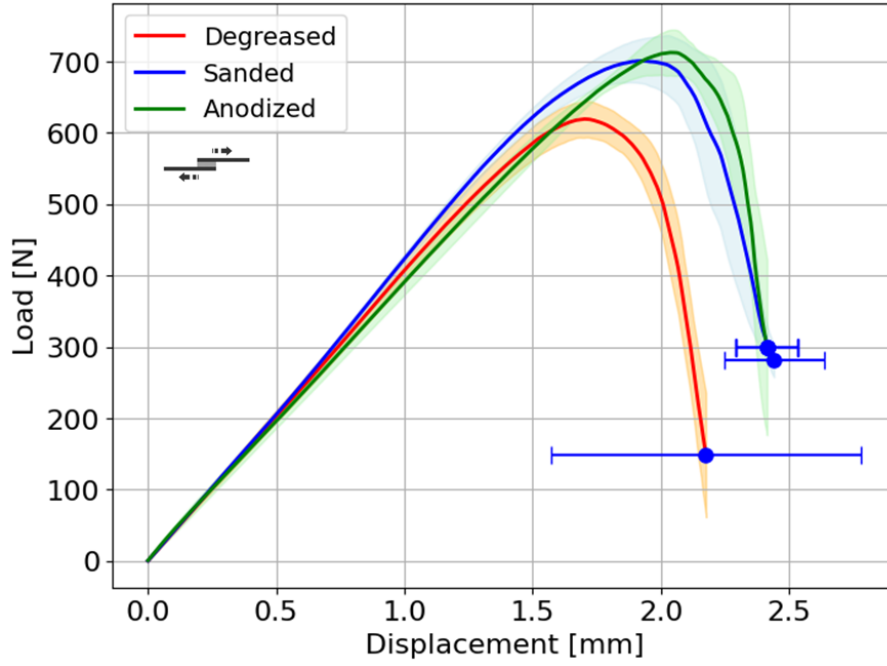


Figure 20: Results of SLJs with substrates in machined condition and the Teroson MS 939 adhesive.

Figure 21 shows the type of failure that occurred in the joint, for each surface treatment. It can be concluded that the failure modes observed in the machined substrates are consistent with those identified in the as-cast substrates. The sanded specimens exhibit an improved failure behaviour, characterised by a greater proportion of cohesive failure, which accounts for their performance approaching that of the anodized specimens.

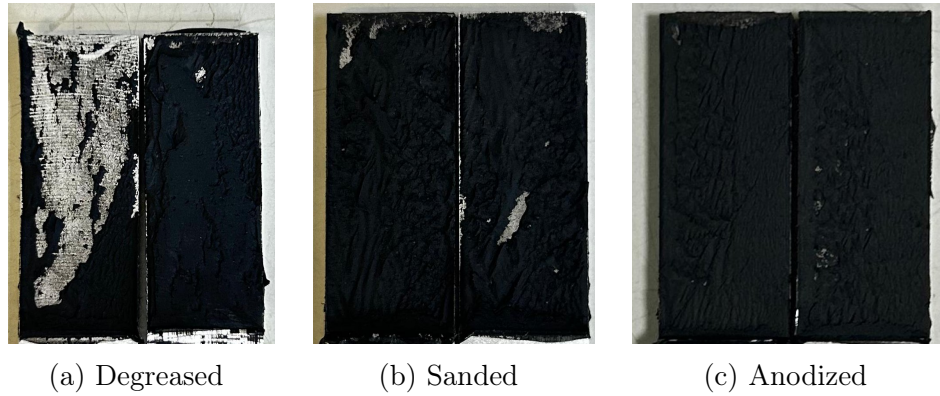


Figure 21: Failure surfaces of the SLJs with machined substrate and the Teroson MS 939 adhesive.

Again, after testing both specimens conditions, as-cast and machined, with three surface treatments, it is possible to compare both conditions for the same surface treatment, this time for the MS polymer adhesive.

Figure 22 presents the comparison between as-cast and machined conditions for

degreased adherends. The machined specimens achieve a higher maximum load, exceeding 600 N, and sustain larger displacements prior to failure, indicating improved ductility and energy absorption. This behaviour can be explained by a higher predominance of cohesive failure in machined specimens, which is generally associated with stronger interfacial adhesion. In contrast, the as-cast specimens peak at around 520 N and fail at lower displacements, consistent with a greater proportion of adhesive failure. This reduction in performance can be attributed to surface irregularities and defects inherent to the as-cast condition, which promote stress concentrations and weaken the joint interface.

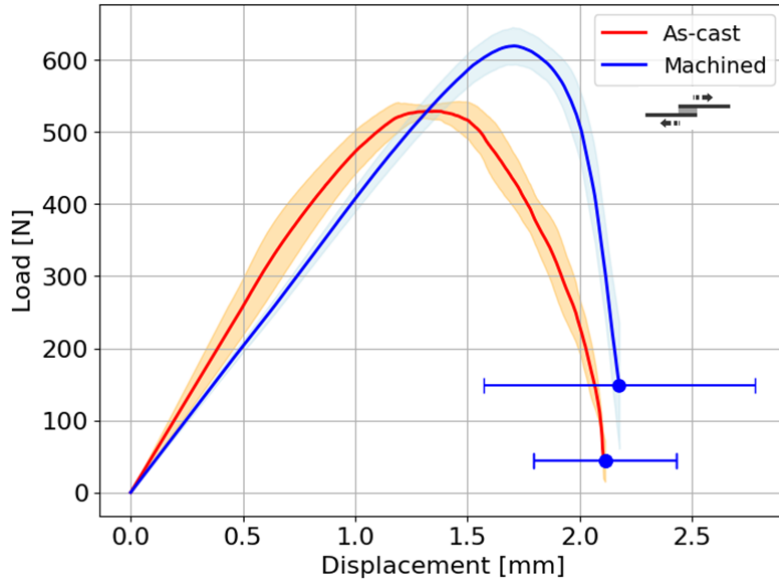


Figure 22: Comparison between substrates' surface condition when degreased, using the Teroson MS 939 adhesive.

Figure 23 presents the comparison between as-cast and machined conditions for sanded adherends. This comparison demonstrates a marked improvement in joint performance for the machined condition. The machined specimens achieve a significantly higher maximum load, exceeding 700 N, compared to approximately 600 N for the as-cast counterparts, as of a larger displacement prior to failure. These results are consistent with the predominance of cohesive failure observed in sanded specimens, which promotes stronger interfacial bonding. In contrast, the as-cast specimens, although improved compared to untreated surfaces, still display earlier failure associated with residual surface irregularities and localised stress concentrations. Overall, sanding combined with machining leads to superior mechanical behaviour, with performance.

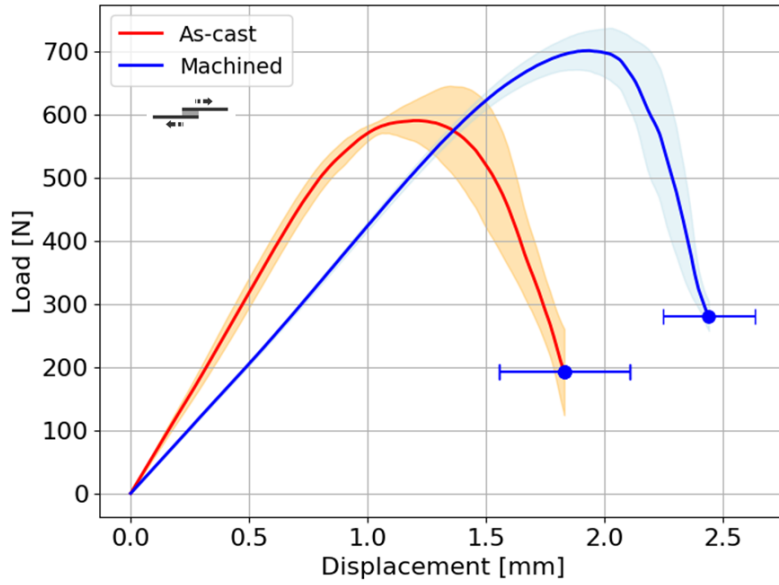


Figure 23: Comparison between substrates' surface condition when sanded, using the Teroson MS 939 adhesive.

Figure 24 presents the comparison between as-cast and machined conditions for anodized adherends. Despite their lower peak load, the machined joints sustain larger displacements before failure, indicating superior ductility and energy absorption. This divergence suggests that while anodization enhances adhesion strength in both conditions, the as-cast surface morphology may provide additional mechanical interlocking that favours higher strength, whereas machining prior to anodization promotes more stable cohesive failure and delayed failure onset. The predominance of cohesive failure in both cases confirms anodization as the most effective surface treatment, though the balance between strength and ductility varies depending on whether machining is applied beforehand.

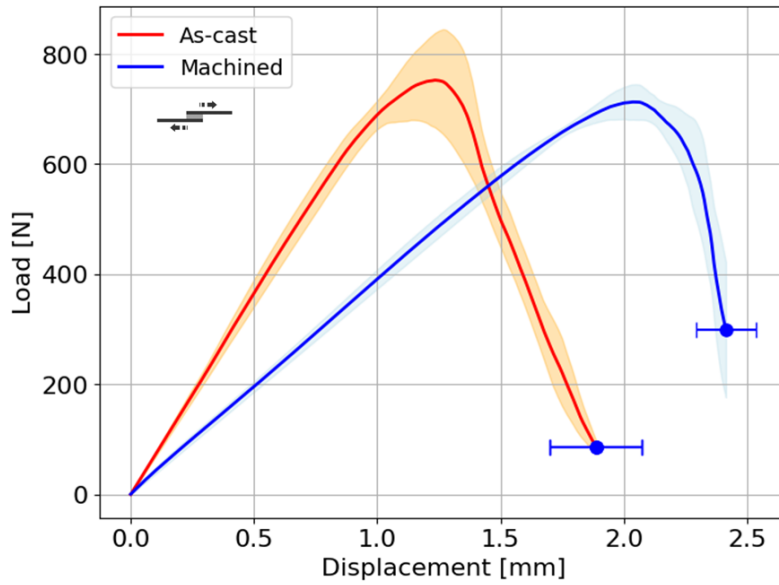


Figure 24: Comparison between substrates' surface condition when anodized, using the Teroson MS 939 adhesive.

A.4.2 90° peel test

As stated before, the 90° peel test involves peeling a flexible steel strip bonded with adhesive to a rigid substrate at a 90° angle. Figure 25 shows the load vs displacement curve obtained directly from the test machine, for the LS-XU film adhesive. For this result, three tests were performed. The peel strength of this film adhesive is of ~ 23 N.

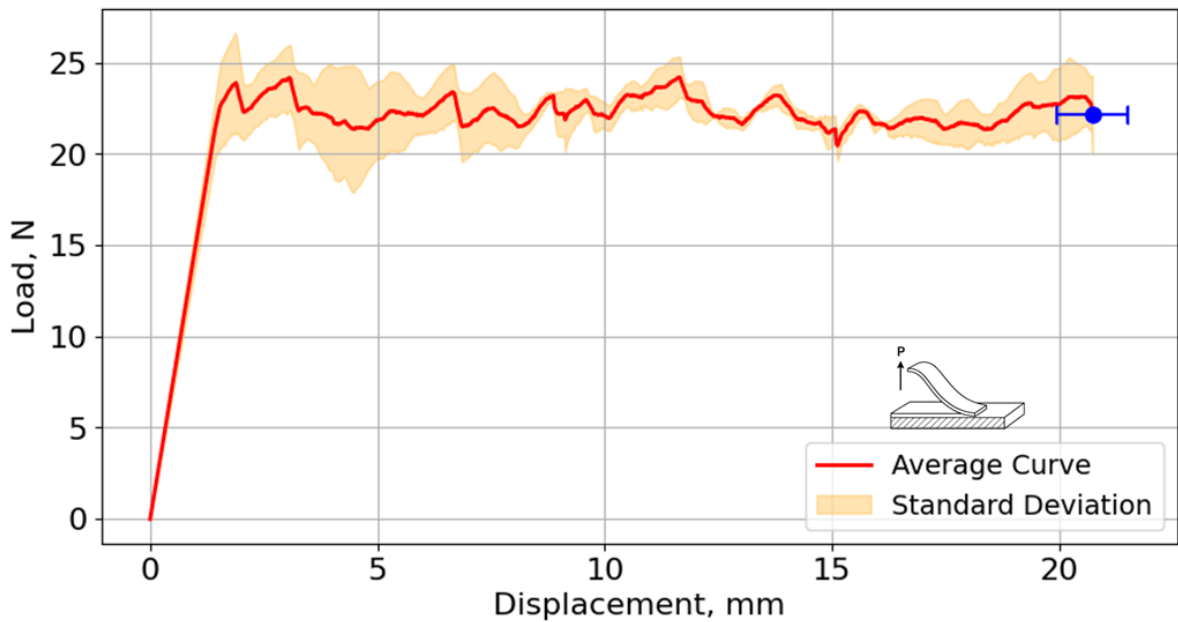


Figure 25: Results of the peel test of the LS-XU film adhesive.

The critical energy release rate, G (in N/mm), is determined from the load vs

displacement data using the relation $G = \frac{P}{b}$, where P is the peel force and b is the bond width. By plotting G against the corresponding displacement, a curve is obtained that characterizes the fracture behaviour of the adhesive. This method ensures that any plastic deformation of the substrate is accounted for, allowing G to reflect the true energy required for adhesive fracture [17]. Figure 26 shows the curve that describes the fracture behaviour of the LS-XU film adhesive. The critical energy release rate, G , for the adhesive film is of ~ 3.2 N/mm.

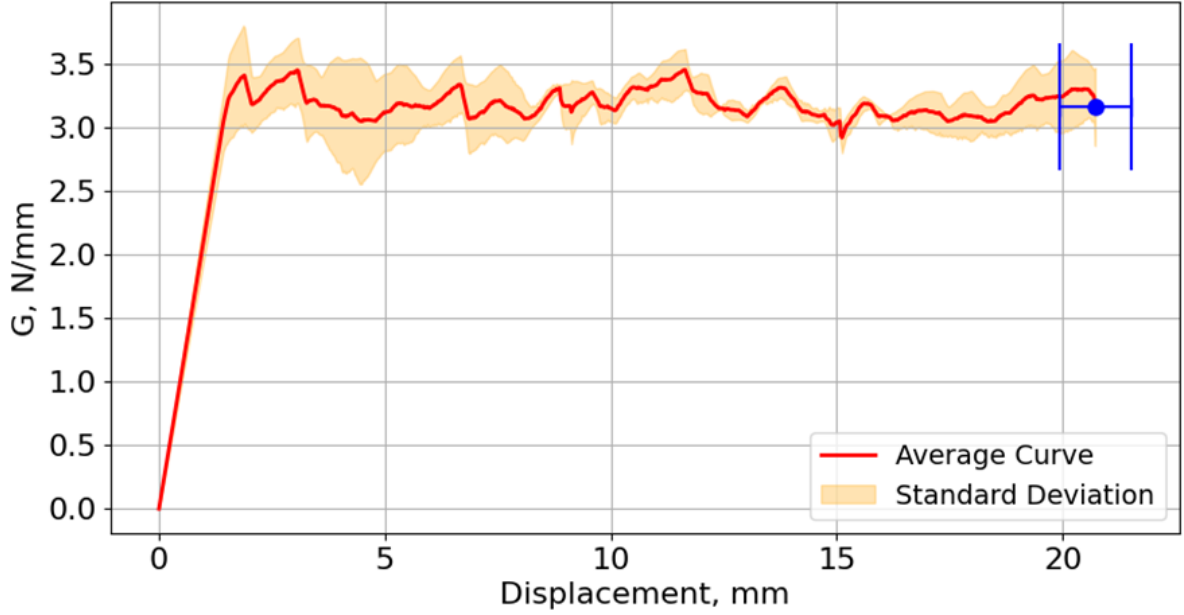


Figure 26: Critical energy release rate, G , for the LS-XU film adhesive.

The same test was performed for the MS polymer adhesive, Teroson MS 939. Figure 27 shows the load vs displacement curve obtained directly from the test machine. Three tests were considered to obtain the curve. The peel strength of this MS polymer adhesive is of ~ 31.6 N.

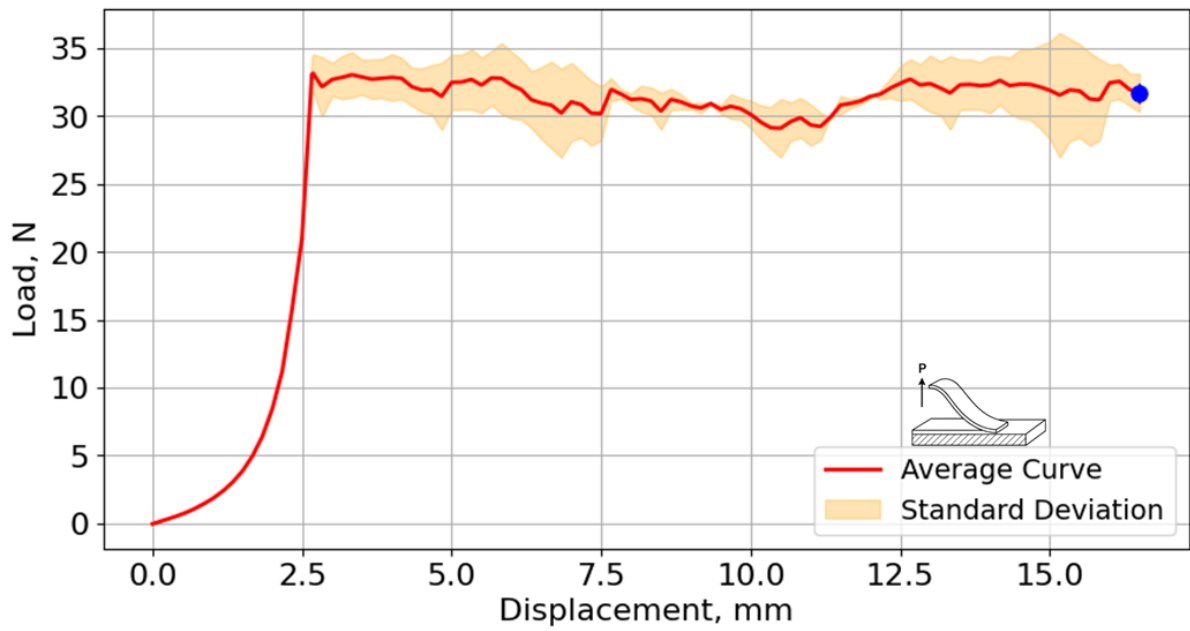


Figure 27: Results of the peel test of the Teroson MS 939 adhesive.

Repetition of the calculations mentioned previously, Figure 28 shows the curve that describes the fracture behavior of the MS polymer adhesive Teroson MS 939. The critical energy release rate, G , for the Teroson MS 939 adhesive is of ~ 4.4 N/mm.

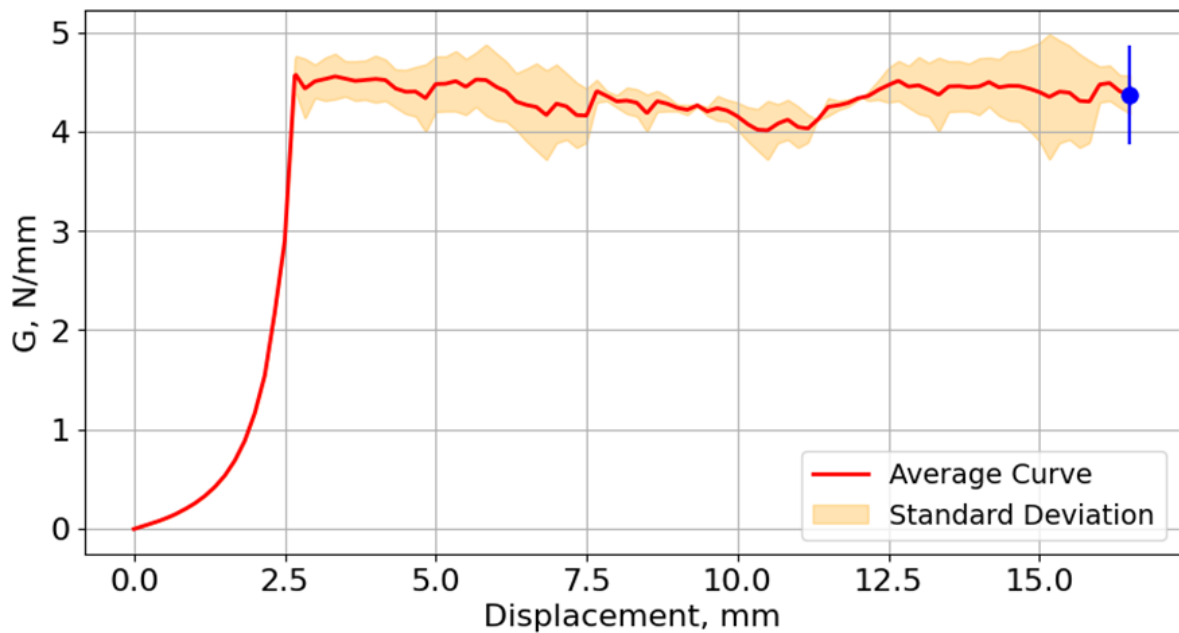


Figure 28: Critical energy release rate, G , for the Teroson MS 939 adhesive.

A.4.3 Numerical validation

Figure 29 shows the comparison between the experimental curve for the LS-XU adhesive film, considering SLJs with anodized substrates and the numerical model.

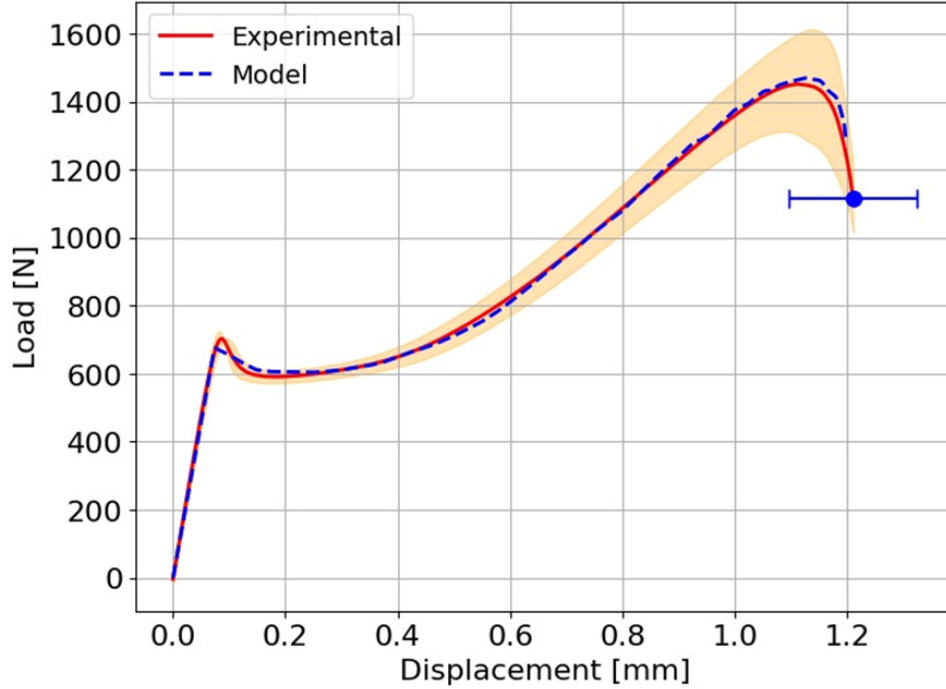


Figure 29: Comparison between experimental and numerical curves for the LS-XU adhesive film.

To obtain these results, an iterative process was taken, considering as reference the stress-strain curve of the adhesive film. This happened because of the need for adjustments in the displacement of the SLJs verified during testing. The adjusted stress-strain curve used in this model is presented in Figure 30.

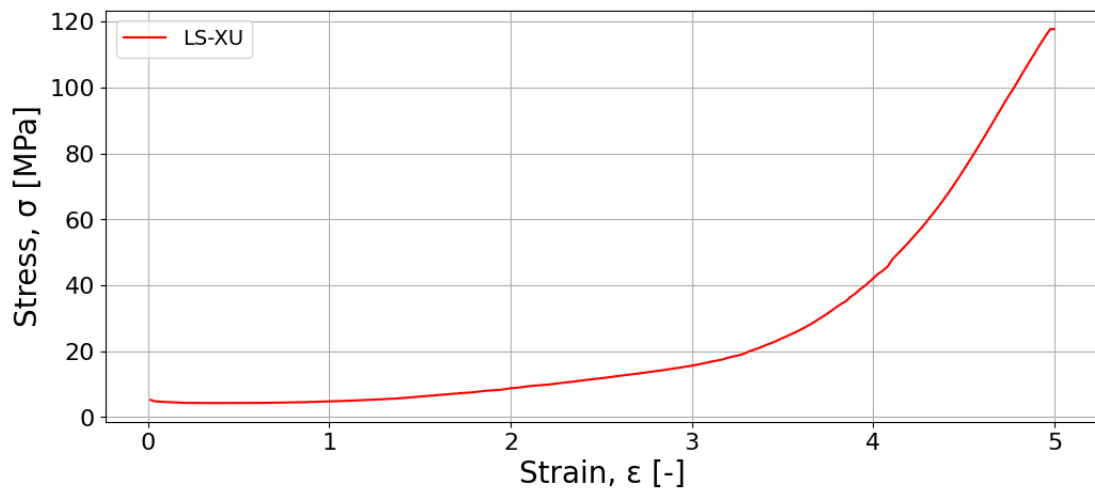


Figure 30: Adapted stress vs strain curve for the modelling of the LS-XU adhesive.

Figure 31 shows the comparison between the experimental curve for SLJs bonded with the Teroson MS 939 adhesive and anodized substrates where the failure was totally cohesive, and the numerical model.

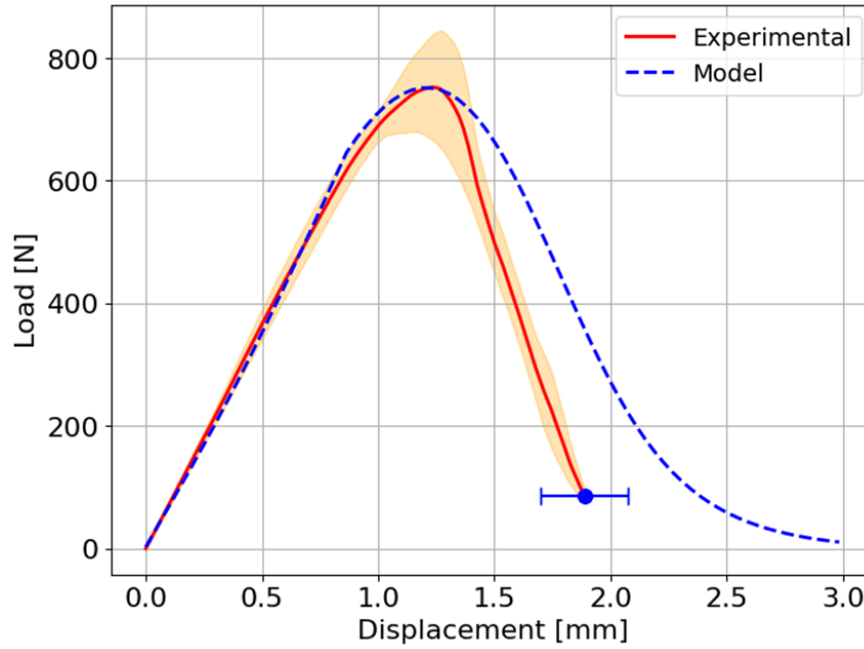


Figure 31: Comparison between experimental and numerical curves for the Teroson MS 939 adhesive.

A.5 Discussion

The results show that both adhesive type and surface treatment strongly affect SLJ performance. For the MS polymer, degreased substrates exhibited mainly adhesive failure and the lowest strength, sanding promoted more cohesive failure and higher loads, and anodized substrates achieved predominantly cohesive failure with the best performance. This confirms that cohesive failure is the most favourable outcome, as it reflects stronger interfacial bonding and greater energy absorption.

With the adhesive film, failure was exclusively adhesive across all treatments, which limited performance. Nevertheless, surface treatment produced noticeable differences. Degreased specimens showed the weakest behaviour, whereas sanding enhanced both strength and displacement capacity, particularly in the machined state. Anodization produced the best overall performance, with machined substrates reaching the highest loads and as-cast substrates achieving slightly lower strength while sustaining larger displacements.

A clear distinction emerges when comparing as-cast and machined substrates. Machining generally enhanced joint strength by removing surface irregularities and promoting a more uniform stress distribution, an effect most evident in the MS polymer and sanded joints where higher loads were achieved. In anodized adhe-

sive film joints, however, the relationship was more complex: machining maximised strength but reduced displacement, while the as-cast condition supported slightly greater deformation before failure. This indicates that machining improves surface uniformity and oxide quality, whereas the residual morphology of the as-cast surface may provide mechanical interlocking that enhances ductility.

The 90° peel tests indicate that the MS polymer joints absorbed significantly more energy per unit width than the film adhesive joints. The difference arises from the failure mechanisms and adhesive rheology. In the adhesive film, failure was dominated by interfacial debonding, producing relatively constant but lower values of G . This behaviour agrees with early peel models [18, 19], which showed that stiff, low-dissipation adhesives have peel energies governed mainly by the interface. By contrast, MS polymer adhesives are highly viscoelastic and dissipate significant bulk energy during crack advance, raising the steady-state G . This observation is consistent with Creton and Ciccotti [20], who noted that soft adhesives combine interfacial toughness with bulk viscoelastic dissipation.

A.6 Conclusions

Overall, the findings highlight that the choice between as-cast and machined conditions is not absolute but depends on the desired balance between strength and deformation capacity. For applications where maximum load is critical, machining offers a clear advantage, particularly when combined with anodization. Conversely, where greater ductility and energy absorption are required, as-cast anodized substrates may provide a more favourable outcome.

The 90° peel tests demonstrated that adhesive behaviour under peeling is governed not only by interfacial adhesion but also by the adhesive's rheology. The adhesive film exhibited stable but relatively low peel strength and G values, consistent with brittle interfacial debonding, while MS polymer adhesive reached higher G values owing to its bulk viscoelastic dissipation.

This distinction is highly relevant for the automotive industry, where peel resistance is critical in sealing systems, trims, and protective layers exposed to dynamic loads and environmental stresses. MS polymer adhesives, with their higher energy absorption and tolerance to interfacial flaws, provide greater reliability for flexible joints and sealing applications, whereas adhesive films remain advantageous for rigid, dimensionally stable assemblies that demand structural precision rather than peel toughness.

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B Paper B

Durability and internal pressure performance of adhesive and welded joints in die-cast aluminium components

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ABSTRACT

Lightweight aluminium die-cast alloys, such as $AlSi_{10}Mg$, are increasingly used in structural and semi-structural applications where reliable joining technologies are essential. This study investigates the performance of two adhesive systems—a cyclic olefin-based hot-melt adhesive (LS-XU) and a silane-modified polymer adhesive (Teroson MS 939), in comparison with friction stir welding (FSW), a solid-state joining method. Single lap joints were prepared in as-cast and machined conditions with sanding or anodizing pre-treatments and subjected to hydraulic oil ageing to evaluate durability. Internal pressure tests were also performed on bonded and welded components to assess load-bearing and sealing capabilities under service-like pressurisation. LS-XU joints exhibited significant degradation after oil exposure and brittle adhesive failure under pressure. Teroson MS 939 maintained cohesive failure behaviour and ductility, demonstrating superior long-term reliability. FSW joints achieved the highest strength but lacked sealing capability, failing through leakage at the weld seam. Complementary numerical modelling using ABAQUS®FE validated the experimental observations and highlighted critical stress distributions within the adhesive layer. The findings underline the importance of matching joining methods to service requirements: MS polymers provide sealing and durability, FSW ensures structural strength, and hybrid strategies may offer the most robust solution for demanding industrial applications.

B.1 Introduction

Lightweight design has become a central objective in modern engineering, with increasing pressure across industries to reduce component weight while maintaining or even improving mechanical performance. Aluminium alloys, for example die-cast aluminium $AlSi_{10}Mg$, have emerged as a key solution due to their low density, good mechanical strength, and corrosion resistance. Die-casting techniques allow the production of complex, thin-walled geometries with excellent dimensional accuracy at relatively low cost, making aluminium die-cast components attractive for large-scale use in automotive, aerospace, electronics, and energy sectors [1, 2]. Their adoption contributes to improved fuel efficiency and lower CO_2 emissions, aligning with regulatory and sustainability goals. The novelty of this approach lies in extending die-cast aluminium beyond decorative or non-critical components towards structural and semi-structural applications, where reliable joining technologies are essential.

Traditionally, joining of metallic components has relied on mechanical fastening or fusion welding. However, both approaches introduce drawbacks in die-cast aluminium. Fasteners add weight, introduce stress concentrators, and require machining, which undermines the cost-effectiveness of die-casting. Conventional welding can lead to porosity, hot cracking, and distortion due to the alloy's silicon-rich microstructure [3]. Adhesive bonding provides an alternative pathway, enabling stress redistribution, vibration damping, and the joining of dissimilar materials without extensive post-processing [4]. The choice of adhesive is crucial, as it must combine sufficient load-bearing capacity with durability under service environments.

In this study, two adhesive systems were investigated: a cyclic olefin-based hot melt adhesive (HMA), and a silane-modified polymer adhesive (SMP).

HMAs are thermoplastic systems that soften when heated, flow to wet the substrate, and solidify upon cooling, providing strong bonds through mechanical interlocking and van der Waals interactions [5]. They are widely used in packaging, electronics, and increasingly in transport applications because they offer rapid solidification, good adhesion to metals and polymers, and ease of automated application. Within this context, cyclic olefin copolymer (COC)-based hot melts have emerged as a particularly promising innovation. These polymers are derived from ring-opening metathesis polymerisation (ROMP) of cyclic olefins, followed by hydrogenation, resulting in an amorphous thermoplastic with low moisture absorption, good optical clarity, and high stiffness [6, 7]. In adhesive form, COCs adhesives provide clean application, uniform bondlines, and fast solidification, which are advantageous for automated assembly. Their potential in structural and semi-structural bonding of lightweight alloys is only recently being explored, making them an interesting candidate for comparative evaluation against more established adhesive classes.

Silane-modified polymers (SMPs) form a broad class of adhesives in which various polymer backbones are functionalised with reactive silyl groups capable of

crosslinking. The most common subclass, and the one relevant to this study, are silyl-terminated polyethers (STPEs), often marketed under the trade name MS polymers. STPEs consist of a flexible polyether backbone terminated with alkoxysilyl groups that cure by moisture-induced hydrolysis and condensation to form siloxane crosslinks [8]. This dual chemistry produces an elastomeric network with moderate tensile strength, high elongation, and pronounced viscoelastic damping. The "hybrid adhesive" designation is frequently used due to the fact that their elasticity and energy absorption typical of polyurethanes are merged with the durability and primerless adhesion associated with silane and silicone chemistries [9]. Compared to epoxies or polyurethanes, MS polymers offer lower stiffness but improved flexibility, making them particularly suitable where joint sealing, vibration absorption, and tolerance to displacement are required. They are widely used in automotive seam sealing, glazing, and panel bonding, and have also been adopted in marine, rail, and construction applications for their durability and ease of application [10,11]. For die-cast aluminium, their one-part, room-temperature cure and ability to bond directly to anodized or sanded surfaces make MS polymers attractive for semi-structural joints requiring both strength and sealing.

Alongside adhesives, friction stir welding (FSW) represents a solid-state joining alternative particularly suited to aluminium alloys. Developed by The Welding Institute in 1991 [12], FSW operates by plunging a rotating non-consumable tool into the joint line, plastically deforming and forging the material together without reaching the melting point. By avoiding solidification, FSW mitigates common fusion-welding defects such as porosity, hot cracking, and distortion, which are especially problematic in silicon-rich die-cast alloys. The intense plastic flow also produces a refined, equiaxed grain structure in the stir zone, with improvements in both tensile strength and fatigue resistance compared to traditional welds [13].

FSW has been widely adopted in aerospace, shipbuilding, rail transport, and automotive body structures because it enables the joining of alloys once considered unweldable, while maintaining dimensional stability and minimising residual stresses [14]. For die-cast aluminium alloys these attributes are particularly relevant, as conventional arc or laser welding often leads to brittle phases and casting defects that compromise joint reliability [15].

To evaluate the suitability of adhesives and FSW for structural die-cast aluminium applications, testing must replicate conditions representative of service. Durability tests, such as immersion ageing in oil, provide insight into the long-term stability of adhesive joints, where chemical or dimensional changes can reduce strength [16]. These tests are particularly relevant in automotive and aerospace environments, where joints are exposed to lubricants, fuels, or temperature cycling. Internal pressure tests provide complementary insights, assessing how joints withstand pressurisation where load transfer and sealing are required simultaneously.

Such tests are critical for housings, enclosures, and pressure-retaining components. Together, these methods establish a comprehensive framework to benchmark adhesive and welded joints under conditions that approximate real-world demands.

The present work investigates and compares three joining strategies for $AlSi_{10}Mg$ die-cast components: a novel cyclic olefin copolymer (COC) hot melt adhesive, a silane-modified polymer (MS polymer) representative of hybrid adhesive systems, and friction stir welding (FSW) as a solid-state joining method. The comparative investigation of a silane-modified polymer adhesive and a COC-based hot melt adhesive, alongside with friction stir welding for joining die-cast aluminium components constitutes a novel approach, as such a study has not previously been reported in the literature. Single-lap joints specimens in as-cast and machined conditions were treated by sanding and by anodizing. Durability tests, including immersion ageing in oil, were employed to examine the stability of these adhesive joints under conditions representative of automotive and aerospace service environments. Other adhesively bonded and welded specimens were manufactured to perform internal pressure tests to evaluate the load-bearing capacity and sealing capability of the joints when subjected to pressurisation, reflecting the requirements of housings, enclosures, and other pressure-retaining components. In addition to the experimental campaign, a numerical model of the internal pressure test for adhesively bonded specimens was developed in ABAQUS®FE, enabling simulation of the joint response and validation of the experimental results. Together, these assessments establish a comprehensive framework for benchmarking adhesive and welded joints in die-cast aluminium, providing new insights into the feasibility of emerging adhesive chemistries and welding methods for demanding industrial applications.

B.2 Experimental details

B.2.1 Materials

A multi-material film adhesive with the commercial designation LS-XU was employed, supplied at a thickness of 0.4 mm and formulated from a cyclic olefin-based polymer by Zeon®Corporation (Chiyoda-ku, Tokyo, Japan). Curing was carried out in a hot press at 159 °C for 45 minutes. Previous work by Rodrigues et al. [17] reported the properties of this adhesive at 0.1 mm thickness, while subsequent investigations on the 0.4 mm variant established the mechanical parameters listed in Table 1.

Table 1: LS-XU mechanical properties

Property	Units	Value
Young's modulus, E	[MPa]	230.18 ± 8.08
Yield strength, σ_y	[MPa]	5.49 ± 0.36
Tensile failure strength, σ_f	[MPa]	10.86 ± 1.48
Tensile failure strain, ε_f	[%]	1066 ± 83
Poisson's ratio, ν	[-]	0.47 ± 0.02
Shear modulus, G	[MPa]	76.67 ± 2.52
Shear failure strength, τ_f	[MPa]	5.09 ± 0.08
Shear failure strain, γ_f	[%]	354 ± 19
Toughness in mode I, J_{Ic}	[N/mm]	0.20 ± 0.05
Toughness in mode II, J_{IIc}	[N/mm]	2.66 ± 0.19

The second adhesive system studied was TEROSON®MS 939, a modified silane polymer (MS polymer) adhesive/sealant supplied by Henkel (Düsseldorf, Germany). This product cures through absorption of ambient humidity, with complete curing achieved after approximately two weeks, yielding a flexible elastomer. The corresponding mechanical properties of this adhesive are presented in Table 2.

Table 2: Teroson MS 939 mechanical properties

Property	Units	Value
Young's modulus, E	[MPa]	2.90 ± 0.01
Yield strength, σ_y	[MPa]	8.24
Tensile failure strength, σ_f	[MPa]	3.14 ± 0.03
Tensile failure strain, ε_f	[%]	2.30 ± 0.04
Poisson's ratio, ν	[-]	0.37
Shear modulus, G	[MPa]	0.94 ± 0.02
Shear failure strength, τ_f	[MPa]	2.59 ± 0.07
Shear failure strain, γ_f	[%]	5.68 ± 0.36
Toughness in mode I, J_{Ic}	[N/mm]	5.2 ± 1.8

The adherends used were $AlSi_{10}Mg$ aluminium alloy substrates, extracted directly from a high-pressure die-cast automotive component. For modelling and analysis purposes, the aluminium alloy was considered to have a Young's modulus, E of 70 GPa and a Poisson's ratio, ν , of 0.33.

B.2.2 Specimen manufacturing

To investigate the effect of hydraulic-oil ageing on joint behaviour, single lap joints were manufactured for each adhesive previously mentioned. Figure 1 presents the dimensions of the single lap joints, where is possible to see that the substrates of $AlSi_{10}Mg$ aluminium alloy were machined to obtain the dimensions 10 x 100 x 3 mm, with an overlap length of 25 mm and 0.2 mm of adhesive thickness.

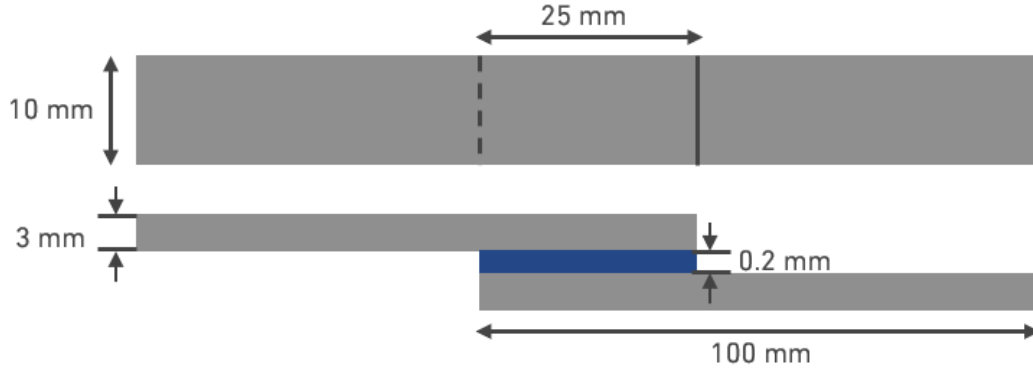


Figure 1: Single lap joint geometry used.

Two substrate conditions were examined, as-cast and machined. Within each condition, surfaces were pre-treated either by P600 sanding or by anodizing, producing four adherend variants: as-cast-sanded, as-cast-anodized, machined-sanded, and machined-anodized.

For internal pressure testing, an automotive aluminium component, made of the aluminium alloy $AlSi_{10}Mg$, provided by Wedrone, Portugal, was bonded to 1.5 mm thick $AlMg_6$ aluminium alloy lid, using both adhesive systems and FSW. Figure 2 presents the internal pressure specimen bonded with the LS-XU adhesive.

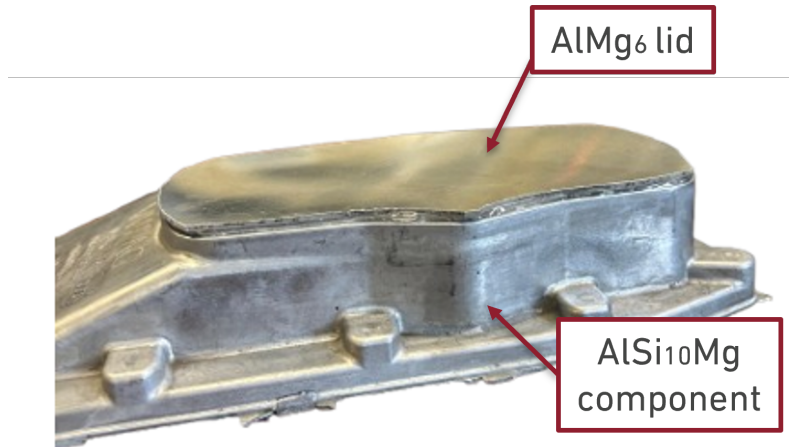


Figure 2: Internal pressure test specimen bonded with the LS-XU adhesive.

Regarding FSW specimens, the lid was bonded to the aluminium component by following the parameters presented in Table 3.

Table 3: Friction stir welding parameters

Parameter	Value
Rotational speed	1200 rpm
Feed speed	300 mm/min
Plunge depth (Z)	1.6 mm (0.1 mm penetration)

B.3 Testing procedures

Durability test

Durability tests were conducted to assess the effect of hydraulic-oil exposure on the mechanical performance of single-lap joints (SLJs). Specimens were fully immersed in hydraulic oil for 32 days at ambient conditions to simulate prolonged contact with lubricants typical of automotive environments. After ageing, the joints were removed, cleaned of surface residues, and prepared for mechanical testing. All tests were performed on an INSTRON® 3367 universal testing machine (Illinois Tool Works, Hopkinton, MA, USA) under quasi-static loading at a crosshead displacement rate of 1 mm/min, selected to avoid inertial and dynamic effects, and to ensure direct comparability with unaged controls.

Internal pressure test

The internal pressure test evaluates the ability of bonded joints to withstand pressurisation under service-like conditions. Pressure is increased under quasi-static loading by driving the crosshead at 1 mm/min. The resulting pressurisation loads the joint in a manner similar to a tensile test, generating stresses mainly perpendicular to the bond line and progressively engaging the adhesive layer until failure. The pressure at the first sign of leakage or rupture is recorded to quantify each adhesive system’s and FSW joint’s resistance to internal loading. This method complements lap-shear and peel tests by assessing performance under realistic loading conditions relevant to real life applications.

B.4 Results

B.4.1 Durability test

For the durability tests, at least three specimens were considered in the presented results.

Figure 3 illustrates the results of the aged SLJs tested with the LS-XU adhesive. Under hydraulic-oil ageing, LS-XU shows an early local peak at small displacement

around 0.05–0.10 mm with a load of about 250–330 N, followed by brief softening and a long hardening branch to failure. The curve behaviour is similar to unaged specimens, as can be seen in Rodrigues et. al work [17]. Peak loads are highest for machined joints at roughly 800–850 N, intermediate for as-cast sanded at about 600–650 N, and lowest for as-cast anodized at around 520–560 N. Displacement at failure is largest for as-cast anodized at ~ 1.15 mm, moderate for machined anodized at ~ 0.95 mm, and smaller for sanded specimens at ~ 0.8 mm.

Machined substrates produce the most durable LS-XU joints under aggressive ageing, retaining strength but failing at smaller displacements, which indicates reduced ductility. As-cast anodized joints are the least reliable, suggesting that anodizing on an as-cast surface is particularly susceptible to degradation in this environment.

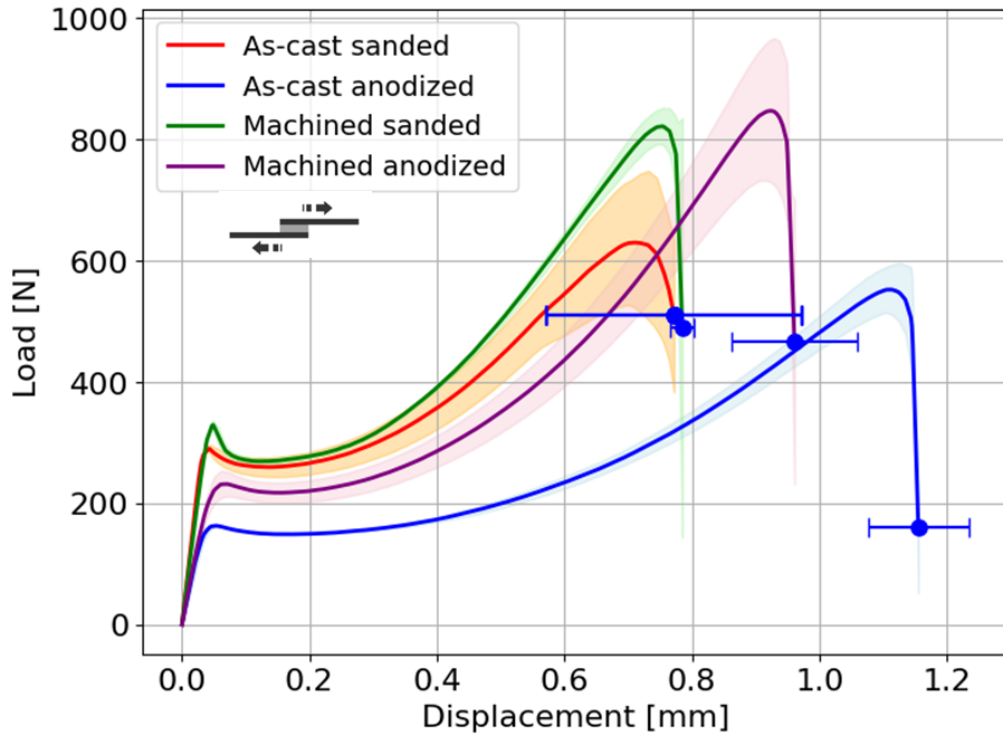


Figure 3: Durability test results for the LS-XU adhesive.

Figure 4 presents the failure modes corresponding to the previous results. All SLJs failed adhesively, consistent with the behaviour of the unaged joints. Adhesive failure is problematic because the interface governs strength rather than the bulk adhesive, which typically lowers fracture energy, promotes abrupt loss of load, and increases sensitivity to surface condition and ageing. In pressurised or fluid-facing assemblies it can create a direct leak path and allow ingress of moisture and contaminants, shortening durability and fatigue life. Prolonged hydraulic-oil exposure also caused shrinkage of the adhesive layer, which can raise residual peel stresses at the edges and further promote interfacial debonding.

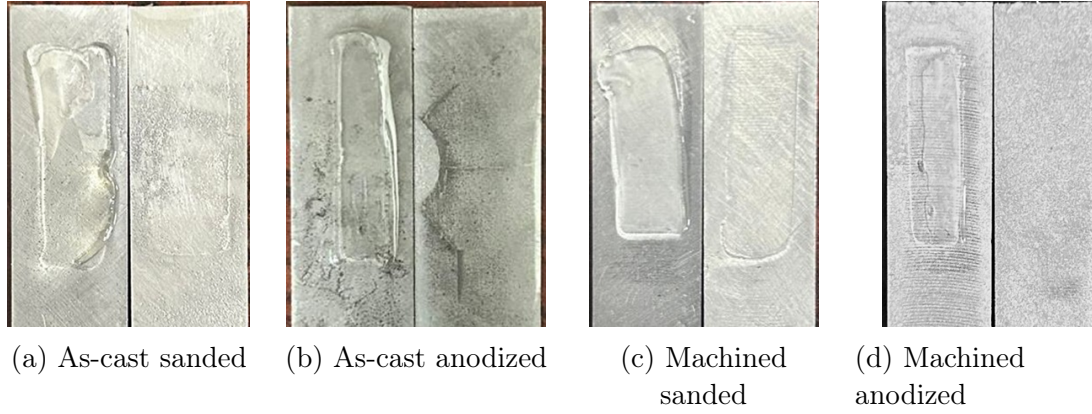


Figure 4: Failure surfaces of the SLJs in durability tests for LS-XU adhesive.

LS-XU is a cyclic-olefin-based hot-melt adhesive whose polymer phase is non-polar and compounded with low-molar-mass ingredients such as hydrocarbon tackifiers and waxes. Prolonged contact with hydraulic oil can make the bonded layer appear thinner through two coupled processes. First, non-polar hydrocarbons from the oil enter the adhesive, cyclic-olefin polymers and copolymers (COC/COP) are known to sorb non-polar solvents, a fact exploited in solvent-bonding methods where cyclohexane softens and even renders COC surfaces tacky due to penetrant uptake and swelling [18–20]. Experimental studies report room-temperature solvent bonding of COC with cyclohexane-rich mixtures and direct observations of surface swelling under such exposure, while quantitative sorption and diffusion data confirm that small organics permeate COP/COC matrices on practical timescales [18, 19, 21, 22]. After the oil desorbs, the polymer does not fully return to its original specific volume, because the prior plasticisation accelerates structural relaxation. The result is a denser layer with a net reduction in thickness.

In addition to swelling effects, hydraulic oil can pull out some of the small, mobile ingredients in LS-XU, mainly the hydrocarbon tackifiers and waxes. Studies on polyolefin hot-melt adhesives show that C16–C24 hydrocarbons can move from the adhesive into non-polar liquids, which means part of the adhesive’s low-molecular-mass fraction is lost to the oil during immersion. Those papers focus on other polyolefin backbones rather than COC, but the extraction step is driven by the additives, not the exact polymer, so the same process is expected for LS-XU. What can change is how fast and how much is extracted, because that depends on the COC matrix. When this additive loss is combined with the in–out sorption of oil that leaves the polymer packed more tightly after desorption, the result is a thinner bond line after hydraulic-oil ageing [23, 24].

Figure 5 shows the critical state of the adhesive LS-XU in the SLJ at which spontaneous joint debonding initiates.

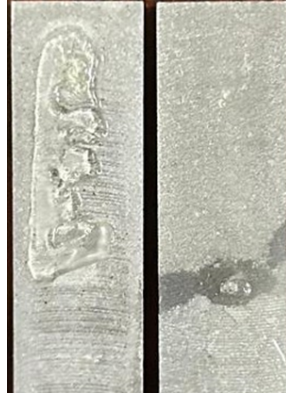


Figure 5: S-XU adhesive shrinkage after contact with hydraulic oil

Since the true impact of oil ageing can only be assessed by direct comparison with the original behaviour. The unaged SLJs results were obtained from previous work. The comparison between unaged and aged as-cast anodized SLJs showed the most noticeable change among the tested combinations, and is presented in Figure 6. The maximum load decreased by approximately two-thirds after ageing, while displacement at failure was also reduced, pointing to a brittle and weakened response. This behaviour is consistent with the shrinkage phenomenon previously explored, with the reduced area of adhesive reducing the performance of the joint.

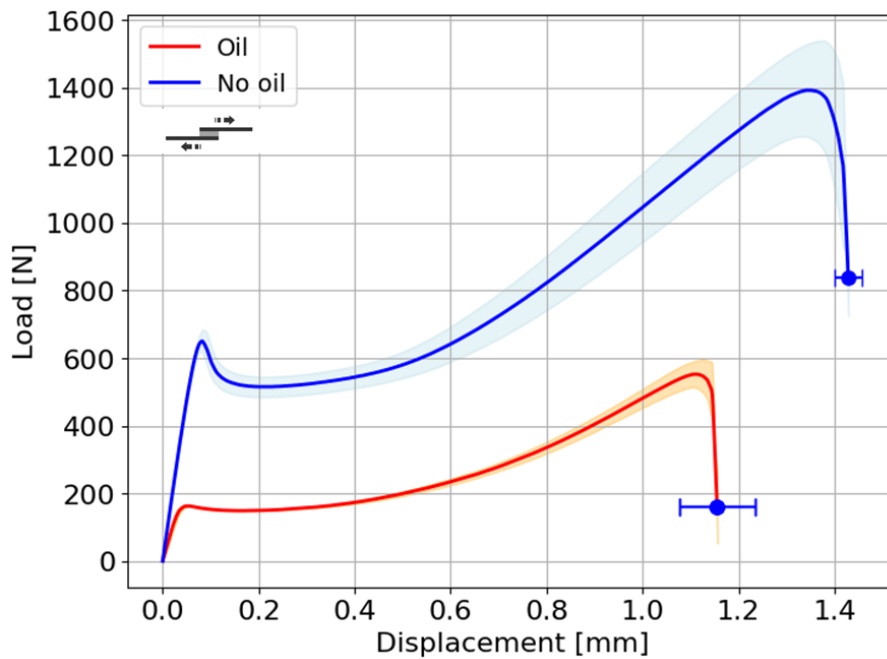


Figure 6: Comparison of machined anodized SLJs bonded with the LS-XU adhesive under normal and durability testing.

Regarding the durability tests performed on the MS polymer adhesive, the results are shown in Figure 7. Teroson MS 939 shows a single peak followed by softening in all conditions, which is consistent with unaged SLJs previously tested in another

work. Machined anodized specimens attain the highest peak load at around 570 N. As-cast sanded specimens peak slightly lower 500 N, at a similar displacement. As-cast anodized reaches a similar high peak of 550 N, but sustains load over the longest tail, decaying to near zero at ~ 3.5 mm. Machined sanded specimens have the lowest strength around 480 N, as well with lower displacement.

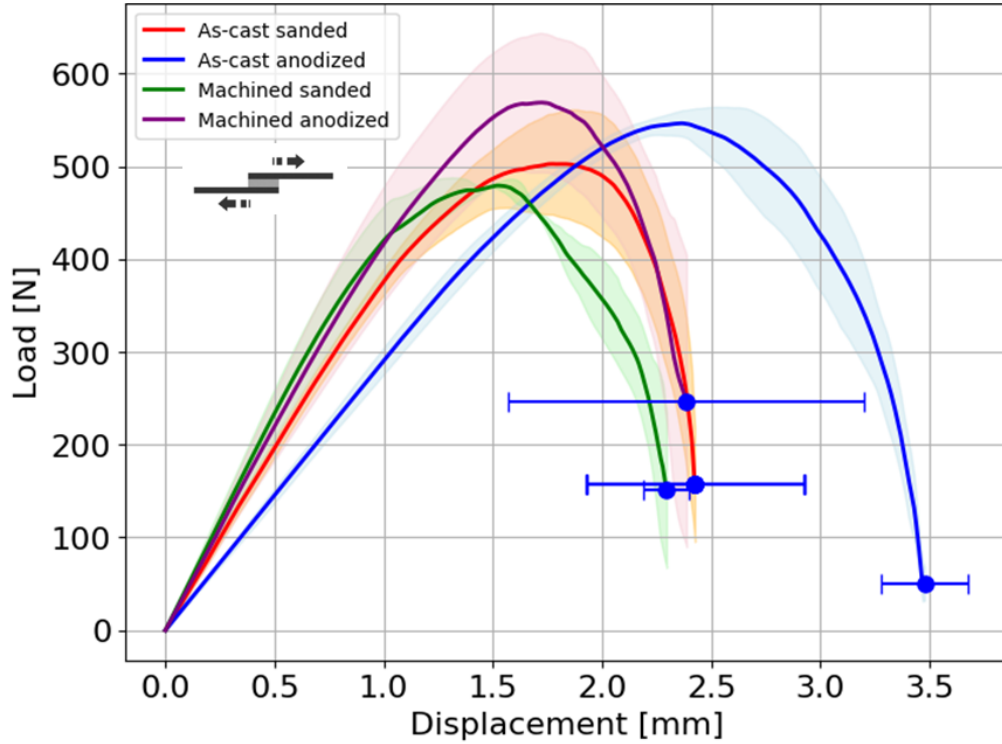


Figure 7: Durability test results for the Teroson MS 939 polymer adhesive.

Figure 8 illustrates the failure surfaces of the tested SLJs. The sanded specimens (a,c) still fail predominantly adhesively, where is possible to see large areas of bare aluminium, indicating that the oil environment weakened the interface, so the crack ran along the bond line. In contrast, the anodized specimens (b,d) retain mainly cohesive failure, with substantial adhesive residue on both sides. The anodic oxide's porous, chemically active layer resists interfacial degradation and provides micro-mechanical anchoring, so the crack is forced into the adhesive bulk even after ageing. This interfacial robustness under oil exposure explains why the anodized joints sustain higher peak loads than the sanded joints in the durability tests.

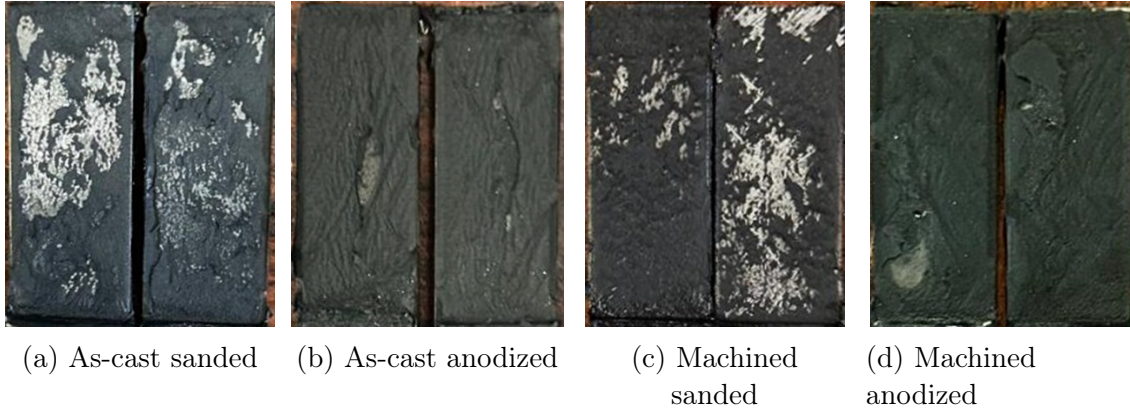


Figure 8: Failure surfaces of the SLJs in durability tests for Teroson MS 939 adhesive.

To highlight the effect of oil exposure, the as-cast anodized SLJs were again taken as the reference condition. The comparison between aged and unaged samples are presented in Figure 9 and revealed a moderate decline in peak load, and also a noticeable reduction in stiffness for the aged specimens. Despite this softer response, the joints sustained larger displacements at failure, resulting in a comparable or even enhanced ability to absorb and dissipate strain energy through viscoelastic deformation. This behaviour confirms that Teroson MS 939 retained its viscoelastic character after ageing, maintaining ductility and cohesive failure modes, and thus exhibited superior durability relative to LS-XU under identical test conditions.

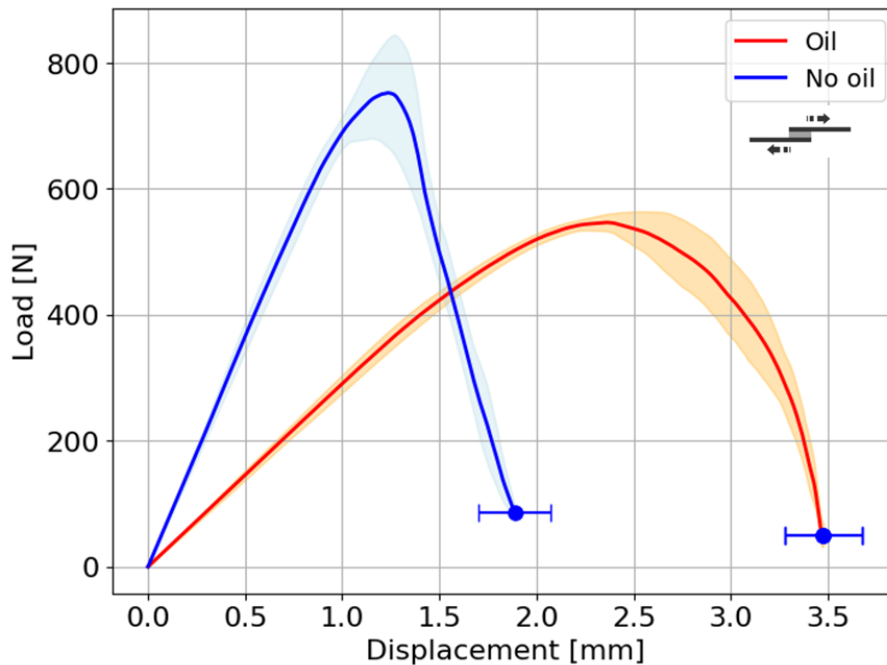


Figure 9: Comparison of machined anodized SLJs bonded with the Teroson MS 939 adhesive under normal and durability testing.

B.5 Internal pressure test

The internal pressure tests were performed on joints bonded with the LS-XU film adhesive, the Teroson MS 939 polymer adhesive, and on friction stir welded (FSW) specimens. Figure 10 presents the load vs displacement curves obtained for the three configurations.

The LS-XU bonded specimens exhibited a steep initial load rise, reaching a maximum capacity of approximately 2.2 kN at a displacement of less than 1 mm. Failure occurred abruptly after the peak, with little residual load-carrying capability, reflecting a stiff and brittle response under pressure loading. The Teroson MS 939 specimens displayed a markedly different behaviour. The load increased progressively to values above 4 kN, while displacements extended beyond 3 mm prior to failure. The curves presented a plateau near maximum load, indicating that the adhesive accommodated significant deformation while maintaining integrity. The FSW specimens showed the highest overall performance, with peak loads around 13.3 kN at displacements exceeding 5 mm. The load-displacement response was nearly linear up to failure, after which a sudden drop occurred due to leakage along the weld line.

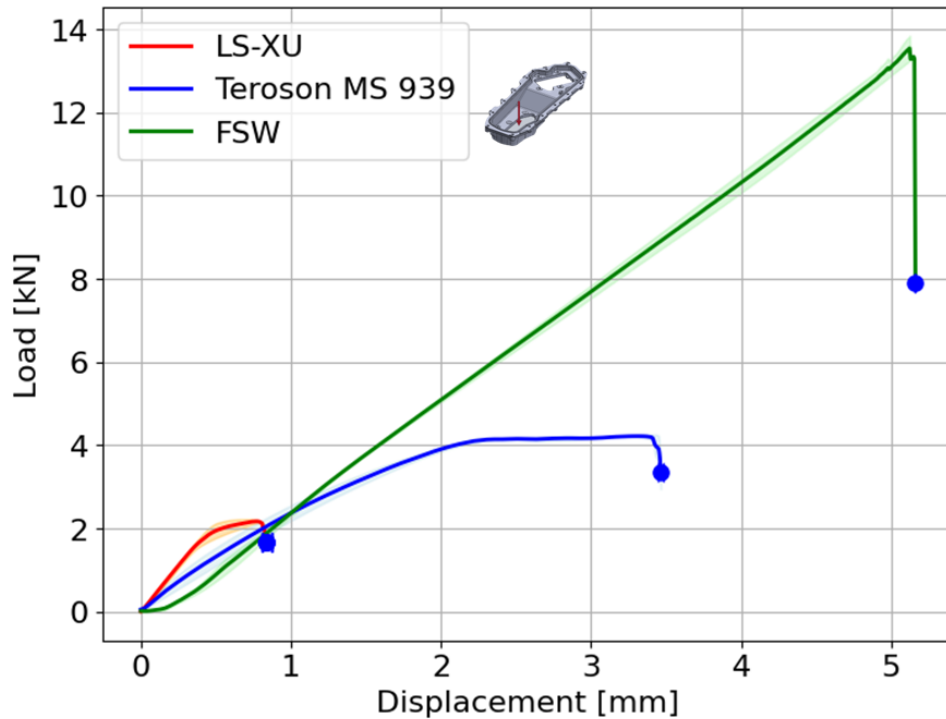


Figure 10: Internal pressure test results for both adhesives, LS-XU and Teroson MS 939.

For the LS-XU specimens, failure occurred adhesively, as can be seen in Figure 11, with detachment concentrated along the inner overlap edges where pressure-driven stresses were most severe. After visual inspection of the failure, localised

blistering and gaps in the film were found, indicating that the adhesive layer was unable to withstand internal pressurisation, leading to rapid crack initiation and propagation across the interface.



Figure 11: Failure mode of the LS-XU adhesive in internal pressure testing.

In the Teroson MS 939 joints, the failure mode is presented in Figure 12 and it involved a combination of adhesive and cohesive mechanisms. Post-test inspection revealed some areas of adhesive residue remaining on the substrates, along with large cohesive tearing within the adhesive layer. This mixed mode indicates that interfacial adhesion was sufficiently strong to resist debonding, while the viscoelastic polymer accommodated deformation before local rupture occurred. The gradual failure observed in the load vs displacement curve is consistent with this behaviour.



Figure 12: Failure mode of the Teroson MS 939 adhesive in internal pressure testing.

The FSW specimens failed by localised leakage along the weld seam. Unlike the adhesive joints, the bonding interface remained intact until the aluminium cover itself began to plastically deform under the applied pressure. Fractographic observations revealed through-thickness cracks in the weld region, suggesting that failure was governed by the mechanical limit of the welded material rather than premature loss of joint integrity. This behaviour confirmed that the welded joints sustained the highest internal pressures before rupture. Figure 13 illustrates the failure of the FSW specimens.



Figure 13: Failure mode of the FSW specimen in internal pressure testing.

B.6 Discussion

The durability tests highlighted the sensitivity of LS-XU to oil ageing, where shrinkage and interfacial debonding caused a severe reduction in strength. The fully adhesive failures left clean substrates, which, while simplifying disassembly, reflected poor durability under service-like conditions. In contrast, Teroson MS 939 retained mechanical capacity and ductility, with predominantly cohesive failures indicating stronger interfacial bonding. These mixed failures complicate repair but are generally desirable in long-term applications where maintaining integrity is more important than ease of rework. For automotive under-hood components, aerospace fuel systems, or marine structures exposed to aggressive fluids, this makes MS polymers the more suitable choice, while film adhesives such as LS-XU are limited to controlled environments.

The internal pressure tests further distinguished the three joining methods. LS-XU joints again showed brittle behaviour, failing adhesively once the interface was compromised. This abrupt loss of performance is unacceptable in applications where pressure containment is critical, such as mechanical housings or structural enclosures. Teroson MS 939 sustained more than twice the load of LS-XU and exhibited a gradual failure process with mixed cohesive behaviour, making it well-suited for sealing and structural functions in automotive, aerospace, and marine assemblies. FSW provided the highest load capacity, but failure along the weld seam highlighted its lack of sealing capability. This makes it ideal for high-strength structures such as aerospace frames, rail vehicles, or heavy-duty machinery, but insufficient on its own in systems where pressure-tightness is required.

Together, these results emphasise that the choice of joining method must consider both mechanical performance and service environment. Adhesives such as Teroson MS 939 offer durability, energy dissipation, and sealing capacity, whereas LS-XU film adhesives are limited by their susceptibility to ageing. FSW delivers superior structural resistance but lacks sealing, suggesting that hybrid solutions — combining welding for strength and MS polymers for sealing — are particularly promising for industries such as renewable energy, shipbuilding, and chemical processing, where both load-bearing and containment are essential.

It is also relevant to note that adhesive joints offer the possibility of disassembly, repair, and maintenance of components, whereas FSW joints, despite their superior mechanical resistance, create permanent bonds that cannot be dismantled.

B.7 Numerical details

Numerical modelling was conducted to complement the internal pressure tests of the bonded joints, focusing on the MS polymer adhesive Teroson MS 939. The hot-melt LS-XU was excluded due to inadequate pressure response and oil durability. The model targets evaluation of Teroson MS 939 behaviour under service-like conditions, enabling validation of the experiments and inspection of stress distributions and cohesive-failure trends not directly observable in tests.

For computational efficiency, a reduced geometry was adopted, representing only the bonded region rather than the full component. The ABAQUS®FE model comprises three parts: a simplified die-cast aluminium substrate for the bond area, the adhesive layer, and the lid. This abstraction preserves the essential stress-strain response within the adhesive while minimizing solution cost.

Boundary conditions replicated the test setup using two reference points (RPs). RP1 was continuum-distributing coupled to the loaded (wetted) surface to apply a uniform U3 displacement, avoiding localised peaks and matching the experimental actuator. RP2 was kinematically coupled to the clamped support surface and fully fixed ($U1=U2=U3=UR1=UR2=UR3=0$), reproducing the rigid fixture. This scheme is presented in Figures 14 and 15 and ensured realistic load application and constraint while keeping the model numerically stable.

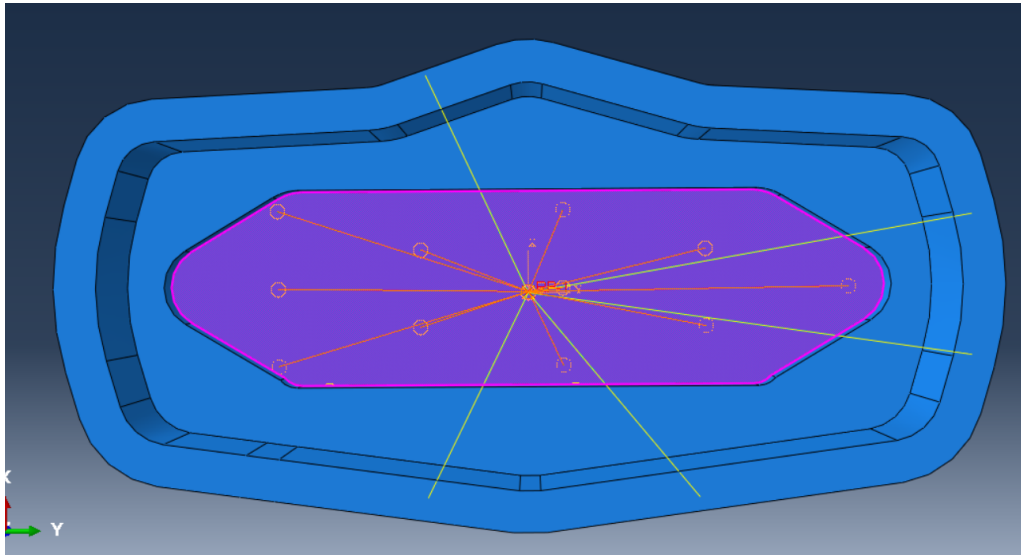


Figure 14: Reference point 1 creation to apply a boundary condition.

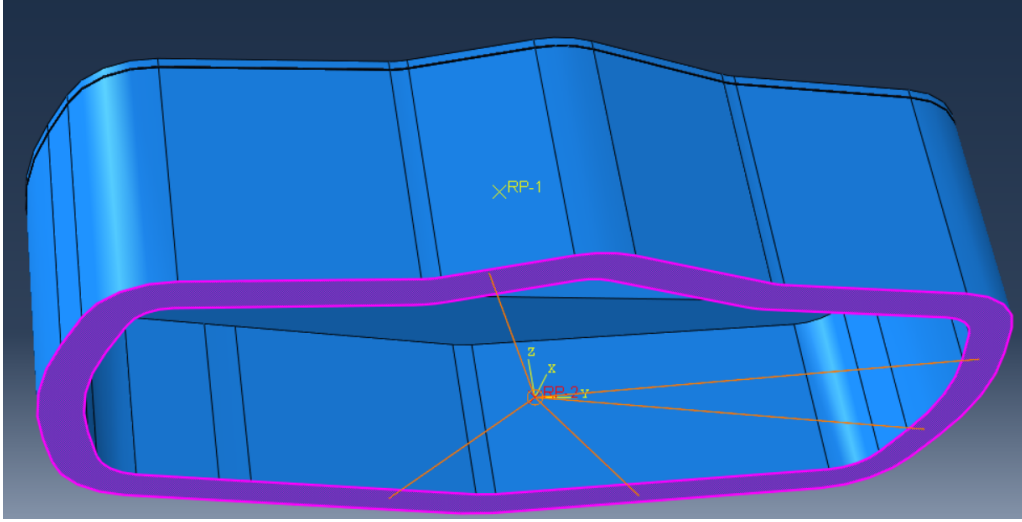


Figure 15: Reference point 2 creation to apply a boundary condition.

Both adherends were assigned elastic-plastic behaviour using their respective aluminium grades ($AlSi_{10}Mg$ for the simplified part, $AlMg_6$ for the lid). The simplified part, being non-sweepable, was meshed with free tetrahedra C3D10 elements with local refinement at the bond to improve stress transfer and tie compatibility. The lid was sweep-meshed with reduced-integration hexahedra C3D8R elements for efficient, accurate linear-elastic response.

The MS polymer adhesive employed a hyperelastic Marlow law for the bulk and a traction-separation cohesive interface to capture cohesive failure. The bulk adhesive was discretised with structured hybrid hexahedra C3D8H elements to avoid volumetric locking and to resolve through-thickness strains. A zero-thickness cohesive layer at mid-thickness used COH3D8 elements with elastic traction stiffness (normal and shear), quadratic nominal-stress initiation, and energy-based evolution (calibrated to the experimental load vs displacement curve). Figure 16 shows the final mesh and assembly.

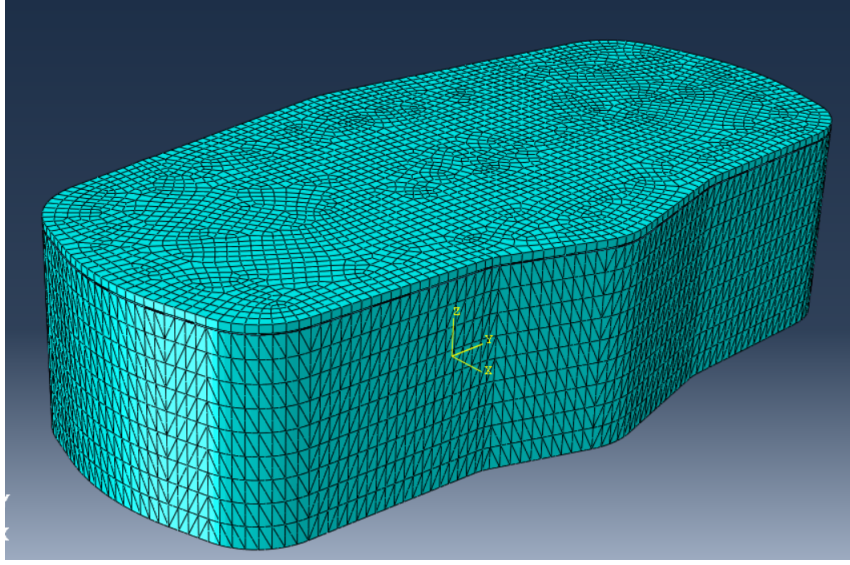


Figure 16: Meshed assembly of the internal pressure test specimen.

Because failure is cohesive within the adhesive, both adherend–adhesive interfaces are modelled as perfectly bonded via surface-based tie constraints. This removes interfacial slip/separation and any penalty-contact compliance, so load transfers directly from the adherends into the bulk adhesive and on to the mid-thickness cohesive zone, where damage initiates and propagates. Mesh densities are matched across the tied faces to maintain smooth stress transfer, and no contact is defined at these interfaces, preventing alternative failure paths and keeping the response governed by the adhesive’s cohesive law. This setup supports efficient evaluation of adhesive stress distributions, prediction of crack-initiation sites, and assessment of progressive damage under service-like loading.

B.7.1 Numerical validation

This numerical study supports the internal pressure tests on the MS polymer joint by examining field responses. The model replicates the test boundary conditions and is used to map peel and shear stresses through the adherends and bulk adhesive, and to track opening, sliding, and damage in the mid-thickness cohesive layer. These results identify where failure initiates, how it propagates under pressure, and which regions are most critical, providing a clear validation of the experimentally observed cohesive failure mode and practical guidance for design improvement.

Figure 17 presents the von Mises stress field in the lid under internal pressure and provides a first validation of the boundary conditions and load transfer. The response is dominated by bending, with a low-stress dome over the wetted area and a circumferential ridge of elevated stress across the bonded land. Peak stresses are concentrated at tight fillets and corner transitions, consistent with geometric

curvature and the shortest load paths into the joint. This spatial pattern matches expectations for mixed-mode loading at the adhesive: peak peel and shear are predicted near the stress ridge and corner hot spots, the most expected sites for damage initiation in the cohesive layer. The absence of false concentrations away from the bond, together with the smooth stress gradients, indicates appropriate meshing and constraints. Overall, the field confirms that the numerical model reproduces the characteristic stress distribution observed in internally pressurised joints and identifies the regions most critical for subsequent cohesive failure analysis.

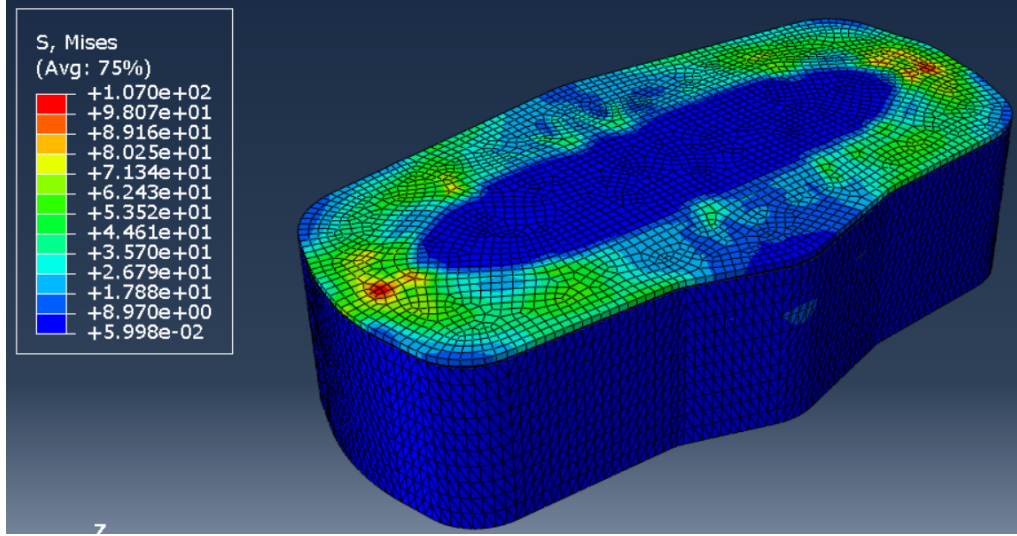


Figure 17: Von Mises stress in the lid under internal pressure.

Figure 18 shows the pre-damage von Mises field in bulk MS polymer adhesive under internal pressure. Stresses form a circumferential ridge across the bonded land and intensify at internal corners and curvature transitions. The peak level at this point (~ 3.09 MPa) is below the material's tensile strength (3.14 MPa), so this field represents conditions just prior to damage onset. Consistent with the traction–separation model, damage is expected to initiate at the internal corners and along the high-ridge zones, where peel and mixed-mode tractions are greatest, and then propagate around the bondline.

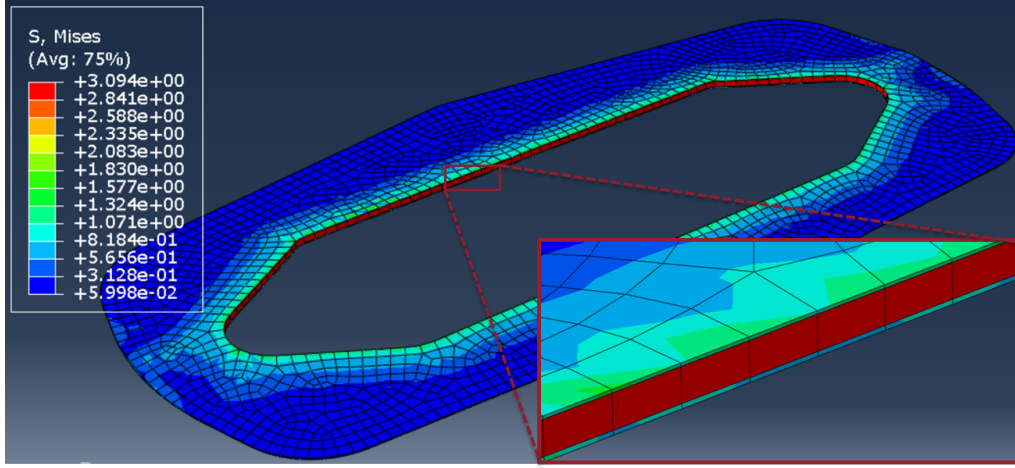


Figure 18: Pre-damage von Mises stress in the bulk MS polymer adhesive under internal pressure.

Figure 19 reports the through-thickness normal stress, S_{33} , in the MS polymer adhesive at the same load step. A continuous tensile band develops along the bonded land, with peaks at the internal corners. The maximum reaches ≈ 3.75 MPa, exceeding the tensile strength of 3.14 MPa. Interpreting initiation by a normal-stress criterion is therefore more conservative than using von Mises, it flags damage onset at this stage because peel (Mode-I) opening dominates at the corners, whereas the von Mises field, being deviatoric, remains lower. This view provides an upper-bound estimate of where failure would start and highlights the corner regions as the most critical locations for subsequent cohesive debonding.

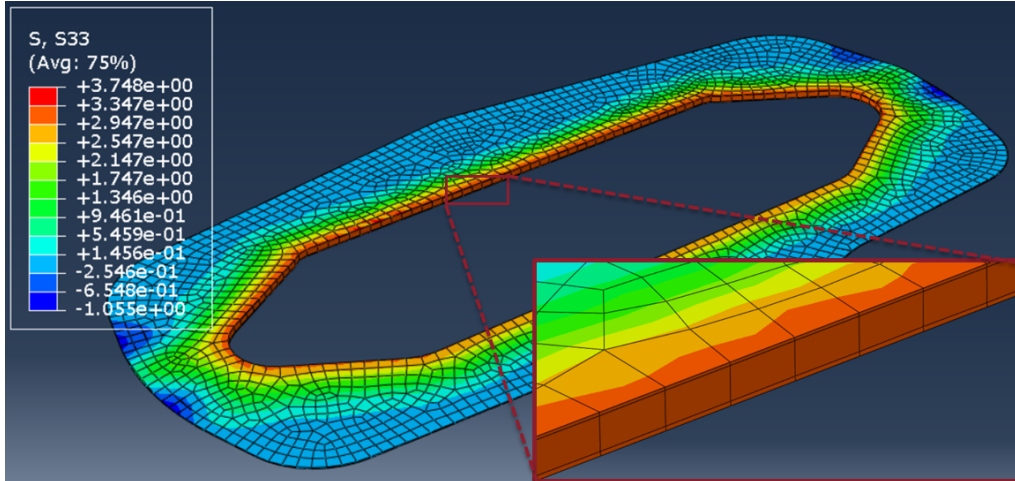


Figure 19: Pre-damage von Mises stress in the bulk MS polymer adhesive under internal pressure.

B.8 Conclusions

This study assessed the performance of die-cast aluminium $AlSi_{10}Mg$ joints produced with two adhesive systems (LS-XU, a film adhesive, and Teroson MS 939, a

MS polymer adhesive) for comparison with also joints manufactured with friction stir welding (FSW), focusing on durability under oil ageing and internal pressure resistance.

The durability tests revealed that LS-XU was highly susceptible to ageing, with shrinkage and interfacial debonding leading to severe loss of strength and brittle adhesive failures. In contrast, Teroson MS 939 retained ductility after ageing, with only moderate reductions in load capacity. Its predominantly cohesive failure mode in anodized specimens demonstrated stronger interfacial adhesion and greater energy dissipation, although at the expense of more complex repair procedures.

The internal pressure tests reinforced these findings. LS-XU joints exhibited abrupt adhesive failure at low loads, while Teroson MS 939 withstood more than twice the load and failed progressively through mixed mode. FSW provided the highest peak load, governed by plastic rupture of the weld seam, but lacked the sealing capacity inherent to adhesives.

Overall, the results demonstrate that adhesive selection and joining method must be matched to service requirements. LS-XU is unsuitable for environments involving mechanical pressurisation or fluid exposure. Teroson MS 939, by contrast, offers both structural contribution and sealing capability, making it appropriate for automotive housings, aerospace fuselages, marine hulls, and chemical-processing enclosures. FSW ensures superior structural strength but should be complemented with polymer adhesives when sealing is critical. Hybrid approaches combining FSW with MS polymers therefore present a promising strategy across industries requiring both load transfer and containment, including renewable energy, shipbuilding, and transportation.

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