



Master Thesis in Mechanical Engineering

Production of edge milling tools using an adhesive joining process

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*"Everything we hear is an opinion, not a fact.
Everything we see is a perspective, not the truth"*
- Marcus Aurelius

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Abstract

Nowadays the use of adhesive joining processes is deeply embedded onto the modern automotive and aeronautical industries as an alternative to the more common mechanical joining options. However, amongst other fields of engineering, such as the milling tool sector, it is still a quite recent and unexplored subject. Thus, in this specific sector an important opportunity exists for the use of adhesive bonding as a substitute for the more common brazing process.

This work focuses on the implementation of this process, divided into three main tasks: the study of an adhesive bonding process between aluminium (AW 7075 T6) and WC/PCD (CTB010), materials used in a common edge milling tool, using an electrically conductive structural adhesive with conductive spheres as the filler; development of a numerical model using cohesive zone models (CZM) suitable to run a parametric simulation able to predict the stresses generated due to centrifugal forces optimising the joint's geometry; and lastly determine the manufacturing procedures for the practical implementation of this process producing and validating tool prototypes.

In practical terms to be suitable for this application, the adhesive joint must meet three main requirements. The first is ensuring that safety standards are respected, the second one is ensuring electrical conductivity, suitable for use with an electrical discharge machining (EDM) sharpening process and finally, ensuring the possibility of using an induction curing process, increasing the flexibility of the production avoiding specific jigs for each tool model produced.

For the first task, using bulk tensile tests, thick adherend shear tests (TAST), double cantilever beam (DCB) tests and end notched fracture (ENF) the adhesive was mechanically characterised. The joining process was studied using small-scale single lap joint (SLJ) specimens manufactured using three configurations: neat state, 5% and 10% volume of spheres, in order to understand in a wider spectrum the effect of the spheres on the mechanical and electrical properties. The assessment of the electrical conductivity of the adhesive layer was done by measuring the specimen's electrical resistance with the 4 probe method and comparing it to a specimen manufactured with the original brazing process. The need for surface treatments was evaluated by measuring the surface energy of both substrates, and then validated by performing the SLJ tensile tests, verifying the type of failure that occurred, and reiterating the process applying the proper solutions.

Using ANSYS's CZM approach based on a contact debonding mechanism a parametric design simulation was performed to optimise the joint geometry using a single bit simplification of the full milling tool, comprised of an aluminium body, the WC/PCD insert and two adhesive joints. This numerical simulation considered 3 geometrical input parameters, the holding notch's height, base angle and the bit's length, and evaluated the stresses generated as the output parameter/criterion. Due

to the large amount of possible combinations, an iterative approach was adopted, focusing on optimising the height and angle first, considering them as primary input parameters and afterwards analysing one other parameter considered as secondary, the length. Also a qualitative assessment of the added cost per bit comparing it to the already commercialised corresponding tool was analysed. In terms of loading conditions a safety testing overspeed rotational velocity predicted by the EN 847-1 standard was used.

In order to validate the real applicability of this joining process, the induction curing process was firstly studied, assessing two possibilities, a safer induction pre-cure followed by a longer oven cure at low temperature to finalise the cure process or a full cure at high temperature using only induction, which was not documented for the adhesive used. To characterise the adhesive polymerisation at different temperatures several differential scanning calorimetry (DSC) tests were performed, one continuous ramp up until degradation and three isothermal tests at different temperatures. The electrical conductivity of this adhesive joint was validated in the real milling tool joint by applying the EDM sharpening process. As for the safety requirements, the test condition used was the one set by the EN 847-1 standard where a rotational speed test is performed at overspeed condition and validated if there is no fracture verified. This test was performed using the highest width and diameter available for the tool model.

The results of these tests allowed to fully determine the performance of the bonded joint, allowing its performance to be compared with that of the brazed configuration. Although important differences in behaviour between the bonded and the brazed joints were identified, the proposed bonded joint was found to be suitable for practical implementation.

Resumo

Atualmente, a utilização de processos de união adesiva está profundamente enraizada nas indústrias automóvel e aeronáutica, sendo vista como uma alternativa às opções de união mecânica mais comuns. Contudo, em outras áreas industriais, tais como o sector das ferramentas de fresagem, esta é ainda vista como uma tecnologia alternativa e relativamente inexplorada. No entanto, neste sector existem diversas oportunidades para o uso de ligações adesivas em substituição dos processos de brasagem habitualmente utilizados.

Este trabalho está dedicado à implementação de um processo de ligação adesiva em ferramenta de fresagem, dividido em três tarefas principais: o estudo do processo de união por meio de adesivos entre alumínio (AW 7075 T6) e WC/PCD (CTB010), utilizando um adesivo estrutural condutor elétrico e esferas conductoras; o desenvolvimento de um modelo numérico com elementos coesivos para simular, de forma paramétrica, as tensões geradas devido a forças centrífugas; e, por último, determinar os procedimentos de manufatura adequados para a implementação prática em ferramentas reais de forma a produzir e validar protótipos.

Em termos práticos, uma junta adesiva para este tipo de aplicação deve satisfazer três requisitos principais. O primeiro é assegurar que as normas de segurança e resistência vigentes para estas ferramentas são respeitadas, o segundo é assegurar a condutividade elétrica, adequada para utilização com um processo de afiação por eletroerosão (EDM) e, finalmente, assegurar a possibilidade de utilizar um processo de cura por indução, aumentando a flexibilidade da produção, evitando gabaritos específicos para cada modelo de ferramenta produzida.

Para a primeira tarefa, utilizando ensaios de tracção, de corte (TAST), e fratura em modo I (DCB) e fratura em modo II (ENF), o adesivo foi caracterizado mecanicamente. O processo de união foi estudado utilizando provetes de sobreposição simples (SLJ) de pequena escala, fabricados utilizando três configurações de adesivo: estado puro, 5% e 10% de volume de esferas, de modo a compreender num espectro mais amplo o efeito das esferas sobre as propriedades mecânicas e elétricas do adesivo. A avaliação da condutividade elétrica da camada adesiva foi feita medindo a resistência elétrica da amostra, comparando-a com uma amostra fabricada com o processo de brasagem original. A necessidade de aplicar tratamentos de superfície foi também avaliada através da medição da energia superficial de ambos os substratos, e depois validada através da realização dos testes de tração em junta, identificando o modo de rotura.

Utilizando uma abordagem de modelação por elementos coesivos no software ANSYS, baseada num mecanismo de contacto, foi criada uma simulação paramétrica adequada para otimizar a geometria da junta, utilizando uma simplificação da ferramenta de fresagem completa, composta por um corpo de alumínio, uma única pastilha de WC/PCD e duas camadas de adesivo.

Esta simulação numérica considerou 3 parâmetros geométricos de entrada, a altura do entalhe, o ângulo da base, e o comprimento da pastilha, e avaliou as tensões geradas como o parâmetro/critério de saída. Devido à grande quantidade de combinações possíveis, foi adotada uma abordagem iterativa, concentrando-se primeiro na otimização da altura e do ângulo, considerando-os como parâmetros de entrada primários e depois analisando um outro parâmetro considerado como secundário, o comprimento. Um estudo qualitativo do custo acrescentado por pastilha comparando-o com a ferramenta correspondente já comercializada foi efetuado. Como carregamento principal, foi considerada a velocidade de rotação prevista pela norma EN 847-1.

A fim de validar a aplicabilidade real deste processo de união, estudou-se primeiro o processo de cura por indução, avaliando duas possibilidades, uma pré-cura por indução seguida de uma cura em forno mais longa a baixa temperatura para finalizar o processo de cura, ou uma cura completa a alta temperatura utilizando apenas indução. Para caracterizar a polimerização do adesivo a diferentes temperaturas, foram realizados vários ensaios de calorimetria (DSC), um em rampa contínua até à degradação do adesivo e três ensaios isotérmicos a diferentes temperaturas. A condutividade elétrica desta junta adesiva foi validada na ferramenta de fresagem real, aplicando o processo de afiamento por eletroerosão. Quanto aos requisitos de segurança, a condição de teste utilizada foi a estabelecida pela norma EN 847-1, onde um teste de velocidade de rotação é realizado em condições de excesso de velocidade. O protótipo encontra-se validado se não for verificado qualquer tipo de falha ou rotura durante o teste. Este teste foi realizado utilizando a maior largura e diâmetro disponíveis para o modelo de ferramenta, representando o pior cenário.

Os resultados destes testes permitiram determinar completamente o desempenho da junta colada, permitindo comparar o seu desempenho com o da configuração brasada. Embora tenham sido identificadas importantes diferenças de comportamento entre as juntas coladas e as soldadas, a junta proposta foi considerada como sendo adequada para a implementação prática.

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1 Introduction

1.1 Background and motivation

Nowadays, the use of adhesive joining processes is deeply embedded onto the modern automotive and aeronautic industries as an alternative for the more common mechanical joining options, such as the use of bolts, rivets, welding and brazing, presenting it self as an very interesting and highly competitive joining technology.

The strong proliferation of this process into the engineering world is clearly driven by its unique advantages, such as the uniform stress distributions, which leads to a better resistance to dynamic fatigue, higher stiffness and load transmission capabilities, the ability to bond dissimilar materials, the possibility of automation of the manufacturing process, design flexibility, regular contours, among others, all these when compared to conventional mechanical joining methods [1, 2].

Nevertheless amongst other industrial sectors, adhesive bonding is a quite recent adoption or even a never thought of option. One of these areas is the tooling industry, more concretely the milling tool sector. A sector that conventionally is divided into three main types of tool construction: monoblock, in which the tool is all made of the cutting material; modular, whose cutting teeth are mechanically fastened to the tool's body allowing replaceability; and brazed, where this joining process is used to bind the hard material to a softer body.

This said, from all the types of tool constructions the brazed ones are the main candidates for substitution with bonding, which is mainly motivated by the large thermal loads to which the tools are subjected during manufacturing, as well as the market's tendency to search for lighter tools but not fully trusting the common solutions for low weight tools, such as mechanical clamping. Many of those issues were felt by FREZITE[®] Woodworking Tools (Trofa, Portugal), the partner which motivated this thesis and which proposed starting the study on a simple edge milling tool used for the processing of a soft material, more specifically wood.

1.2 Objectives

This thesis has three main objectives, the first is to fully characterise the adhesive used and the joining process between the aluminium and the tungsten carbide (WC)/polycrystalline diamond (PCD) materials used in a real edge milling tool, ensuring that all the manufacturing and work requirements are met.

The second objective is to implement a parametric design simulation in order to optimise the geometry of the edge milling tool applying the mechanical properties determined previously into a cohesive zone model (CZM), using the Ansys[®] FEA software.

Finally, all the information acquired about these adhesive bonding process and

geometry optimisations were applied into a real milling tool, manufactured using an induction cure process. As a result of this thesis, a fully functional prototype was produced, validated with the proper testing methods predicted by the safety standard for woodworking tools, EN 847.

1.3 Research methodology

The key objectives of this thesis are the following:

- Perform a careful literature review, with the main focus on the state of the art regarding the use of adhesive bonding in the manufacturing of milling tools;
- Carry out experimental tests to determine material properties and joint behaviour, namely bulk tensile tests, thick adherend shear tests (TAST), double cantilever beam (DCB) tests, end notched flexure (ENF) tests and single lap joint (SLJ) tests;
- Develop a numerical model of the edge milling tool using cohesive elements applying a parametric study in order to optimise the tool's geometry;
- Manufacture an induction cured prototype of the edge milling tool according to the EN 847 standard and taking into consideration all the steps taken until now.

1.4 Thesis outline

This thesis is divided into seven main parts. This introductory chapter describes the background and motivation of this work, as well as a brief description of the problem in hand and its objectives.

Chapter 2 starts with a review on the state of the art of milling tools, followed by an analysis of the field of adhesive joints, their classification, failure modes and design methodologies. Next, by combining both previous topics, an overview on the application of adhesives in the milling tool industry is done. Lastly, three approaches commonly used to analyse strength in adhesive bonding are discussed.

Chapter 3 clarifies the experimental procedures used throughout this work to assess the mechanical properties of the adhesive under study and the bonding process between the body and cutting insert materials. This tests cover all the parameters needed to simulate numerically an adhesive joint recurring to a cohesive law, from bulk to fracture properties, as well as studying the specificity of the aluminium to PCD bonding process.

Chapter 4 explains the numerical model developed in this work and the parametric simulation used to optimise the tool geometry.

Chapter 5 presents the steps taken in order to manufacture the induction cured prototypes and the criterion's used for its 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

2.1 Milling tool industry

2.1.1 Tool characterisation

By definition, a milling tool is a rotating cutting tool normally having its main feed direction perpendicular to the rotation axis, for working various surfaces [3]. In terms of the orientation of the many components the cutting edges can be parallel or square to the axis of rotation, and even a combination of both. As for the tool's axis in relation to the positioning of the surface to be cut, the two most common orientations are displayed in Figure 1.

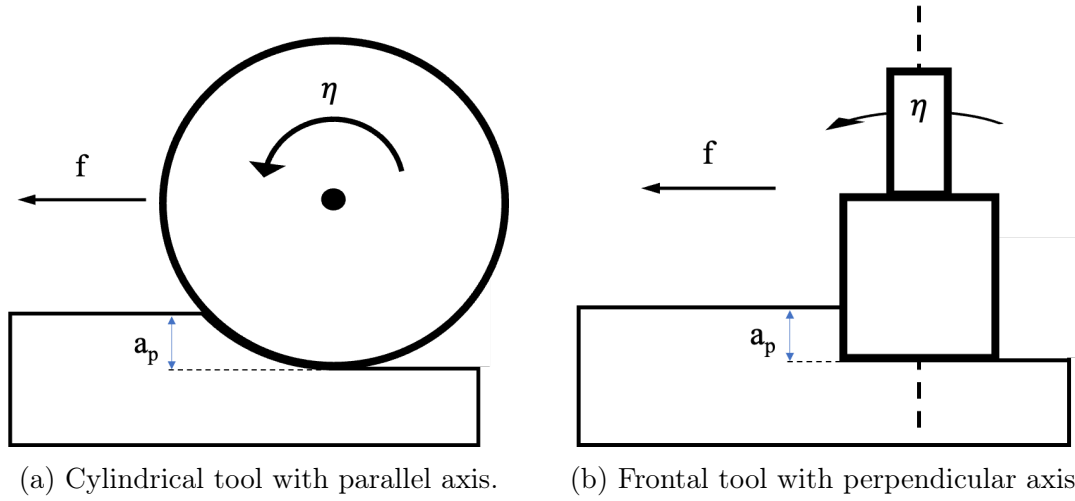


Figure 1: Schematic representation of the two possible tool axis orientations in relation to the surface.

Furthermore, these can be classified by the EN 847 standard in terms of their construction into the following groups [3]:

- **One-piece:** Without bonded or detachable parts, made in one-piece;
- **Composite tool:** Cutting parts (tips) firmly connected to the body, e.g. welding, brazing or adhesive fixing;
- **Complex tool:** One or more cutting parts are exchangeably mounted in the body through detachable fixing elements;
- **Tool set:** one or more individual tools (e.g. milling tool, circular saw blade) clamped together on a tool carrier (e.g. sleeve, arbor) designed to function as one tool.

Having this said, with the exception of the one-piece tool, all tools have two main components: a body, the part of the tool which holds the cutting parts or on which

the cutting parts are formed; and a cutting part, the functional piece or pieces of the tool each comprised of chip producing elements [3], which can also be called bit or insert. The cutting edges, face and flank are therefore elements of the cutting part. In the case of a multi-toothed cutter tool, each tooth has a cutting part [3].

Other than the already detailed specifications, milling tools also incorporate several additional mechanisms to increase its performance, from deflectors to chip breaking systems, among other solutions which improve the cutting capabilities of these tools.

In terms of main dimensions and cutting parameters, some can be highlighted as the most relevant:

- **Cutting diameter** (d): maximum possible diameter of the tool's cutting edge, in mm;
- **Cutting width** (b): maximum possible width of the tool's cutting edge, in mm;
- **Spindle speed** (η): rotational speed supplied to the tool, in rpm;
- **Feed rate** (f): speed at which the material is being feed to the tool, in ms^{-1} ;
- **Depth of cut** (a_p): depth of material to be removed, in mm.

However, many others exist and can be calculated recurring to the previous ones, such as the material removal rate (MRR), cutting velocity (v_c), amongst others.

2.1.2 Hard materials

This type of process requires certain characteristics from the materials used in the tools, these range from as good wear resistance and hardness, to high toughness and thermal conductivity, as well as low friction and expansion coefficients, among others. However there is no perfect material and each one has its strengths and proper applications. During the last century, with the rapid evolution of material technologies, many new hard materials reached the market, mostly with increased hardness but at the cost of lowered toughness. This phenomenon can be seen in Figure 2. Starting with alloyed tool steel, characterised by having more than 0.6% alloying elements (e.g. high alloy 12% Cr steel), and then high speed steel (HSS), having more than 12% total of alloying components (W, Mo, V, Co,...), there is still a good degree of toughness, common among most metals, although limited in the hardness. Then came cemented carbides that consist in fine particles of carbide, such as tantalum (TaC) or tungsten carbide (WC), bonded by a low fusion point metal, being the most common cobalt (Co) - ISO 513. Cermet's followed, which are composite materials combining cemented carbides composed of ceramic (cer) and metal (met) materials, e.g. titanium nitride (TiN), titanium carbonitride (TiCN)

and titanium carbide (TiC). When material deposition techniques penetrated the milling tool market the use of hard coatings, such as the titanium ceramics and aluminium oxide (Al_2O_3), applied by chemical vapor deposition (CVD) or physical vapor deposition (PVD) methods became a powerful way to obtain milling tools with tough cores but a harder surface - ISO 513. More recently, the sole use of ceramic materials also became an option, adopting alumina, silicon nitride (Si_3N_4), amongst others. And finally, sintered cubic boron nitride (CBN) and sintered diamond - polycrystalline (PCD - ISO 513) or monocrystalline (MCD) - reached the market. These are undoubtedly the hardest materials available, although they are also quite brittle.

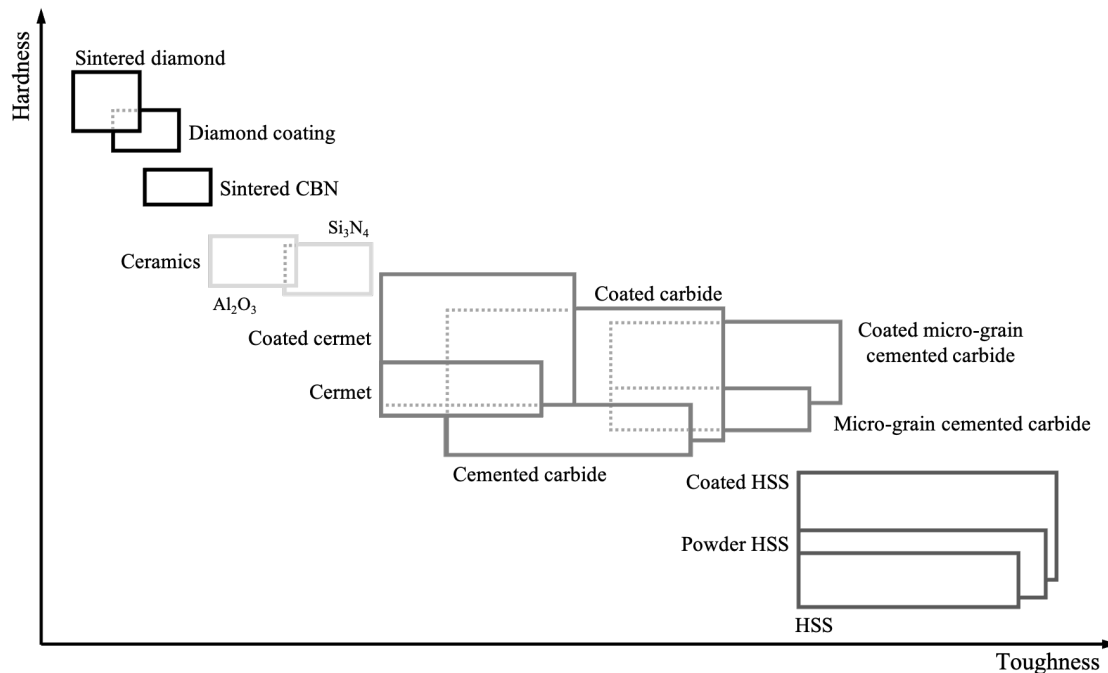


Figure 2: Graphical comparison of the hardness versus toughness of the most common cutting tool materials. Adapted from [4].

While working, the cutting edge of a tool can reach temperatures as high as 800°C due to impacts and friction. In the case of industrial woodworking tools, low work temperature limitations are set due to the possibility of a combustion phenomenon, demanding the lowest friction coefficient possible to lower this heat effect. One of the most common materials to be used in this application is sintered diamond due to its low friction coefficient and since the raw materials to be processed are mostly soft these tools exhibit a high tool life without constant need for re-sharpening, making its use highly economical while delivering good surface quality.

Sintered diamond is the highest hardness material used in the milling tool industry, its manufacturing process can be by a high pressure, high temperature method (HPHT) which is the closest synthetic process to the natural one or by chemical vapor deposition (CVD) where a carrier substrate is needed, commonly tungsten

carbide (WC). Both monocrystalline (optical and electronic) grades or polycrystalline (optical, electronic, thermal, mechanical and electrochemical) grades can be manufactured, however for technical mechanical application such as milling tools the CVD with polycrystalline structure is the way to go [5].

With the progressive development of harder materials, milling processes became more efficient and faster since, in general, higher cutting speeds could be applied. Nevertheless, as said in the beginning, not all materials can be used in all situations and obviously depending on the work piece material, work temperature and severity of the process different hard cutting material can be used.

2.1.3 EN 847 standard

The EN 847 - "Tools for woodworking - Safety requirements" - standard combines all the safety requirements which concern designers, manufacturers, suppliers and importers of tools for cutting wood and materials with similar physical characteristics to wood [3]. This document also includes information that the manufacturer will provide to the users, from definitions and hazard lists, to design and mounting requirements, and even tool identification.

It is divided into three parts:

- Part 1: Milling tools, circular saw blades;
- Part 2: Requirements for the shank of shank mounted milling tools/circular saw blades;
- Part 3: Clamping devices.

The first section is the only with relevant information for this study, providing useful nomenclatures, lists of possible hazards to be prevented and the procedures to validate the safety of the final product of this thesis, amongst other information more relevant for the design of the tool it self and not the change of joining process.

Significant work hazards

This standard only exists since during their production and use, many hazardous situations can happen while using milling tools. However, in order to prevent them it is necessary to identify the possible significant hazard situations, which can be defined under this standard as the ones in Table 1. This allows to establish design safety requirements along with procedures for the production and handling of these tools.

Table 1: Significant hazard situations. Adapted from [3].

Hazard	Condition or cause
Cutting and severing	• Cutting hazard when mounting or dismounting the tool • Kickback or contact with the rotating tool
Ejection of parts	• Disintegration or partial break up to tool body • Incorrect assembly of tool components • Movements of cutting parts fixed by friction • Fly in/out of cutting parts or separate components • Unbalance of the tool while rotating • Kickback when machining • Fixing of the tool on the machine spindle • Modification of position of tool components
Vibrations	• Unbalance of tool

Safety requirements

As stated in the standard, all tools shall be designed and made of such materials in order that they will withstand the forces and loads expected when used and maintained in compliance with the manufacturer's instructions.

This said, both one-piece tools, composite tools and complex tools must be designed taking into account the safety factor displayed in Table 2, which mandates them to safely support the loads in nominal conditions that can be validated with the procedures detailed on the same table. And since in the case of woodworking milling tools the centrifugal stresses are the most severe ones, all of the experimental validation procedures are based on rotational tests under overspeed conditions.

Table 2: Safety validation procedures based on tool type. Adapted from [3].

Tool type	Validation procedure	Safety factor
One-piece and composite tools	Calculation of the stresses or centrifugal test against fracture	Safety factor of 4: $\eta_p = 2 \cdot \eta_{max}$
Complex tools	Test procedure described on EN847-1, 5.1.3.4	Safety factor of 2.25: $\eta_p = 1.5 \cdot \eta_{max}$

2.2 Survey of adhesive joints

An adhesive consists of a material that can be used to join surfaces together while resisting their separation under load. Prior to the joining process, the materials used

are called substrates, and afterwards are generally referred to as adherends. The interphase is defined as the physical region between the adhesive and the adherend with different chemical/mechanical properties from the respective materials, while the interface is the geometrical plane of contact between the surface and the two materials [1]. All attraction forces between substances are a consequence of intermolecular interactions existing between them, and can be designated as a adhesion phenomenon [1]. On the contrary, cohesion is defined by the intermolecular forces inside the substance itself, not allowing it to break apart under load.

Adhesives have been used for centuries, however, up until the last century, most were obtained from natural products, such as skins, fish, milk and bones [1]. Primitive hunters included beeswax in the feathers used as arrow stabilisers - fletching - to improve aim, which can be considered as an early example of adhesive materials in use [6]. Over the last century, adhesives based on synthetic polymers, such as epoxy resins, have been developed and studied as viable alternatives to typical connection methods such as bolting, riveting, welding and brazing.

From all the technological developments achieved in adhesive bonding, structural adhesives became the most interesting for mechanical engineering applications ensuring the strength and stiffness of the structures they join, resisting significantly higher loads than the most common non-structural adhesives or sealants [1, 7, 8].

Their use presents some significant advantages when compared to conventional joining processes [1, 2]:

- Uniform stress distributions, resulting in higher stiffness and load transmission capabilities, that lead to cost and weight reductions - Figure 3;
- The ability to bond thin sheets of material;
- Allowing efficient plate bonding;
- Capability to easily join dissimilar materials;
- Easily automatable process;
- Flexibility in joint design;
- Allows smooth surface finishes, due to the lack of necessary discontinuities such as holes.

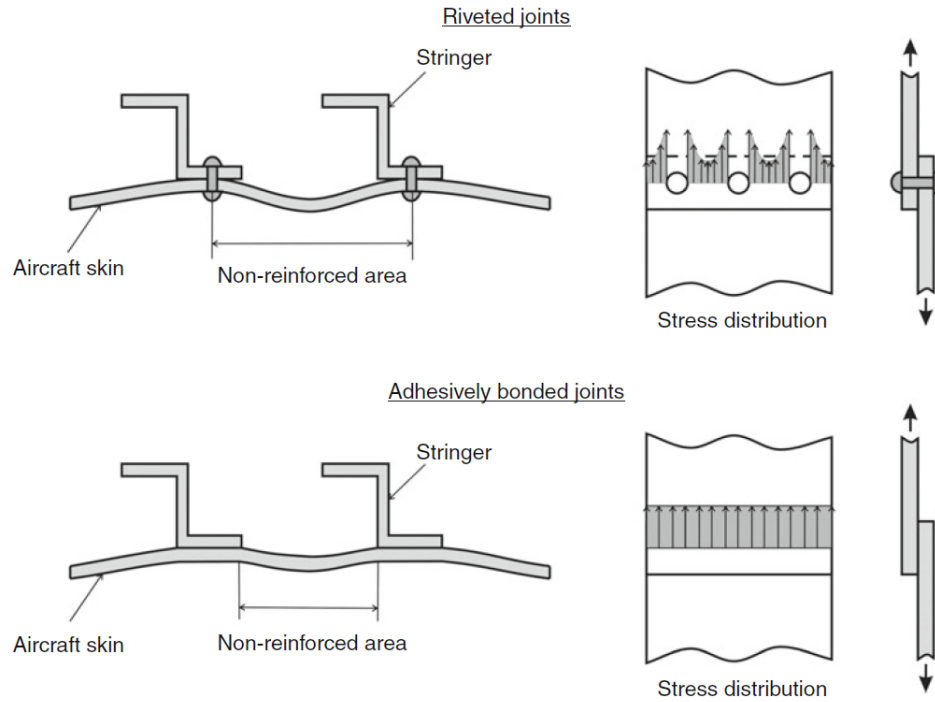


Figure 3: Stiffness improvements (left) and stress distribution (right) of adhesively bonded joints when compared to riveted joints [1].

However, as expected, adhesive bonding also exhibits some important disadvantages, for example [1, 2]:

- The need for careful surface preparation;
- Usually requires the use of templates to maintain every component in the wanted position, if the cure process is not instantaneous;
- Some adhesives need specific cure conditions such as temperature, which some times represents a production/economical disadvantage;
- Limited resistance to extreme temperature and humidity conditions, due to their polymeric nature;
- Poor performance under peeling and cleavage stresses, since these lead to stress concentrations that diminish joint strengths;
- Difficulties in performing quality control.

2.2.1 Adhesive classification

Adhesives can be classified according to different parameters: polymer base, functionality in the polymer "backbone", physical form, functional type, chemical family and method of application [1].

The polymer base can be either natural or synthetic. Vegetable or animal based adhesives as well as natural gums are included into natural based adhesives, e.g. natural rubber, bee wax and casein-based and protein-based adhesives. As for synthetic base adhesives these include all those that are not characterised as natural, for example, acrylics, epoxies, silicones and polyesters [1,9].

The functionality of the polymer “backbone” can be thermosetting, thermoplastic, elastomeric and hybrid. Thermoset adhesives are polymers whose cure process is irreversible due to chemical reactions at room or high temperature that make it permanent. They can be supplied as one-part, with dormant reactive agents, or multiple-part systems. The one-part adhesives usually need high cure temperatures and since their shelf life is reduced it is common to store them at low temperatures. Multiple-part systems often cure at room temperature and have a longer shelf life. Thermoplastic adhesives are usually cured from a molten state and can be remelted several times without significant change in their properties. As for elastomers, they are typically capable of high elongation, good toughness and peel strength. Hybrid adhesives result from a combination of the previous [1,9].

Physical form is divided into liquid, paste, film or powder, and generally can be a sign of how it must be applied. Liquid adhesives are applied using rolls, sprays or brushes and have good wettability, filling any existent gap with ease. Paste adhesives can be comfortably applied on vertical surfaces, due to their high viscosity. Film adhesives are perfect to restrict bondline thickness as constant and are easy to handle. Powder adhesives typically have to be heated or dissolved into a solvent to be transformed into a liquid form, prior to application [1,9].

Functionally speaking adhesives can be defined as structural or non-structural. But can also be referred to as hot-melt, conductive, water-base, pressure sensitive, ultraviolet cured, among others categorizations [1].

In terms of chemical family they can be characterised as epoxies, acrylics, polyurethanes, amongst others. Epoxies are thermoset structural adhesives being considered the most versatile ones since they in general are strong and brittle, but can be manufactured to be more flexible and tough without loss of tensile strength. Acrylics provide fast cure and high strength, however they are more expensive than epoxies. And polyurethanes are tough and flexible even at low temperature, but heat and moisture sensitive [1].

In terms of application method, they can be applied by coating, spraying or brushing, depending on viscosity [1,9].

2.2.2 Failure modes and joint design

Adhesive joint can suffer from several failure modes, however, when using metal or ceramic substrates only three are possible: cohesive failure of the adhesive, adhesive (interfacial) failure and cohesive failure in the adherend [1] - Figure 4.

Cohesive failure is defined as the tear of the the materials' internal connection, separating it self into two parts. When cohesive failure of the adhesive occurs both adherends remain covered with an adhesive layer - Figure 4. Some of the common causes of this type of failure are thermal stresses, inadequate overlap length, among others.

Adhesive failure occurs when the joint fails at the interface between the adherend and the adhesive. This can result from poor surface preparation involving contaminants, an improper degreasing process or the lack of required surface treatments.

Finally, in certain cases, when the adhesive joint is stronger than the substrates, a cohesive failure of the adherends is possible if the loading conditions reach the materials' strength limit, failing before the adhesive bond. All of the previously described failure modes are represented in Figure 4.

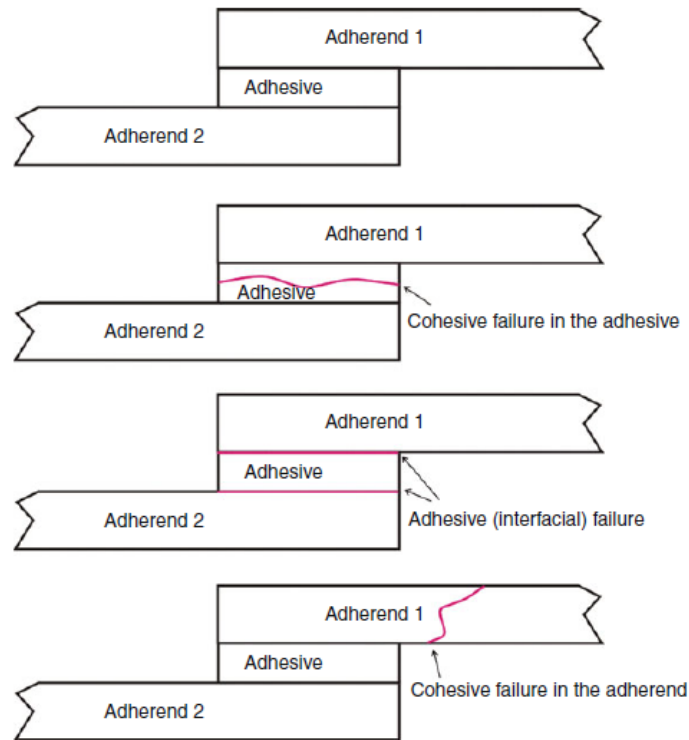


Figure 4: Schematic representation of cohesive and adhesive failure modes [1].

As all other materials, adhesives can be exposed to several mechanical loading conditions. Being the most common: normal, shear, peel and cleavage stresses, represented in Figures 5a, 5b, 5c and 5d, respectively.

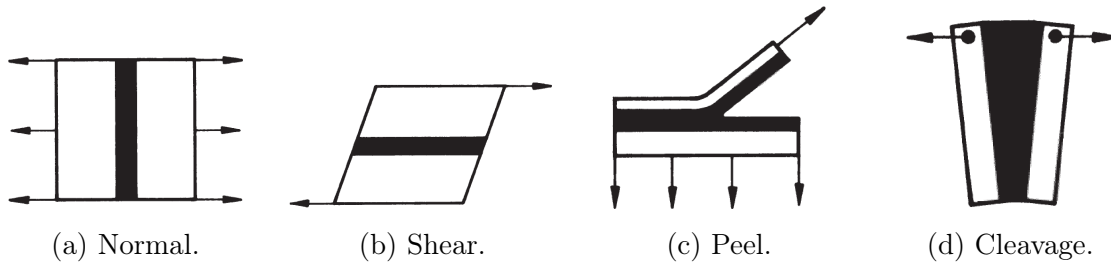


Figure 5: Types of stresses acting by adhesive joints. Adapted from [10].

The type of stress felt by the adhesive joint depends on the way the load is applied, the substrate and adhesive properties as well as the geometry of the joints themselves. This said some typical joint configurations can be highlighted such as the single-lap joints - the most commonly tested one due to its simplicity -, along with double-lap joints, scarf joints and stepped-lap joints [11], all represented in Figure 6.

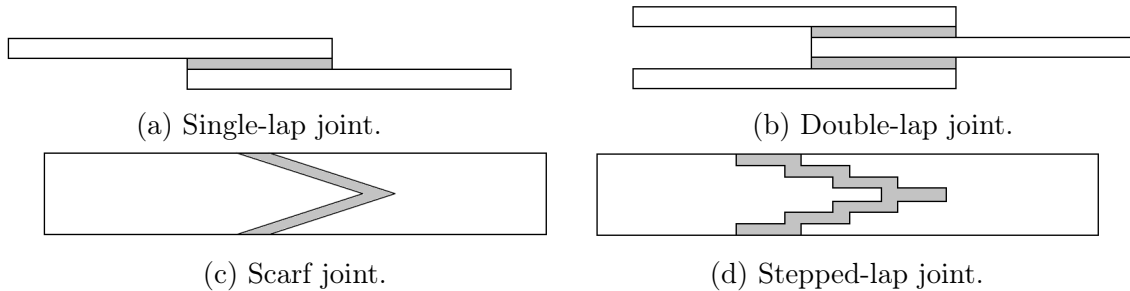


Figure 6: Most common joint configurations. Adapted from [11].

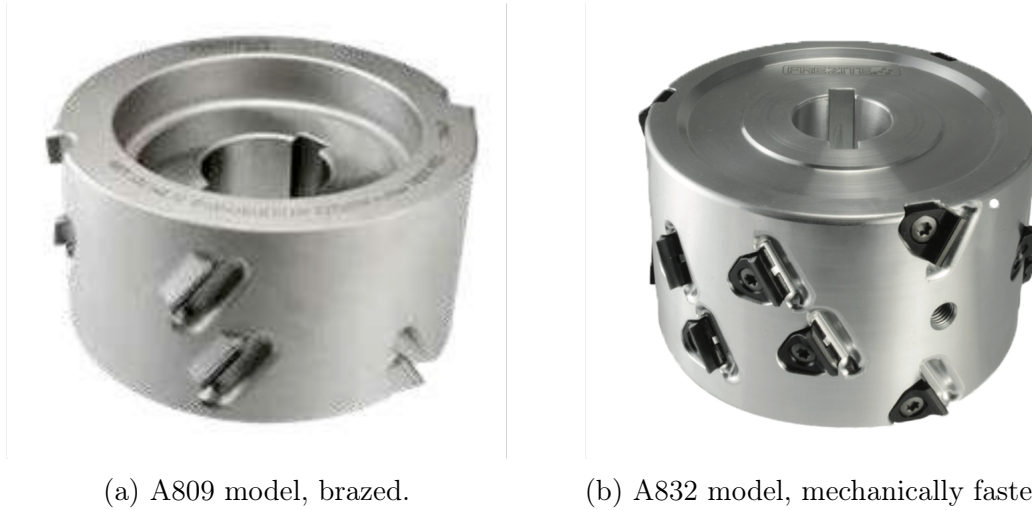
2.3 Adhesives in the milling tool industry

Nowadays the use of adhesive joining processes is deeply embedded onto the modern automotive and aeronautical industries as an alternative to the more common mechanical joining options. Even though studies have been carried out since the 1980's on the advantages and problems associated to the use of adhesive bonding as a tool joining process substitute, the main focus was on either on their applicability to lathe tools or in purely academic research activities. However, not many studies have been carried out specifically considering the milling tool sector, which represents a quite recent and unexplored subject, presenting itself as an interesting opportunity to use adhesive bonding as a substitute for more common joining processes, using some of the advantages seen in the lathe tools studies and applying them to the milling tool industry. Since one-piece tools do not need a larger scale joining processes, obviously both braze-joined and mechanically fastened tools appear as the main contestants for this change of process, and this is seen in previous work on this area.

Being this section about adhesive bonding in the milling tool industry it is important to first describe how the current dominant processes take place and its main characteristics and disadvantages in the industrial environment. As said previously, in terms of hard cutting materials, ceramics, carbides and polycrystalline diamonds are used, due to very good mechanical properties at high temperatures and high resistance to wear and corrosion. However, they are brittle and very difficult to machine. This fact makes brazing a very compelling joining method to implement as the joining process in milling tools. Induction brazing is characterised as a thermal joining process in which two or more metal/ceramic parts are joined together by a molten filler metal with a lower melting point than the adjoining materials, generally higher than 450°C, that is heated by an induction process. Braze-joined components have relatively high yield strengths (>100 MPa) and allow for applications at high temperatures. Since one of the most common materials used as a filler is pure silver the temperature needed to melt it is precisely 961.78°C, demanding that the material used in the body must withstand those temperatures without melting and being able to reach them by induction heating. Steel is a obvious choice due to its ferromagnetic properties, which increase the effectiveness of the induction heating phenomenon, and its low thermal conductivity, that reduces the heat diffusion effect out of the localised heating zone, enabling the filler to achieve its melting point in just a few seconds. However, in general this process also presents certain disadvantages such as large geometrical distortions, micro fissures created by the high manufacturing temperatures, implying high reject rates in production, a reduction of the tools wear resistance, and thermal buckling in tools with high slenderness ratio, making it a imperfect manufacturing process. At FREZITE the studied edge milling tool model corresponding to this joining process is the A809 model - Figure 7a).

However, even tough the brazing process is accepted as a efficient and safe method for steel bodies, the necessity of using steel consequently implies a heavy tool, which does not follow the demand of the market, looking for lighter tools that need less power to operate at the same velocity and create less stresses in the milling machine. This fact created the necessity for another joining method that allowed the use of lighter carrier bodies with low weight alloys as the raw materials - the mechanically fasted tool sector was created as that solution. Using, for example, aluminium alloys in the body and creating small carriers for the PCD cutting parts that can be mechanically fastened to the tool's body it is possible to create the so wanted low weight tool. Nevertheless there are some disadvantages to this process that due to its nature increases the tool's design complexity, as well as not always maintaining a contact stiffness high enough to prevent vibrations, shortening the life of the cutting inserts and often producing pieces with lower quality surface finish. At FREZITE the studied edge milling tool model corresponding to this joining

process is the A832 model also called Pluma due to its clear low weight selling point - Figure 7b).



(a) A809 model, brazed.

(b) A832 model, mechanically fastened.

Figure 7: Examples of woodworking milling tool solutions with different constructions, adapted from FREZITE® Catalogues.

The issues described above have opened the door for an adhesively bonded solution. Such approach has the potential to represent the best of both worlds, ensuring the low weight of the mechanically fastened tool and the theoretical precision of the brazed one.

Even though the specificity of this case study involves the substitution of brazing with adhesive bonding, evolving from a heavier steel body to a lighter one using an aluminium alloy, there are many additional situations where this joining process swap has the potential to be game changer, especially in tools that have inserts with large dimensions and tools that are highly susceptible to thermal buckling.

From the academic point of view, as previously stated, several studies have been done on similar applications in which the same concerns might apply. In Russia, around the 1980s, preliminary studies on the implementation of adhesives as a replacement of brazed tools were reported, as mentioned in [12], however, practical experimentation under particular operating conditions had not been done yet. This was introduced by Darwish and Davies at [12], where the practical study of adhesive bonding for metal cutting tools started. Up until then it was known that the brazing process had a reject percentage as high as 10 to 20% during production of cemented carbide tools due to thermal micro cracking in the inserts [13–15]. This said, the use of adhesive bonding introduced it self as a solution to improve economically the production cycle, as well as reducing the need for skilled labour and improved damping capabilities [12]. Darwish and Davies also concluded that heat cured toughened epoxy resins should have high success for tool manufacturing due to increased thermal resistance, and that adhesive bonding in the production of tools implicated reduced cutting forces, lower tool wear and, also in accordance with

future studies, better surface quality [12, 16–18], all considered as a consequence of reduced vibration related to the damping effect provided by adhesives.

Nevertheless the thermal insulation created by the adhesive layer was reported as an issue both to the adhesive as well as for the insert [12]. Compared to braze-joined or mechanically clamped tool the cutting edge temperatures were superior and the thermal distribution along the tool presented a discontinuity in the results due to the referred effect [19]. As a solution, the introduction of conductive metallic powders into the adhesive, such as aluminium, copper, among others, was reported to improve both electrical [20] and thermal [19, 21, 22] conductivity's, and often even strengthening the adhesives up until a certain critical weight percentage. Yet, in comparison the use of a cooling fluid revealed a much more efficient effect in comparison with the powder fillers, enhancing the recommendation of using always, when possible, a coolant. This concern is obvious when processing thermal sensitive materials, such as Duraluminium (Al-Cu), still the increased cutting edge temperature detailed previously was found to not have influence in the final performance of the workpiece [23]. However, the statement that one of the main concerns with this process application is the thermal insulation created by the adhesive layer still stands and measures should be taken into account to prevent them since most adhesives have their properties dramatically reduced at high temperatures.

Going forward, it is important to take note that most of the previous studies only considered cemented carbide tools used in lathe machines, that have a static positioning with a near constant contact between cutting edge and the workpiece. However, for milling tools with multiple cutting edges, even though the applications are similar, the interactions between all the parts are slightly different. For example, it is possible that in this case cyclic fatigue behaviour impact considerations resulting in might have an unforeseen relevance that should be studied. Also the rotational velocity of the tool and the use of harder materials, such as PCD, should reduce the cutting edge temperatures due to convection based heat dissipation and lower friction forces.

That said, after analysing the specificity's of this application, the adhesives used in the milling tool industry should fulfil, in most cases, the following requirements:

1. **Stiffness** to maintain the cutting edge positioning while sustaining high impact forces;
2. **Damping** to reduce the magnitude of vibrations, improving surface quality;
3. **Toughness** to withstand constant cyclic impact during work;
4. **Compatibility with common manufacturing processes** used in milling tool production such as heat based curing processes (induction, oven-curing, etc.), and EDM or laser based sharpening processes;

5. Being a **one-part liquid or paste adhesive** to increase productivity using a fast full-cure or pre-cure process, to ensure proper wetting and positioning of the cutting parts, and flexibility due to a large pot life;
6. **High glass transition temperature** to maintain resistance for long stages at high working temperatures - more common in metal milling tools;
7. **Chemical resistance** to the specific fluids used during the manufacturing and, if necessary, cooling/lubrication agents used while in work conditions.

Taking these considerations into account, the most likely structural adhesive to be used is an heat cured epoxy. Such adhesives combine high strength, resistance to higher temperatures and all around versatility, being able to fulfil all the requirements needed since it is possible to manufacture them with certain properties based on specific necessities, from toughness to electrical conductivity, among others.

Since the applicability of this adhesive bonding process is quite recent, not many studies have been carried out to assess the success of its application. Nevertheless, besides the advantages that it might bring, some concerns arise, such as:

1. **Thermal insulation** that decreases heat dissipation, increasing the work temperatures that influences the insert's wear resistance as well as the adhesive mechanical properties;
2. **Bad adhesion** to the substrates;
3. **Lower joint resistance** since adhesives have lower strengths than the common brazing materials;

All these considerations, positive and negative, make the implementation of adhesives in this sector a very interesting engineering challenge in terms of both design and safety, since in the milling tool industry it is crucial to ensure worker safety. Even though most tools are heavily protected to prevent accidents, the high rotational speeds can turn a loose cutting bit into a dangerous projectile. Due to the relatively limited experience in using adhesives in the manufacturing of milling tools, it is important to study their behaviour under normal manufacturing and work conditions, starting with tools for softer materials, like wood where lower strengths are required, and both temperature and work fluid resistance have less/no relevance. Only after this case is mastered it will be possible to transition to tool suitable for working stronger materials like aluminium, steel, and other metals which require larger working forces and temperature.

2.4 Strength prediction approaches

As is the case for all other joining processes, adhesive joints must be carefully designed taking into account the loads that the joint will need to withstand. However, if only the mechanical loads are taken into account the calculations will be certainly incorrect, since many other variables are at play, from immeasurable defects, to crack formation and environmental conditions. To this extent, several approaches have been developed over the years to allow the design of bonded structures taking these factors into account, instead of simply applying empirical safety factors. For predicting the failure of adhesive joints three main approaches can be discussed: continuum mechanics, fracture mechanics and damage mechanics.

2.4.1 Continuum mechanics

Continuum mechanics considers both the adhesive and the adherends as continuous, as well as a perfect bond between them, not taking into account the properties of the interface created [24]. Since the mediums are assumed as perfect and continuous, stresses and deformations are the parameters to be studied, considering their maximum values as the failure condition.

This method provides various fracture criteria, from maximum stress to maximum strain, however, they fail to predict correctly the failure of the adhesive joint due to the existence of singularities at the tip like geometries present in the joint, as shown in Figure 8. When using finite element analysis, these highly mesh sensitive zones do not allow convergence since their stress values always increase with mesh refinement. And, even though different authors presented approaches to solve this problem, they are only applicable to continuous structures, not allowing the description of defects or different materials making them useless for adhesive joint simulations [24].

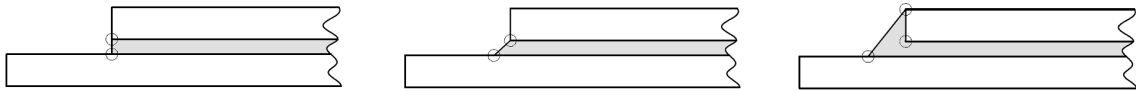


Figure 8: Singularities present at the edges of the overlap. Adapted from [24].

2.4.2 Fracture mechanics

Contrarily to the approach of continuum mechanics, fracture mechanics assumes discontinuities, enabling the existence of cracks, defects or other damage variables caused during manufacturing or use [24]. As a result, this model analyses quantitatively the behaviour of structures containing cracks prior and during propagation, assessing for each situation if the crack size is higher than the critical failure size. Several criteria can be defined to describe fracture mechanics, but the most common are based on the stress intensity factor concept and energetic considerations.

In regards to material discontinuities, generally a stress concentration factor - K_t - is used to describe the stress distribution, however, for sharp cracks such as the one represented in Figure 9 would not be able to distinguish between similar geometries since at the crack tip the stresses would always tend to infinite.

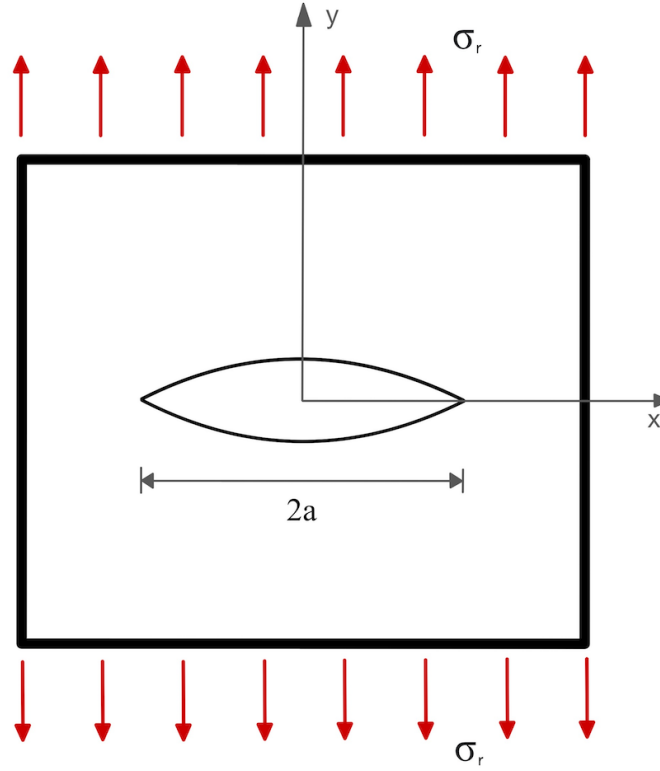


Figure 9: Schematic representation of a sharp crack.

Hence the appearance of a stress intensity factor, K , to represent into a scale parameter the stress distribution near the crack tip, more commonly represented as:

$$K = Y\sigma_r\sqrt{\pi a} \quad (1)$$

being Y a non dimensional factor, that depends on the geometry and loading distribution, σ_r the remote stress applied perpendicularly to the crack length, a . Crack propagation will occur when the stress intensity factor, K , is equal to a critical value - the material fracture toughness K_c .

This method considers three failure modes: mode I, for normal loading; and mode II or mode III, for different types of shear loading, as pictured in Figure 10. However, a combination of these fracture modes is the most common representation of what happens at the crack tip for real loading conditions.

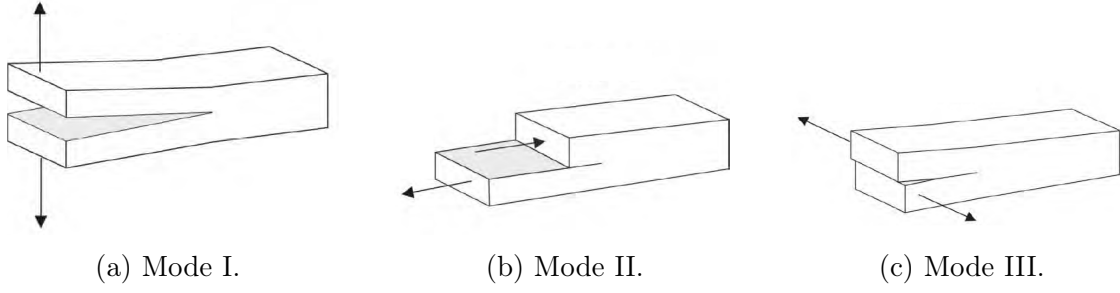


Figure 10: Fracture modes for an adhesive joint [24].

This said, each fracture mode has its own stress intensity factor, K_I , K_{II} and K_{III} for mode I, II and III respectively.

On the other hand, the energy based criterion considers crack propagation when the available energy, G - energy release rate - is equal to a critical value where the crack propagates, G_c - critical energy release rate - [24].

And, since all the criteria mentioned describe the same phenomenon, they can be associated by a physical relation, which for plane stress is [25]:

$$G = \frac{K^2}{E} \quad (2)$$

being E the Young's modulus. And, for plane strain is [25]:

$$G = \frac{K^2}{E} (1 - \nu^2) \quad (3)$$

where ν is the Poisson's ratio.

When comparing both methods, the critical energy release rate criterion is much more reliable, due to the difficulty of determining K in certain contexts, e.g. when the crack grows near the interface [24].

When using adhesives considering their fracture behaviour, bulk materials tends to propagate cracks in mode I, however, in adhesive joints, due to the restrictions created by the adherends, cracks are forced to propagate in mixed mode I+II. This mode mixicity can be represented by a mode ratio, given by [24]:

$$\varphi = \tan^{-1} \sqrt{\frac{G_{II}}{G_I}} \quad (4)$$

For mixed mode cracks to propagate, it is necessary to combine the effects of both modes using suitable criteria, such as [24]:

$$\left(\frac{G_I}{G_{Ic}} \right)^\alpha + \left(\frac{G_{II}}{G_{IIc}} \right)^\beta = 1 \quad (5)$$

being G_{Ic} the critical energy release rate in mode I, G_{IIc} the critical energy release rate in mode II, and α and β constants.

To represent the previous behaviour one might use fracture envelopes where

knowing both mode I and II critical energy release rate, it is possible to approximate the fracture behaviour using the linear or quadratic criterion, which can be seen in Figure 11.

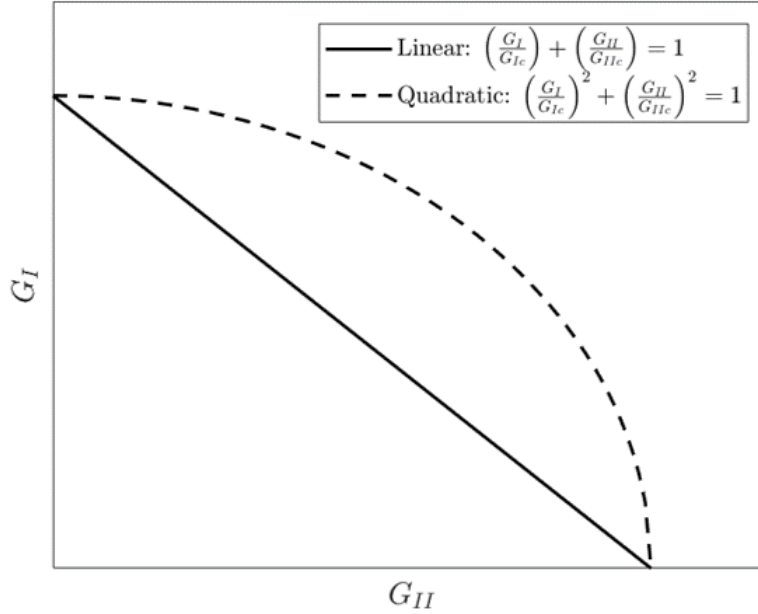


Figure 11: Schematic representation of fracture envelope approximations, using linear and quadratic criterion.

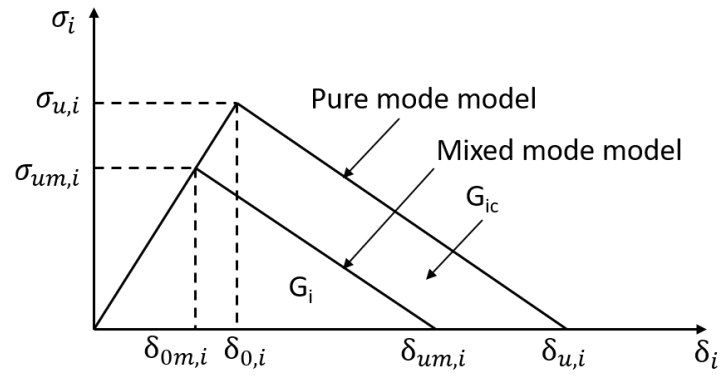
As an inconvenience, fracture mechanics is not suitable for describing damage initiation, only damage propagation [24].

2.4.3 Damage mechanics

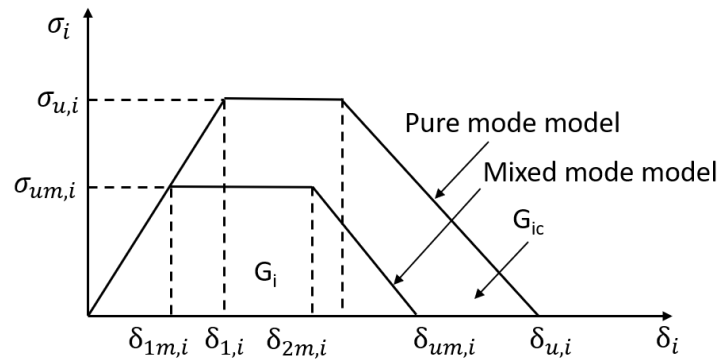
Since both of the previously mentioned approaches exhibit flaws when modelling the common behaviour of adhesives, a new method was developed in order to study damage initiation and propagation called damage mechanics. The most commonly used method to predict damage is a cohesive zone model (CZM), which is generally based on interface elements with no thickness, that establish the bonding properties between two solid surfaces. Each element considers a damage variable that, after a stress criterion is satisfied, is used to simulate material degradation by applying a relaxation process based on a fracture energy criterion.

When compared to continuum and fracture mechanics approaches, this method allows the modelling of non-linear processes while avoiding stress singularities, as well as not needing the existence of pre-cracks nor the need for user interference for its propagation to occur [24].

This damage mechanism is then applied to the behaviour of the adhesives recurring to traction-separation laws, being the two most common ones schematically represented in Figure 12. Triangular laws are used in most cases due to their simplicity, and trapezoidal laws for very ductile adhesives.



(a) Triangular traction-separation law.



(b) Trapezoidal traction-separation law.

Figure 12: Schematic representation of traction separation laws, $i=I,II$.

3 Experimental procedures

3.1 Materials

Two different adhesives, manufactured by a major adhesive producer were previously used by FREZITE in the early stages of this change of joining process. Firstly, a two step UV light and heat cured epoxy based adhesive, and afterwards a solely heat cured aluminium doped epoxy based adhesive, both selected following the recommendation made by manufacturer, being the last one also previously tested by a global hard metal producer for these type of application. Classified as structural adhesives, these amine/epoxy one component adhesives have several differences, being the most notable one the type of cure process. However, both fulfil all the requirements previously described in the introductory section for an adhesive used in the milling industry as a brazing substitute.

Comparing them with other common structural adhesives previously used by the Advanced Joining Process Unit (AJPU) such as the Huntsman Araldite AV138 and Nagase-Chemtex XN1244, whose properties are listed in [26], it is clear that given the requirements for an almost unlimited pot life, high stiffness and toughness, compatibility with both induction curing and the adhesive layer electrical conductivity requirements - in order to continue to allow the use of the electrical discharge machining (EDM) process for the sharpening of the milling tools - this work will only focus on the one that better met them. Thus, the aluminium doped epoxy adhesive is the one chosen for this purpose since it presented several advantages such as good mechanical properties, being an one-part epoxy, compatible with induction curing and improved electrical properties due to the aluminium filler, amongst others.

The general characteristics of this adhesive can be seen in Table 3 and a representation of its cure cycle is presented in Figure 13.

Table 3: General characteristics of the adhesive used.

Adhesive	Supplied as	Fillers	Cure type	Cure cycle
Epoxy resin	One-part	Aluminium	Heat	150 °C/40 min

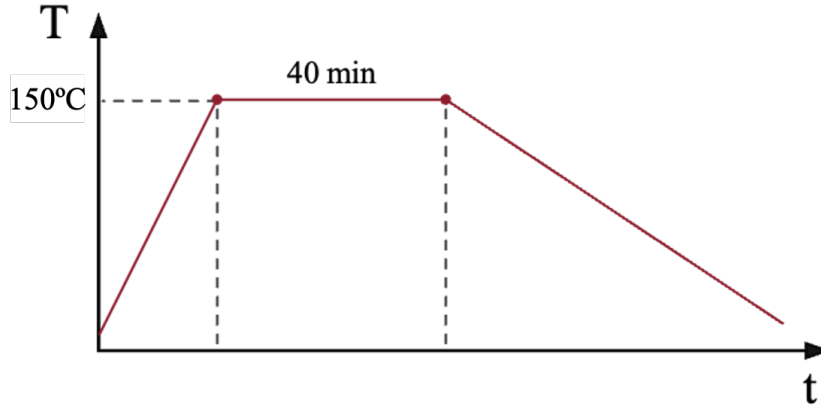


Figure 13: Cure cycle of the adhesive under study.

The most relevant properties provided by the supplier's datasheet for the adhesive chosen can be seen in Table 4.

Table 4: Most relevant properties of the adhesive chosen for the study.

Property	Adhesive
Density/ $\text{g}\cdot\text{cm}^{-3}$	1.42
Viscosity/ $\text{Pa}\cdot\text{s}$	140
Tensile strength/MPa	64
Shear strength/MPa	33
Elongation at break/%	2.8
Young's modulus/MPa	3800
Electrical resistivity/ $\Omega\cdot\text{cm}$	$> 1 \cdot 10^{13}$

In addition to the use of this adhesive, the necessity of an additive will be studied, necessary to control two parameters, the adhesive layer thickness, as well as reducing its electrical resistivity by introducing more conductive elements into the adhesive layer. As for the filler it self, the use of conductive microspheres was the the path taken. The general characteristics of the spheres can be found at Table 5.

Table 5: Most relevant properties of the spheres used.

Property	Spheres
Density/ $\text{g}\cdot\text{cm}^{-3}$	2.52
Diameter/ μm	125-150
Electrical resistivity/ $\Omega \cdot \text{cm}$	$1.59 \cdot 10^{-6}$

For the substrates, three materials were used depending on the type of specimen manufactured. For the characterisation of the adhesive properties all the substrates were machined from DIN 40CrMnMo7 steel, a high strength steel used with the objective of avoid plastic deformation. The general properties of the steel substrates can be seen in Table 6.

Table 6: Mechanical properties of the substrates used for the adhesive characterisation.

Property	DIN 40CrMnMo7
Young's modulus/ MPa	210000
Poisson's ratio	0.3

However, for the study of the real adhesive joint two other materials were used, more specifically a 7000 series aluminium and a tungsten carbide (WC)/polycrystalline diamond (PCD) hybrid hard material. For the aluminium, the substrates were water-jet cut using AW 7075 T6 aluminium plates. The most relevant properties of the aluminium can be seen in Table 7.

Table 7: Most relevant properties of the aluminium used by FREZITE.

Property	AW 7075 T6
Density/ $\text{g}\cdot\text{cm}^{-3}$	2.80
Young's modulus/MPa	71000
Poisson's ratio	0.33
Electrical resistivity/ $\Omega \cdot \text{cm}$	$5.26 \cdot 10^{-6}$

As for the WC/PCD substrate, the specimens were laser cut from disks of CTB010 synthetic diamond manufactured by Element SixTM (Burghaun, Germany).

This material consists of two layers, the first one to which the adhesive will adhere is the tungsten carbide with approximately 1.1 mm thickness, and the second is the polycrystalline diamond layer responsible for maintaining the cutting edge with approximately 0.5 mm thickness. For simplicity reasons, this material will be called only PCD in the remainder of this document, which is also its commercial nomenclature. However it is important to stress that the adhesive will be adhering only to the WC side and not to the polycrystalline diamond itself. The most relevant properties of the PCD material can be seen in Table 8.

Table 8: Most relevant properties of the cutting material used by FREZITE.

Property	CTB010
Density/ $\text{g}\cdot\text{cm}^{-3}$	4.08
Young's modulus/MPa	1000000
Poisson's ratio	0.1
Thickness/mm	1.6
Electrical resistivity (WC)/ $\Omega\cdot\text{cm}$	$\approx 2\cdot 10^{-5}$
Electrical resistivity (PCD)/ $\Omega\cdot\text{cm}$	$\approx 1\cdot 10^{13}$

3.2 Testing methods

All the experimental procedures mentioned in this section have two main purposes: the first is to fully characterise the adhesive, resulting in a cohesive law that will be inputted into the numerical models. This will be obtained by the tests detailed in the two first subsections; and the second is to ensure that the joining process between the materials fulfils all the requirements already set, which will be done with recourse to the test detailed in the third subsection.

The experimental work developed in this thesis followed an optimisation process that intertwined the following steps:

- Fully characterise the adhesive in the neat state;
- Study of the aluminium to PCD bonding process, evaluating the surface treatments needed and the effect of the conductive spheres on the strength and conductivity of the adhesive layer, optimising the sphere percentage to be used;
- Fully characterise the adhesive with the optimised spheres percentage.

In order to characterise the strength of the adhesive, bulk tensile tests and thick adherend shear tests (TAST) were carried out in order to determine the tensile and shear properties, respectively.

As for the fracture characterisation, double cantilever beam (DCB) and end notched flexure (ENF) tests were performed to determine fracture toughness in mode I and mode II, respectively.

With the purpose of validating the bonding process between the aluminium and the PCD, a new small scale specimen geometry had to be created to take into account the important differences between the mechanical proprieties of both materials, due to the fragility of the hard material under flexural loading and the high costs associated to the PCD. To manufacture the specimens, additional components were added to an already existent mould due to the small size of the specimens and new spacers also had to be made. As for the adhesive cure cycle, the same one was used as in previous tests. After the configuration was set, a new friction based fixture system was designed to correctly fixate and test these small specimens enabling the evaluation of the failure mode and maximum load sustained. The electrical conductivity of the adhesive layer was determined by measuring the resistance of the specimen using a 4 probe method to improve the accuracy of the measurement. To analyse the bonding properties of the materials at different stages, from raw to different treated states, a surface energy test was performed by measuring the contact angle of three different liquids considering in each iteration possible solutions for the problems that occur.

All the tests were performed using a universal testing machine, more specifically an INSTRON® 3367 whose load cell is capable of measuring up to 30 kN. And finally, for each specimens type at least three specimens were tested and its data treated.

3.2.1 Tensile and shear strength tests

Bulk specimen tensile test

Bulk specimens are manufactured by machining, from a cured adhesive plate, the specific profile (informally designated as “dogbone”), based on the British standard BS 2782 [27], shown in Figure 14.

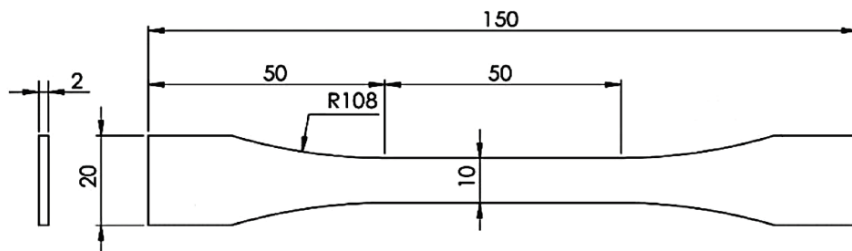


Figure 14: Illustration of bulk specimen’s geometry, dimensions in millimetres.

These type of specimens are tested under tensile loads up until failure, Figure 15. The loads and displacements of the specimen are acquired by the load cell and an extensometer, respectively, and a stress-strain curve is generated. With this curve the determination of the Young's modulus, tensile strength and an evaluation of the ductility of this material are possible.

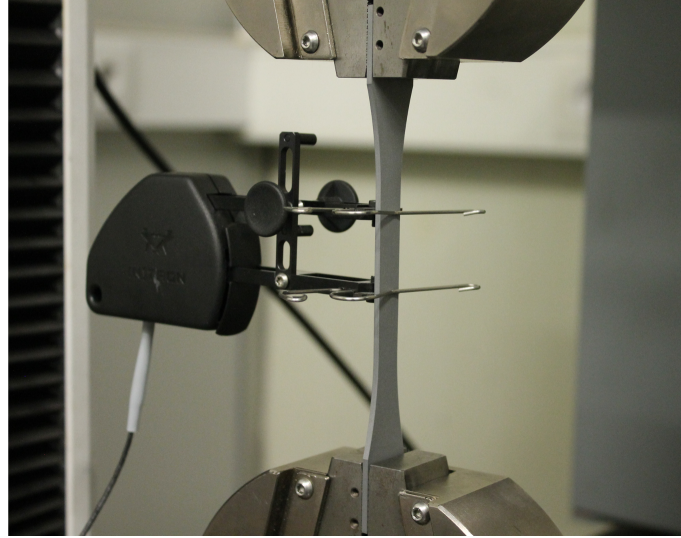
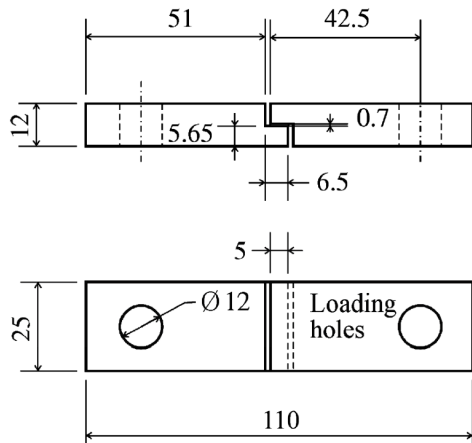


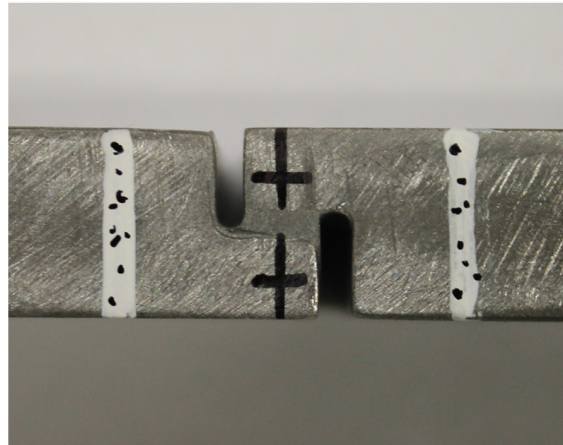
Figure 15: Bulk specimen testing setup.

Thick adherend shear test (TAST)

TAST specimens are produced as an adhesive joint with thick hard steel adherends, whose specification can be seen in Figure 16a.



(a) TAST specimen's geometry.



(b) High contrast auxiliary pattern.

Figure 16: Representation of TAST specimen, dimensions in millimetres.

By applying a tension load in the loading holes, both load and displacement data are recorded in the same way as before. However, in order to obtain a more precise measurement of the displacement, this data was obtained recurring to an

image correlation analysis setup, as presented in Figure 17, where the specimens were painted with a high contrast auxiliary dotted pattern to increase the quality of the measurements - Figure 16b.

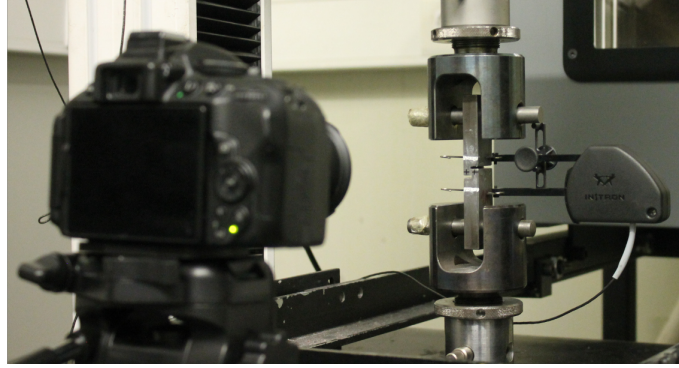


Figure 17: TAST specimen testing setup.

As a result, a stress-strain curve is obtained. All these procedures allow the determination of the shear modulus and strength, as well as an assessment of the ductility of the material.

3.2.2 Mode I and mode II fracture tests

Double cantilever beam (DCB) test

In order to determine the fracture energy in mode I, DCB tests were performed. This specimen incorporates two bonded rectangular beams with equal dimensions. This, as well as a schematic representation of the testing method can be seen in Figure 18.

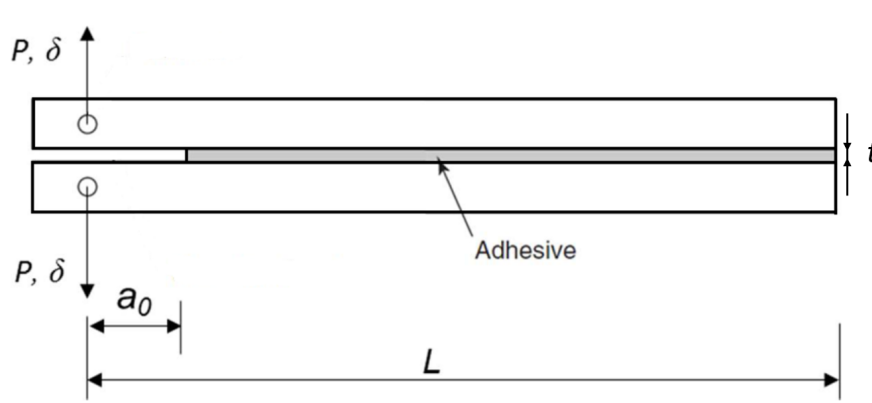


Figure 18: Schematic representation of a DCB test, dimensions in millimetres.

Moreover, is important to refer that in this type of test there are several dimensional parameters that can be changed such as a_0 , the length from the loading pins to the end of the region without adhesive which is considered as the pre-crack length; h , the thickness of each adherend; and t the adhesive thickness.

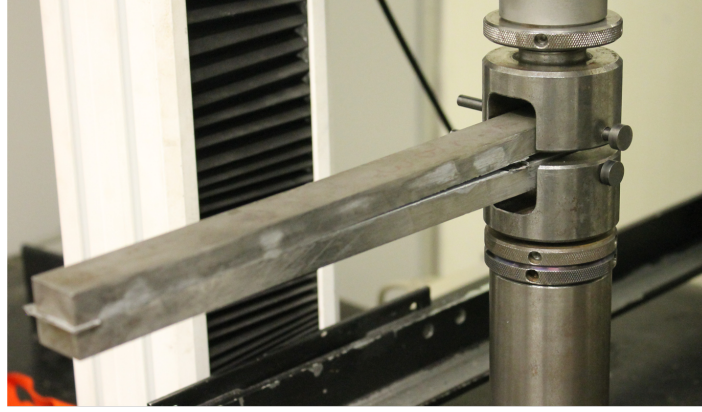


Figure 19: DCB specimen testing setup.

As for the data acquisition, both the load and displacement are recorded and, afterwards the critical energy release rate in mode I, G_{Ic} , is determined recurring to an appropriate data reduction scheme, presented in the Subsection 3.3.

End notched flexure (ENF) test

Geared toward determining the fracture energy in mode II, several ENF tests were performed using the same specimens as previously described for the DCB test. However with a different schematic representation of the ENF test presented in Figure 20.

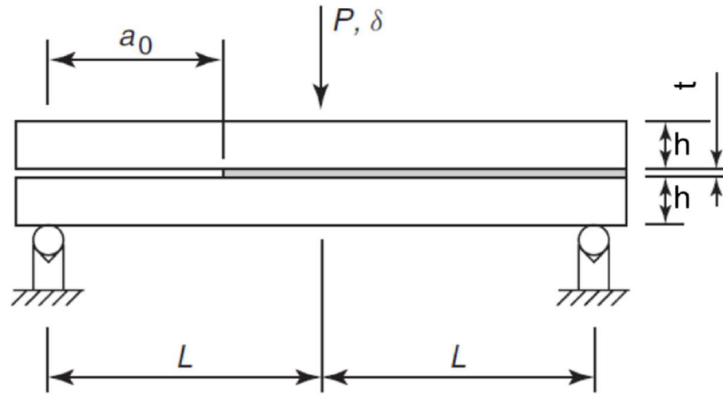


Figure 20: Schematic representation of a ENF test, dimensions in millimetres.

Similarly to the previous test method, there are several key dimensional parameters: a_0 is the initial crack length, P the load applied, δ the displacement recorded at the centre of the ENF specimen, h the height of each substrate, L the horizontal distance from each support to the load application point and t the adhesive thickness. Once again, both the load and displacement just previously described are recorded and, afterwards the critical energy release rate in mode II, G_{IIc} , is determined recurring to an appropriate data reduction scheme, presented in the Subsection 3.3.

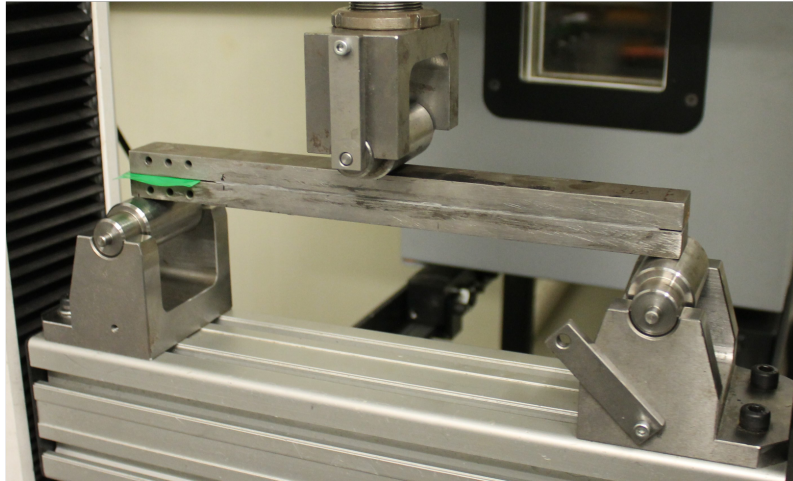


Figure 21: ENF specimen testing setup.

3.2.3 Single lap joint (SLJ) tests

In terms of geometrical configuration only the thicknesses of the adhesive layer - 0.15 mm - and PCD - 1.6 mm - were known in the beginning. Due to the high cost of polycrystalline diamond, the remaining dimensions had to be small to reduce costs. Taking this into account, both the adhesive layer overlap length and width were set as 12.5 mm and 8 mm, respectively. Afterwards, only the aluminium thickness and substrate length had to be set.

The first was obtained with a simple yielding design study making use of the software JointDesigner where an Al-Al SLJ was simulated using both the Volkersen [28] and Adams et al. [7] criterion's to assess at what thickness the aluminium would not yield first than the adhesive. The aluminium properties were set for a high strength alloy with lower yield stress than the real one used to introduce safety into the calculations and the adhesive properties were the ones set in the respective data-sheet. From these analysis resulted the following graphics, Figures 22 and 23, which relate to a aluminium thickness of 3 mm.

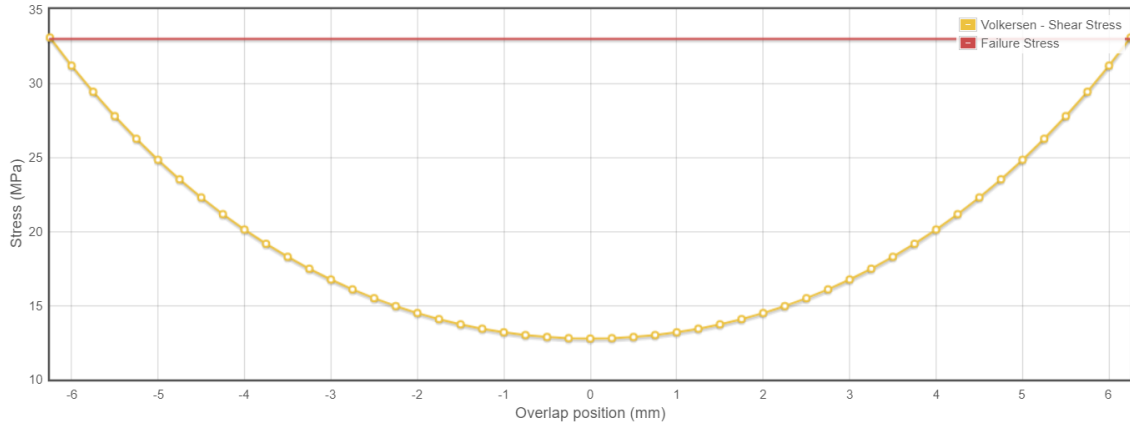


Figure 22: Graphical representation of the Volkersen [28] shear stress distribution (yellow) for the design of the aluminium substrate considering the adhesive failure stress (red), made in JointDesigner.

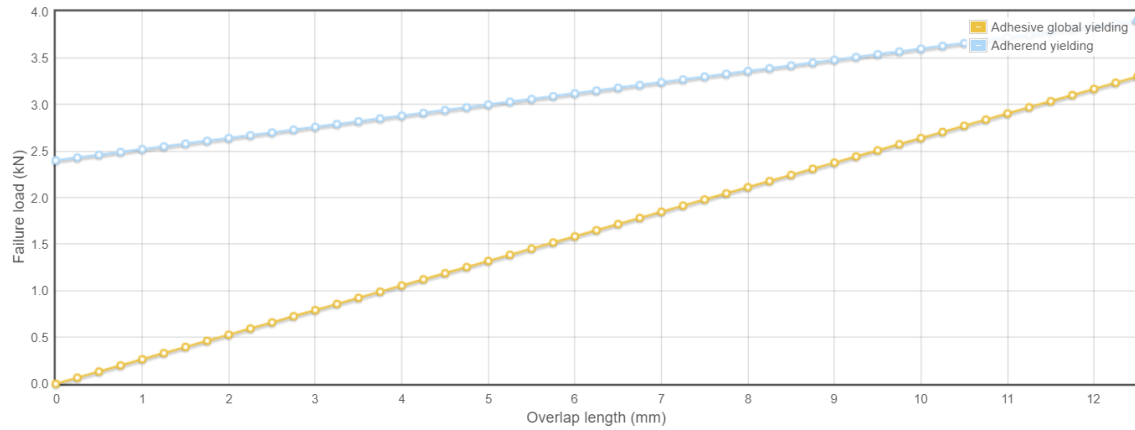


Figure 23: Graphical representation of the Adams et al. [7] yield criterion for the design of the aluminium substrate (blue) considering the point of adhesive yielding (yellow), made in JointDesigner.

The overall length of the substrates cannot be excessively long due to the low flexural fragility of the PDC but must be long enough to enable clamping the specimens to a testing fixture apparatus. Balancing these two conflicting requirements, the final dimension was set to 32.5 mm.

With the rough geometry set, some additional features had to be added, such as a hole for the fixation alignment pins (milled for the aluminium and wire EDM for the PCD) and in the case of the aluminium a milled surface in the region of the overlap length to have the same surface conditions of the real milling tool holding sockets. This said, the final dimensions of each substrate are as shown in Figure 24.

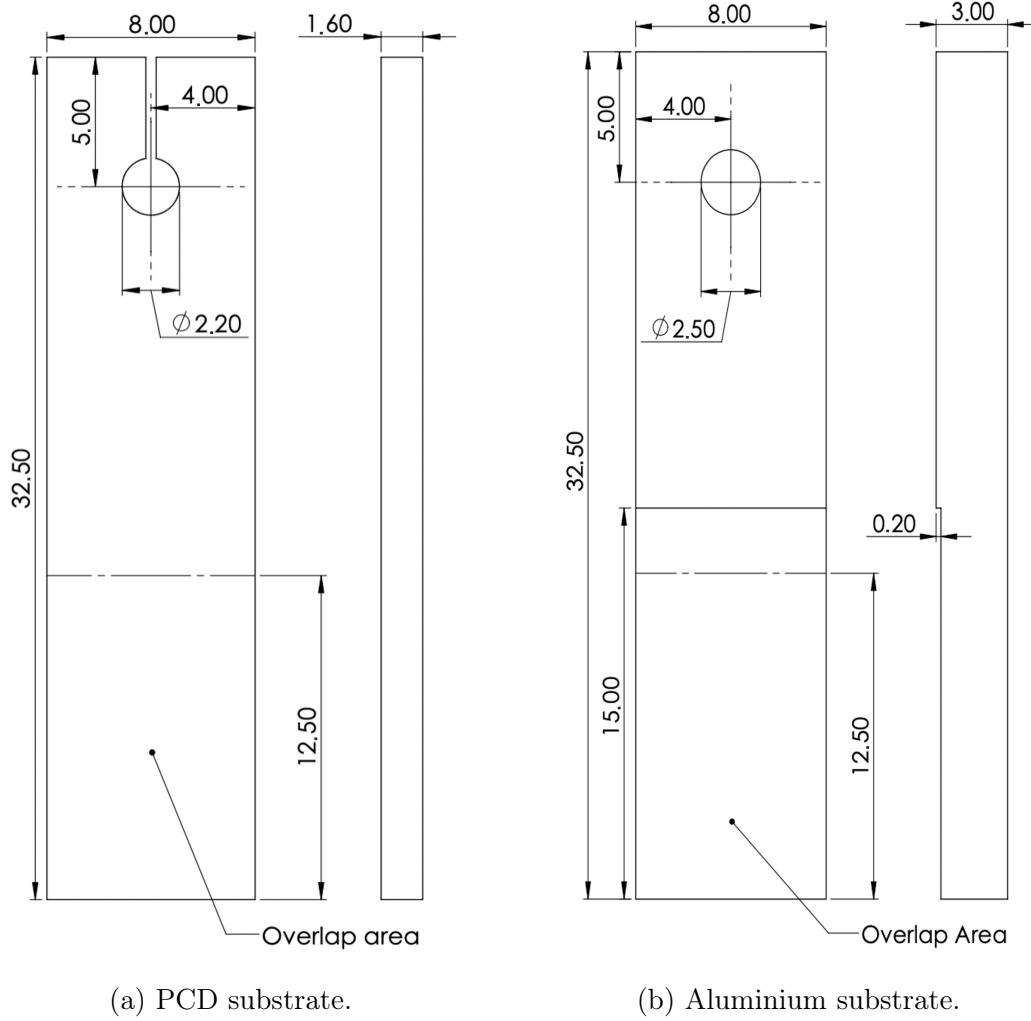


Figure 24: Technical drawing of the SLJ substrates, dimensions in millimetres.

To improve the fixation of the specimens, and prevent undesired flexural stresses the use of tabs is encouraged while performing SLJ tests. In this case it is more than necessary to design the tabs presented in Figure 25, due to the unique characteristics of the materials and the specimen geometry, making the final SLJ specimen configuration as presented in Figure 26. It is important to note that the tab thicknesses are not equal to the theoretical ones required by the specimen dimensions due to standard material availability, however, the closest values were picked to minimise this effects.

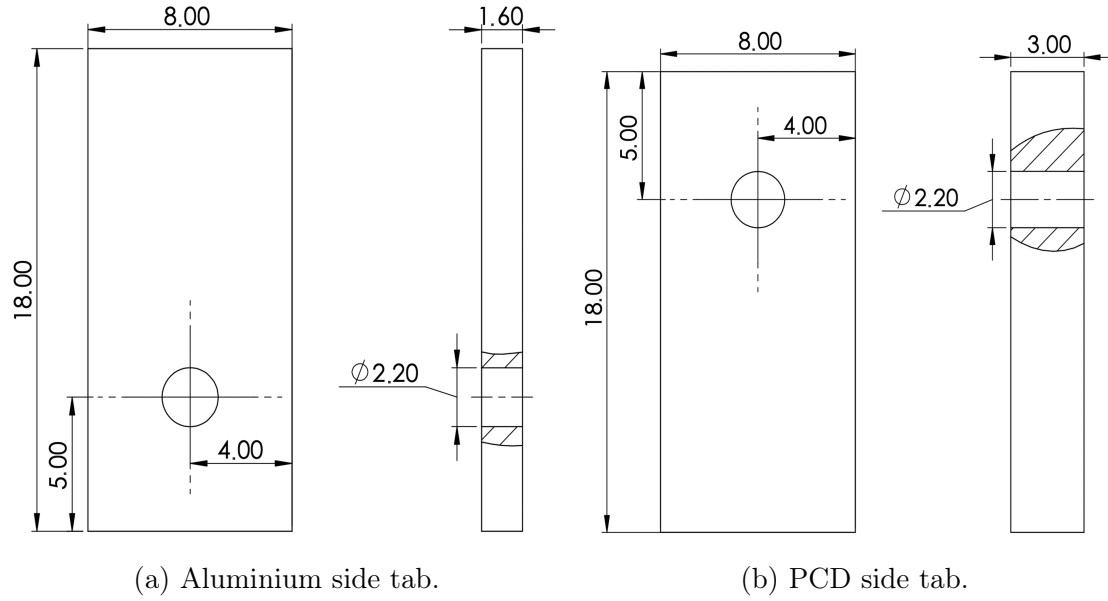


Figure 25: Technical drawing of the SLJ tabs, dimensions in millimetres.

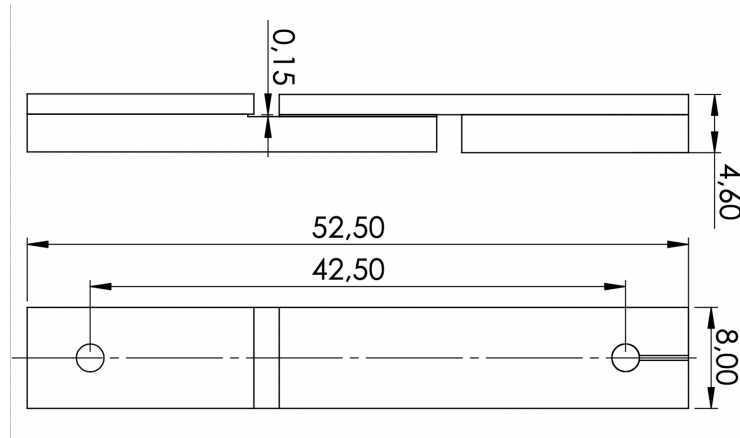


Figure 26: Technical set drawing of the final SLJ test configuration to be fixed to the test apparatus, dimensions in millimetres.

As for the double plate screwed friction based test apparatus, a new design had to be implemented to support the small dimensions of the SLJ specimens and prevent incorrect alignments resulting in undesired flexural loading. Its main requirements were fitting the existent test machine setup, i.e. total apparatus width of less than 35 mm and hole to accommodate a 14 mm loading pin, and allowing a quality specimen fastening, i.e. correct alignment, uniform screw clamping force distribution and sufficient substrate support leaving the overlap area free. However, the most relevant one in terms of mechanical design was the screw selection since its strength and resistant area were responsible for the maximum frictional force that the systems would endure without slippage. In order to define a suitable screw diameter the following calculations had to be made considering the mechanical interactions in the systems represented in Figure 27.

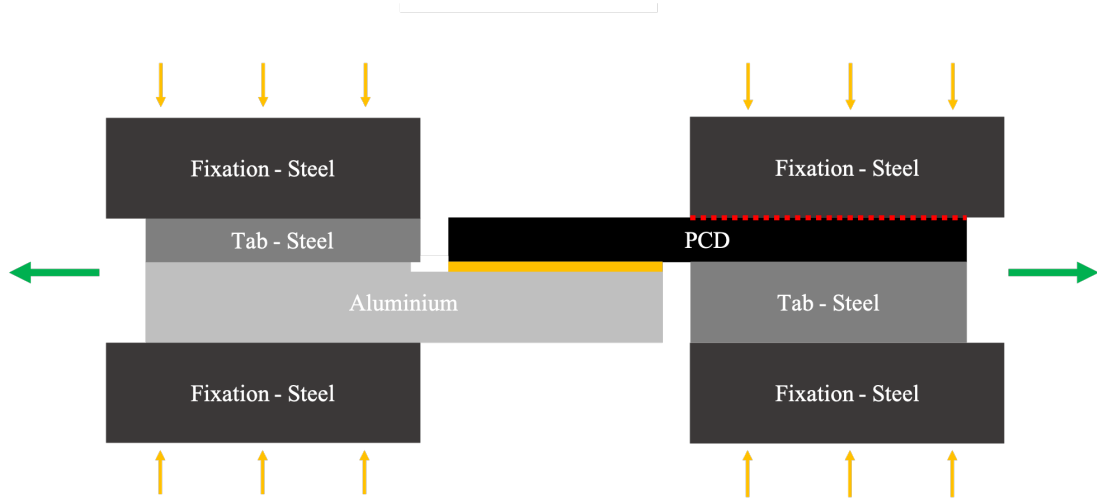


Figure 27: Schematic representation of the fixture apparatus, the forces involved - load applied (green arrows) and screw clapping force (yellow arrows) - as well as the critical friction surface pair (red dotted line).

Table 9: Friction coefficients of all the surface pairs present in Figure 27 at a dry static state.

Surface pair	Friction coefficient (μ)
PCD/Steel	0.05 to 0.15
WC/Steel	0.4 to 0.6
Steel/Steel	0.5 to 0.8
Aluminium/Steel	0.61

Consequently, the balance equations relate the maximum load - N_{max} - sustained by the adhesive resistant area with the minimum static friction threshold - F_a - resultant of the critical surface pair:

$$F_a = N_{max} \Leftrightarrow \mu \cdot N_p = \tau_f \cdot A \quad (6)$$

where μ is the smallest static friction coefficient from Table 9, τ_f is the failure shear stress of the adhesive used obtained in the adhesive characterisation step, A is the adhesive resistant area and N_p is the maximum screw preload described as:

$$N_p = s \cdot \sigma_y \cdot A_{resist} \quad (7)$$

being s the safety factor for non permanent fixation, σ_y the yield stress of the screw material category and A_{resist} the screw resistant area.

This said, all the known parameters used in the calculation are present in Table 10.

Table 10: Properties considered in the calculation of the screw diameter.

μ	τ_f / MPa	A / mm ²	s	Screw class	σ_y / MPa
0.05	41.4	100	0.7	12.9	1080

Resulting in the following resistant screw area:

$$A_{resist} = \frac{\tau_f \cdot A}{\mu \cdot s \cdot \sigma_y} \geq 27.38 \text{ mm}^2 \quad (8)$$

By consulting the standard diameters as a function of the screw resistant area the one chosen was the CHC screw ISO 4762 M8x30 - 12.9 since the resistant area - 36.70 mm² - was higher than the minimum value calculated previously. As for the aligning pins used, a couple of cylindrical pins ISO 8734 2x24 were more than enough since their job is only to do a rough alignment of the specimens.

Taking all the previously mentioned requirements into consideration the fixture system was designed as displayed in Figure 28 and manufactured from 12 mm thick CK45 steel sheets with rectified surfaces and an oxidation treatment to prevent rusting, lead to a quick and effortless testing process.

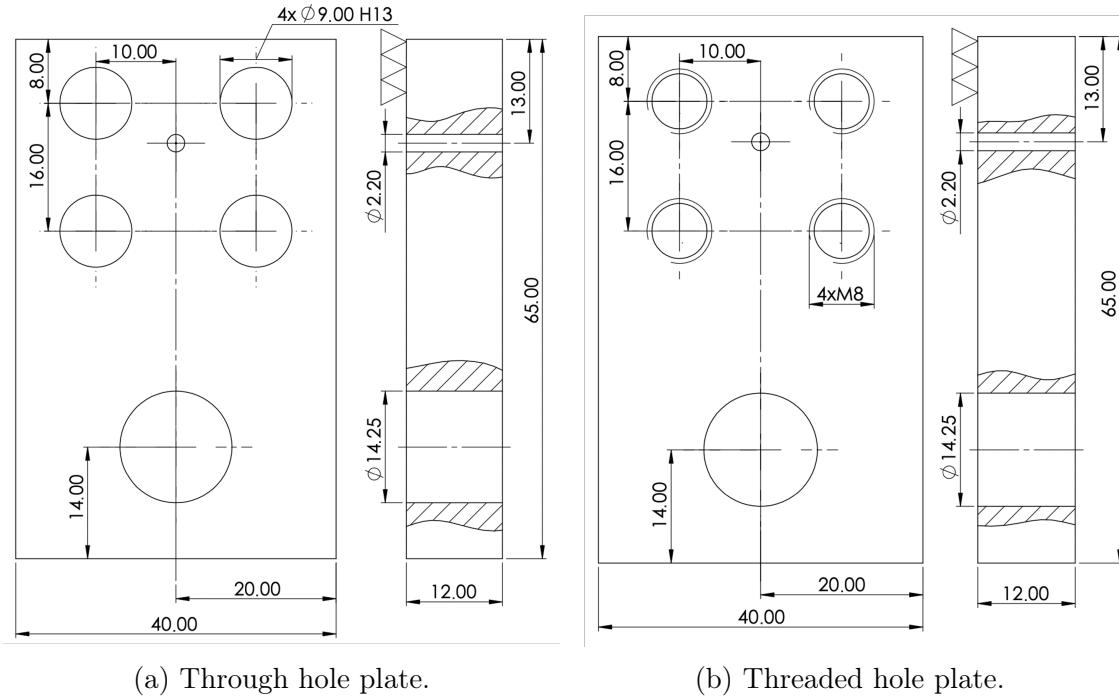


Figure 28: Technical drawings of the fixation plates for the SLJ tests, dimensions in millimetres.

As for the manufacturing of these specimens using the already existent moulds, a couple of changes had to be made to support the small dimensions of the SLJ

specimen geometry. Due to the large distance between pins, lateral spacers were manufactured with aluminium strips preventing the lateral movement of the substrates. Several specimens could be manufactured at once with the mould setup presented in Figure 29, starting only with 9 specimens but going up to a maximum of 12.

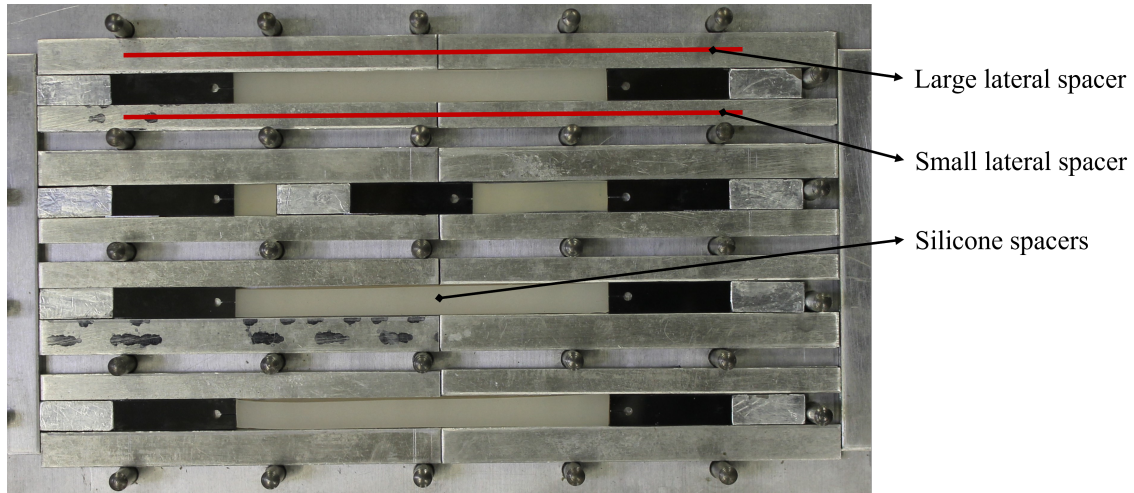


Figure 29: SLJ manufacturing mould setup, capable of producing up to 12 specimens.

To ensure an uniform pressure distribution and therefore guarantee the same adhesive thickness of 0.15 mm throughout the whole overlap length, the use of spacers with the exact dimensions needed was the path taken. However since the theoretical measurements for the aluminium and PCD sides were respectively, 2.95 mm and 1.55 mm, these had to be manufactured from 3.00 mm and 1.60 mm metal strips using abrasive methods to achieve the respective measurements.

Other form testing the bonding process between aluminium and PCD, these SLJ specimens were used to study influence of a conductive filler in improving the electrical properties of the adhesive layer. This said, three configurations were tested: neat adhesive (0% volume of spheres), adhesive plus 5% volume of spheres and adhesive plus 10% volume of spheres.

Finally, applying all the previously described steps the tensile tests were performed as seen in Figure 30, where both load and displacement data was recorded and fracture surfaces analysed to access their failure mode.

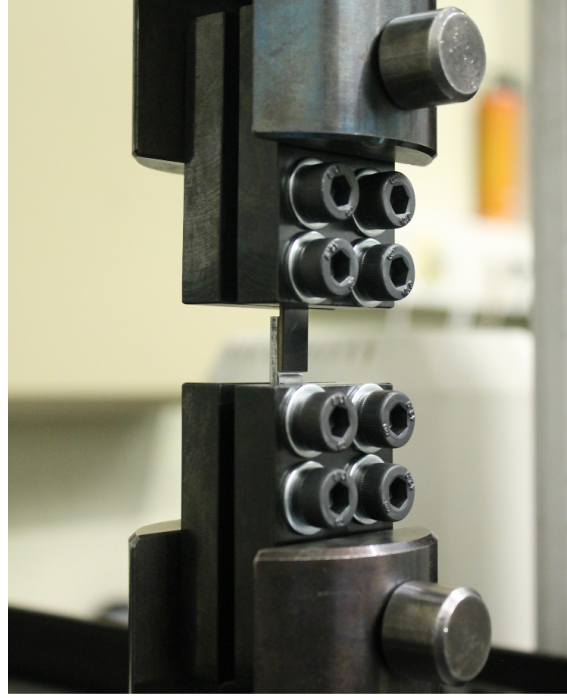


Figure 30: Complete SLJ specimen setup, shown performing a test.

3.2.4 Electrical conductivity tests

To measure the electrical conductivity of the adhesive layer the previously described SLJ specimens were used prior to performing the tensile tests. The method used was a simple electrical resistance measurement using a multimeter with the 4 probe method, Figure 31, and compare the differences between the original metallic brazed PCD/steel configuration against the adhesive joined PCD/aluminium setup with and without spheres - Figure 32 - while adjusting the sphere percentage to make the adhesive layers' resistance as close as possible to the original brazed one. The maximum resistance value measurable is $120\text{ M}\Omega$, meaning that above this threshold the multimeter will present an overflow state.

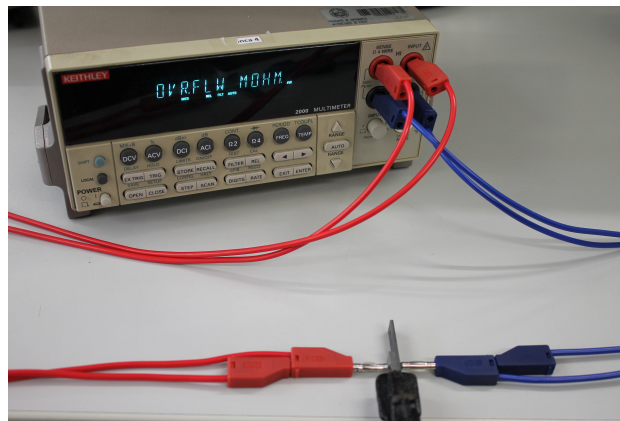


Figure 31: Electrical resistance measurement setup using the 4 probe method for the assessment of the adhesive layer conductivity.

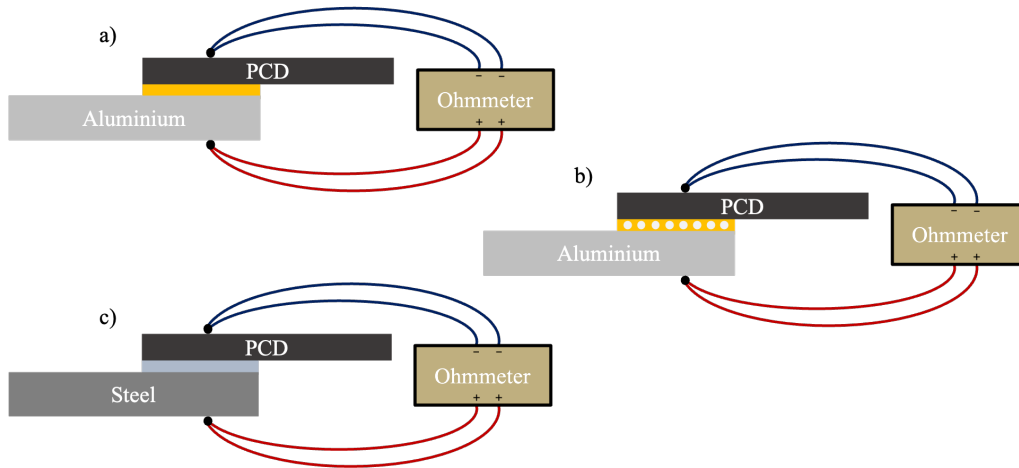


Figure 32: SLJ specimen configurations to study the adhesive layer conductivity, a) neat adhesive, b) adhesive+spheres and c) brazed(Ag).

3.2.5 Surface energy tests

Prior to manufacturing, to ensure a good adhesion to the substrates, it is common to use certain methods to determine need for the application of surface treatments, from more qualitative test such as adhesive film tests (ASTM D2141) and calibrated liquids (ASTM D2578) to more quantitative ones like peel tests (ISO 8510-1/ISO 8510-2) and even measuring the surface energy through a contact angle test (ASTM D2578-04). This last method will be the one used to study the necessity of surface treatments considering as a rule of thumb that the substrate surface-free energy should be higher than that of the adhesive in order to have good adhesion.

To measure the contact angle created by a liquid when it comes in contact with a surface, generally, an optical contact angle measuring machine and respective contour analysis software are used - Figure 33. In this case a DataPhysics Instruments GmbH (Filderstadt, Germany) OCA series machine, more precisely the OCA 15EC model, combining high resolution optics, exact liquid dosing and precise sample positioning with a software that is able to accurately determine the contact angles.

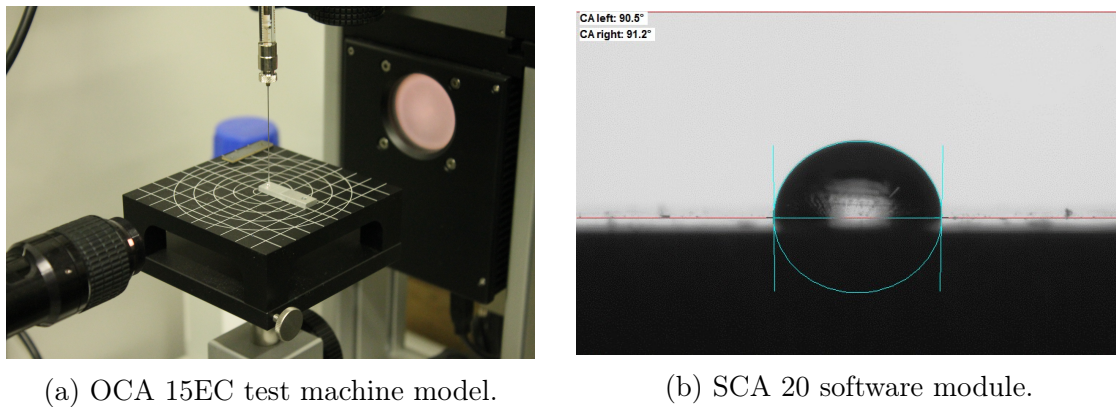


Figure 33: Optical tensiometer test for contact angle measurement.

In theoretical terms the contact angle is the angle formed by a liquid at the three-phase boundary where liquid, gas and solid intersect, Figure 34. It is commonly known as a wettability measure since angles higher than 90° imply an hydrophobic surface (low surface-free energy), and values smaller than 90° relate to hydrophilic surfaces (i.e., one with a relatively high surface-free energy), being 90° the threshold value for this property [1].

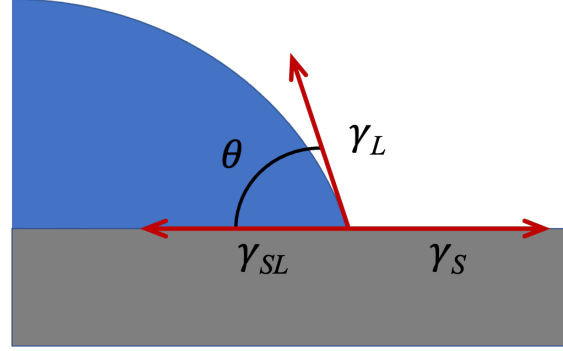


Figure 34: Contact angle at a solid-liquid-gas contact line. Adapted from [1].

As seen in the previous figure, the contact angle (θ/rad) is related to the surface-free energies of the solid substrate (γ_S) and wetting liquid (γ_L), along with the interface free energy (γ_{SL}) by the well-known Young equation [1]:

$$\gamma_S = \gamma_L \cos \theta + \gamma_{SL} \quad (9)$$

Therefore in order to determine the surface energy of a solid a method where the contact angles of test liquids whose surface tensions are well known must be implemented. Knowing that the liquid surface energy can be subdivided into the sum of several components representing the degree of bonding attributed to certain adhesion forces, such as dispersive and polar forces, these can be used to calculate the interfacial tension γ_{SL} between the solid and a liquid based on a suitable model [1].

An often applied model is the one developed by Owens, Wendt, Rabel and Kaelble (OWRK model) [29, 30] which considers the geometric mean of the dispersive and polar components of the liquid's surface tension, γ_L , and of the solid's surface energy, γ_S :

$$\gamma_{SL} = \gamma_S + \gamma_L - 2\sqrt{\gamma_S^d \gamma_L^d} - 2\sqrt{\gamma_S^p \gamma_L^p} \quad (10)$$

substituting this expression in the Young equation (eq.9), the polar and dispersive components of the solid's surface energy can be determined from the linear regression line - $y = a \cdot x + b$ - in a suitable plot.

$$\frac{\gamma_L(1 + \cos \theta)}{2\sqrt{\gamma_L^d}} = \sqrt{\gamma_S^p} \cdot \left[\frac{\sqrt{\gamma_L^p}}{\sqrt{\gamma_L^d}} \right] + \sqrt{\gamma_S^d} \implies \gamma_S = a^2 + b^2 \quad (11)$$

This linear regression only needs contact angle measurements of at least two different test liquids. However, with just two points this method contains no information on the accuracy of the result, therefore it is recommended to use at least three test liquids for the determination of the surface energy of solids. The three liquids used were water, etilenoglicol and n-hexadecane whose surface-free energy components are displayed in Table 11.

Table 11: Surface-free energy components of all 3 liquids used determine by linear regression the solid substrate surface energy, γ_S .

Surface energy / mJm^{-2}	Water	Etilenoglicol	n-Hexadecane
γ_L - total	72.8	48.8	27.5
γ_{dL} - dispersion	22.6	32.8	27.5
γ_{pL} - polar	50.2	16.0	0.0

As a final note it is relevant to detail that the contact angle considerations previously stated is the simplest approach that does not take into account some of the surface conditions that affect this parameter such as surface roughness, which in a general way increases the wettability of the surface if the contact angle is lower than 90° and vise versa, however for a simple analysis is more than suitable.

3.3 Data reduction scheme

In order to obtain the energy release rate in mode I and mode II a data reduction scheme must be implemented [31]. There are two classical methods, the Compliance Calibration Method (CCM) [32, 33], based on the Irwin-Kies equation:

$$G_{Ic} = \frac{P^2}{2b} \frac{dC}{da} \quad (12)$$

where cubic polynomials are used to fit the compliance ($C = C_3 \cdot a^3 + C_2 \cdot a^2 + C_1 \cdot a + C_0$) as a function of the crack length (a), and the Corrected Beam Theory (CBT) [33–37], also derived from the previous equation:

$$G_{Ic} = \frac{3P\delta}{2b(a + |\Delta|)} \quad (13)$$

but with a correction factor Δ , proposed in 1992 by Wang and Williams [34], to take into account the crack tip rotation and deflection:

$$\Delta = h \sqrt{\frac{1}{13k} \left(\frac{E_x}{G_{xy}} \right) \left(3 - 2 \left(\frac{\Gamma}{1 + \Gamma} \right)^2 \right)} \quad , \quad \text{with} \quad \Gamma = \frac{\sqrt{E_x E_y}}{k G_{xy}} \quad (14)$$

where h is the thickness of the substrate, E_x and G_{xy} its longitudinal normal and shear modulus, E_y the modulus in the thickness direction, and k the shear stress distribution constant for correcting the deflection caused by the shear forces.

To determine the crack length correction a linear regression can be obtained experimentally after loading the specimens at three different load levels, which can be graphically represented in Figure 35.

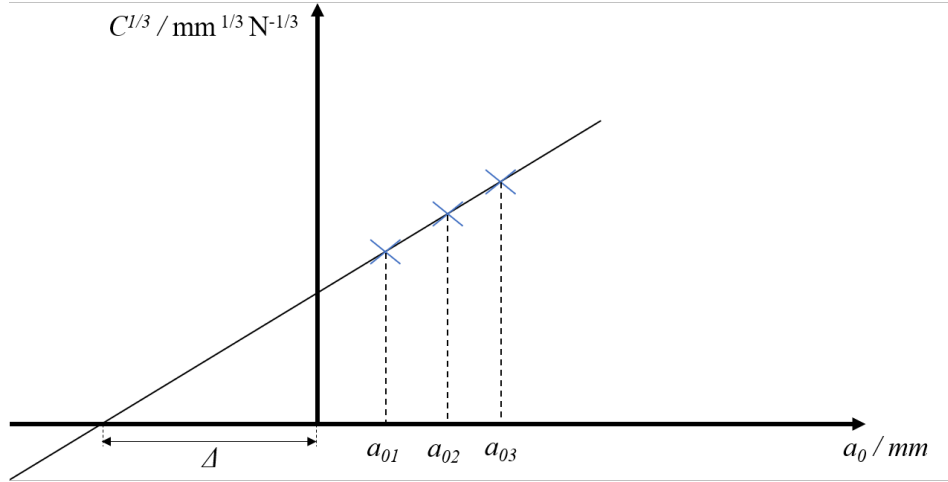


Figure 35: Graphic representation of the method used to determine the crack length correction, Δ . Adapted from [24].

However, both these methods are dependent on the assessment of the exact crack length, increasing the difficulty of their implementation, specially when a sudden crack propagation occurs and/or when analysing mode II fracture [32, 33, 38].

Considering that, in reality, the crack tip does not fully behave accordingly to linear elastic fracture mechanics, there is the need to consider a fracture process zone (FPZ), seen in Figure 36, that develops ahead of the major crack tip caused by plasticization and nucleation of several micro-cracks. This phenomenon is more severe the more ductile the material since the energy dissipated in the FPZ increases making so that the it must be taken into account in the data reduction scheme [31].

Taking these facts into consideration the compliance-based beam method (CBBM) is the one chosen to treat the fracture toughness data, since it is based on the concept of equivalent crack length, which bears in mind the phenomena previously described [31, 39], and solely depends on the compliance of the specimen during the duration of this test.

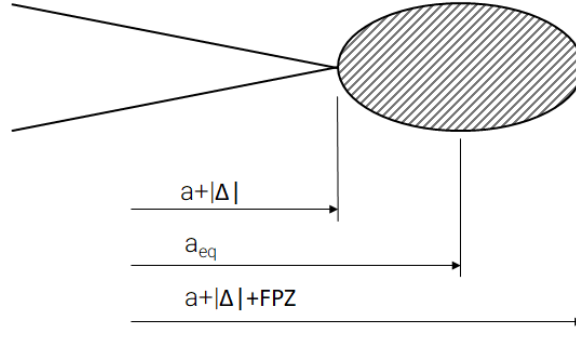


Figure 36: Schematic representation of the equivalent crack length and fracture process zone concepts. Adapted from [31].

Using this method, the energy release rate in mode I is defined as [31]:

$$G_{Ic} = \frac{6P^2}{b^2h} \left(\frac{2a_{eq}^2}{h^2E_f} + \frac{1}{5G_{13}} \right) \quad (15)$$

being P the applied or measured load depending on the type of loading condition, b is the width of each specimen, h is the specimen height, G_{13} is the respective shear modulus of the substrates, a_{eq} is the equivalent crack length, whose value is given by the solution of an equation derived from Timoshenko's beam theory [31]:

$$C = \frac{\delta}{P} = \frac{8a_{eq}^3}{bh^3E_f} + \frac{12a_{eq}}{5G_{13}bh} \quad (16)$$

and E_f is the corrected flexural modulus, whose propose is to correct the fact that this method does not take into consideration the stress concentration and substrates' rotation close to the crack tip [31]:

$$E_f = \left(C_0 - \frac{12(a_0 + |\Delta|)}{5bhG_{13}} \right)^{-1} \frac{8(a_0 + |\Delta|)^3}{bh^3} \quad (17)$$

being 0 the index set for initial values - where a_0 is the initial crack length previously defined for each method in subsection 3.2 and C_0 the initial linear compliance - and Δ a correction factor for the crack length derived from the one used in the CBT method given by the Equations 14 and ??, considering an isotropic material and 0.85 for the constant k [40].

Mode II fracture energy can be determined by [41]:

$$G_{IIc} = \frac{9P^2a_{eq}^2}{16b^2Eh^3} \quad (18)$$

where

$$a_{eq} = \left(\frac{a_0^3 C_c}{C_{0c}} + \left[\frac{C_c}{C_{0c}} - 1 \right] \frac{2L^3}{3} \right)^{1/3} \quad (19)$$

with

$$C_c = C - \frac{3L}{10bhG_{13}} \quad (20)$$

and

$$E = \frac{3a_0^3 + 2L^3}{8bh^3C_{0c}} \quad (21)$$

being L half of the ENF specimen total length and index c indicates the corrected value of a variable.

4 Numerical details

The numerical parametric simulation was performed using the commercial software ANSYS® Workbench™, an integrated platform containing several application packages that can interact with each other, sharing data with one another and creating complex mixed simulations in various areas of engineering at the same time. This software has a very graphical and user friendly interface comprised of blocks that interconnect with each other, as seen in Figure 37.

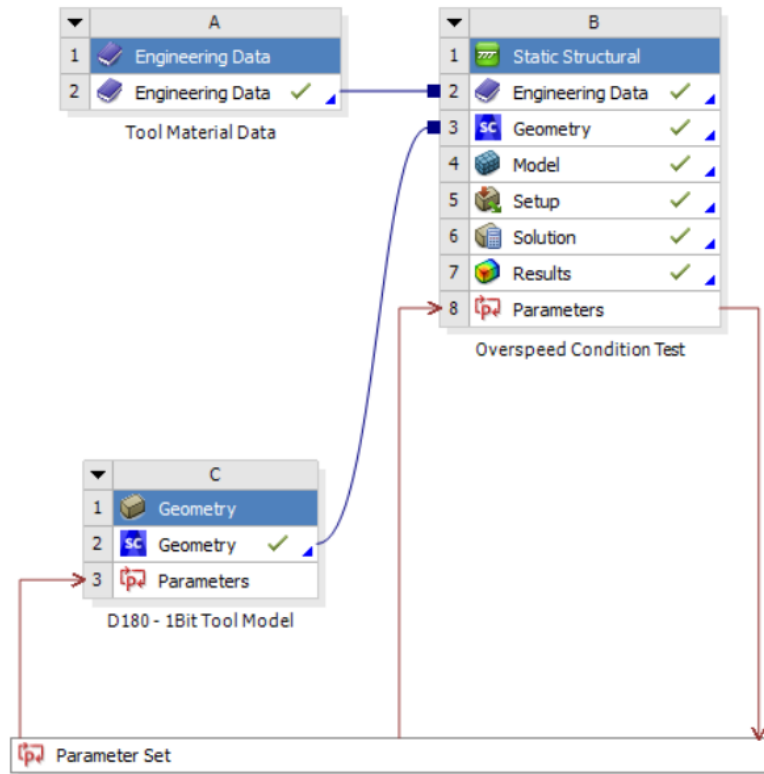


Figure 37: Block structure of the ANSYS® Workbench™ software, for a parametric simulation.

For this simulation a static structural analysis system was used as well as two additional material data and geometry blocks. Using the cohesive zone model (CZM) capabilities of the software an adhesive joined milling tool was tested using contact debonding. Finally a parametric set block was used to perform a design study of the tool's geometry, optimising its capabilities.

4.1 Cohesive zone modelling (CZM)

The concept of CZM was originally proposed by Barenblatt [42] and Dugdale [43], and has been used extensively to simulate both adhesive as well as composite fracture under static, dynamic and cyclic loading conditions.

In the MechanicalTM software package, cohesive zone models (CZM) for adhesive bonding can be based on interface elements or contact elements. The interface elements are capable of representing the cohesive zone at the interface between two different adherends and can account for the separation across the interface. Therefore they are commonly used for interfacial delamination studies.

The use of contact elements is referred to as contact debonding in which two surfaces are bonded with a CZM material. This material's behaviour is based on damage mechanics, that takes into account continuum and fracture mechanics, to study damage initiation and propagation, respectively. Cohesive zone models are typically based on elements with no thickness, which establish the connection between two solid surfaces, which in this case are the CONTA174/TARGE170 element pairs. The contact elements must use bonded contact with the augmented Lagrangian method or pure penalty method.

Debonding allows three modes of separation, mode I debonding for normal separation, mode II debonding for tangential separation, and mixed mode debonding for normal and tangential separation where a power law defines the mode mixicity of the loading conditions, as seen in Equation 22.

$$\left(\frac{G_I}{G_{Ic}}\right)^{\frac{\alpha}{2}} + \left(\frac{G_{II}}{G_{IIc}}\right)^{\frac{\alpha}{2}} = 1 \quad (22)$$

The behaviour of the adhesive is, then, simulated using suitable traction-separation laws that takes the previous properties and considerations into a graphical representation of the joints strength.

In Ansys[®] MechanicalTM a mixed mode cohesive zone model with bilinear material behaviour is used, this is defined by traction and critical fracture energies, which are based on the model proposed by Alfano and Crisfield [44] - Figure 38. The properties specified by this model are: the normal, E, and tangential, G, stiffness's; the maximum stresses under tensile, σ_{max} , and shear, τ_{max} , loading; and the critical fracture energies in mode I, G_{Ic} , and mode II, G_{IIc} . Also a few extra auxiliary parameters are set, the artificial damping, η , tangential slip under normal compression, β , and power law exponent for mixed-mode debonding, α .

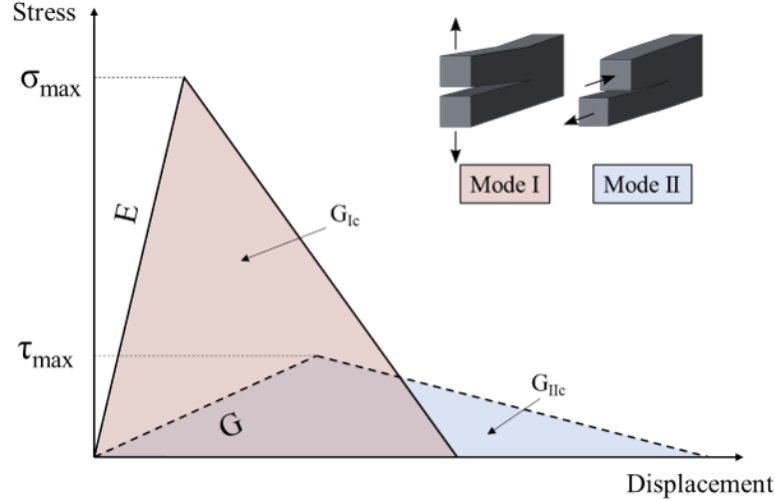


Figure 38: Mode I and Mode II cohesive model representative scheme.

Debonding is also characterised by convergence difficulties in the Newton-Raphson solution during material softening. An artificial damping coefficient, η , also called viscous damping coefficient is provided to overcome these problems by introducing a small viscosity in the cohesive zone material model.

After debonding is completed, the surface interaction is governed by standard contact constraints for normal and tangential directions. Frictional contact is used if friction is specified for the contact elements.

4.2 Milling tool numerical model

To perform a static structural analysis of this milling tool model, using the MechanicalTM software package, several steps need to be taken: define material properties, import the geometry, establish the connections between all parts, apply a proper mesh, introduce fracture mechanisms, setting the loading and boundary conditions, as well as establishing the solution outputs.

4.2.1 Materials

The material used in this simulation are, as previously described in Section 3, aluminium, PCD and an adhesive configuration to be set by Paper A. The first two materials will follow a isotropic linear-elastic behaviour defined by the Young's modulus and the Poisson's ratio, as for the inertial properties the material's density will also be specified.

The adhesive adopted a mixed mode cohesive zone behaviour with fracture-energy based debonding - described in Subsection 4.1. In the present work, all of the adhesive properties were obtained through Paper A. To improve the convergence of the model in the softening stage, an artificial damping coefficient (1×10^{-5} s)

was used following the recommendation in the programs literature to establishing a value lower than the minimum time step considered. The tangential slip variable was deactivated, since no such behaviour is known to occur in this simulation. As for the power law exponent, the default value of 2 was used, corresponding to a linear behaviour. Finally, similarly to the previous materials the adhesive's density was also considered to simulate the wanted inertial behaviour.

4.2.2 Geometry

Using Autodesk Inventor[®] the tool model with a nominal diameter of 180mm was created, Figure 39. Since the CZM approach used in ANSYS is based on a contact debonding mechanism the CAD model had to be adapted to allow this type of simulation. Considering that all inserts are at the same distance from the rotational axis, a single bit simplification of the full milling tool is possible, due to the fact that all feel the same centrifugal force. The model was then modified in order to consider four components, an aluminium body, the PCD bit and two adhesive joints, one at the base and another at the back of the insert, each divided into two separate layers to allow the contact debonding mechanism between them. Also at this stage the design simulation's parameters - holding notch's height (H), base angle (θ) and length (L) - were embedded in the model in such a way that all slave dimensions would adapt to the geometrical changes without any errors within the stipulated parametric ranges.



Figure 39: One bit partial edge milling tool 3D model obtained with Autodesk Inventor[®].

Then using the Workbench's Associative Interface configuration for Inventor CAD manipulation, the previous model was imported into Ansys through the Space

Claim software, where the design parameters were assigned as such inside Workbench.

4.2.3 Connections

Since this model relies on contact debonding the proper connections methods must be used between both the interfaces between the adherends and the adhesive, and the adhesive layer's halves, where the CZM model will be applied.

For the interfaces a bonded contact pair was used with the default formulation method, augmented Lagrange method. As for the cohesive layer, the connection type was also bonded now with a pure penalty formulation method.

All connection pair were set to have a symmetric target/contact surface behaviour, the trim contact option was disabled as well as the small sliding consideration.

4.2.4 Mesh

The mesh could be divided into adherends (black and grey) and adhesive (yellow) - Figure 40 - each with its own mesh parameters, divided into the directions of the vertical (w_V) and horizontal (w_H) widths, as well as their lengths (l). This said, all the adherend and adhesive edges parallel to one of the specified directions would have respectively the same number of divisions, only concerning the region after and including the aluminium-adhesive interfaces. The rest of the aluminium body was automatically meshed.

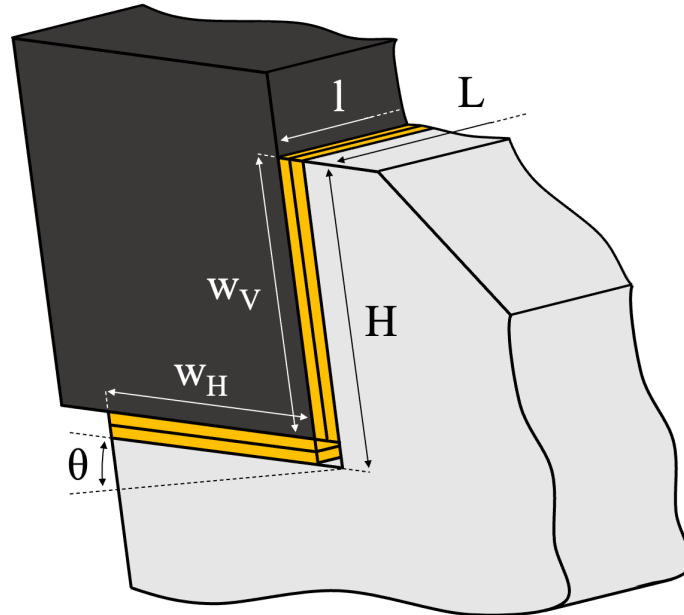


Figure 40: Three-dimensional scheme of the edge milling tool's geometrical mesh and parameters.

To maintain a regular mapped mesh a few face meshing commands were set, for both the adherends and the adhesive layers. Several mesh sizing steps divided the

parallel edges by the number of divisions specified by the mesh parameters. These sizing commands were bias with factors of 5 for vertical and horizontal directions, and 10 for lengths. This increased the mesh density near the corners to improve the solutions, a common procedure for meshing adhesive joints, since the corners are the most sensitive and stressed areas of the model's crack formation starts, most of the times.

The elements used were 8-node linear 3-D structural solid elements - SOLID185 - for the regular solid bodies (adhesive and PCD insert), and 4-node linear 3-D structural solid elements - SOLID285 - for the irregular aluminium body. And for all the bonded connections, 8-node linear 3-D surface-to-surface contact/target element pairs were used - CONTA174/TARGE170.

A representative configuration of the meshing established near the adhesive bonded is displayed at Figure 41.

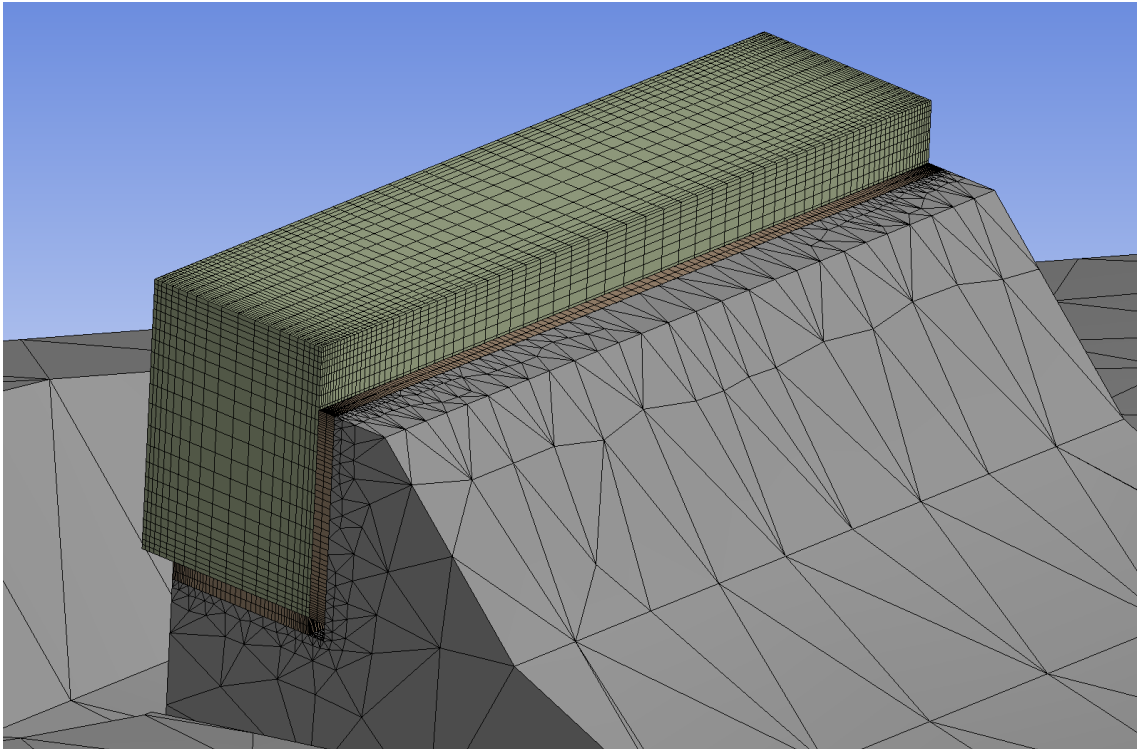


Figure 41: Representative image of the mesh used to simulate the inertial loading of the partial edge milling tool model.

Mesh convergence

To validate the mesh convergence, making sure that singularity effects are not present, a failure model was studied considering all the same setup characteristics except with a different loading condition, where a displacement-based loading in the direction of the centrifugal force was applied up until failure. The mesh was evaluated taking into consideration the influence of the adherend and adhesive mesh refinement in separate.

Then the P - δ curves obtained were compared for different mesh refinements up until no significant variation was found. The final mesh parameter configuration was set to the values presented in Table 12, corresponding to the model's original height, angle and length values, also present in the same table.

Table 12: Final converged adhesive mesh configuration corresponding to the original model parametric dimensions.

Mesh parameter	Adher.	Adhes.	Geom. parameter	Value
Back width (w_V)	35	55	Height (H/mm)	2
Base width (w_H)	30	50	Base angle ($\theta/^\circ$)	15
Length (l)	100	200	Bit length (L/mm)	14

4.2.5 Fracture

To enable CZM into the simulation it is necessary to apply a Contact Debonding mechanism to the model, where the properties of a CZM material, are attributed the wanted connection pairs.

4.2.6 Loading and boundary conditions

In woodworking tools, the most severe stresses felt by the tools bonded layer are due to centrifugal loads. Therefore, considering the safety validation test defined by the EN 847 standard, an overspeed loading condition was set in accordance to the tool's diameter and maximum rotational velocity allowed - see Table 15 in Section 5. As such, to allow an easier convergence the load step was subdivided into small increments going from 0 to the maximum overspeed rotational velocity.

In terms of boundary conditions a cylindrical support was allocated to the tool's shaft hole where radial, tangential and axial movements were set as fixed. Also, since a simplified tool model was used, radial symmetry conditions must be simulated by fixating the displacements in the normal direction to each symmetry face.

4.2.7 Analysis settings

Convergence problems pose a great challenge in adhesive models due to the debonding behaviour of the bilinear CZM contact formulation. For that reason, automatic time stepping was used to allow the solver to reduce the time step down to 5×10^{-4} s when necessary, while at the same time, minimising the number of calculation cycles needed by increasing the time step size once again up to 1×10^{-2} s.

The weak springs option was set to off, and all others were set to program controlled.

4.3 Parametric simulation

To optimise the joint geometry, a parametric design simulation was performed using the simplified single bit model of the full milling tool. This numerical simulation considered 3 geometrical input parameters, the holding notch's height (H), base angle (θ) and length (L), and evaluated the generated stresses as the output parameter/criterion. As for the mesh, it had to accompany the changes in the geometry, maintaining the same mesh density that was validated for convergence. Therefore, all mesh parameters, both back (w_V) and base (w_H) layer widths, as well as their length (l) were set to follow the respective changes in geometry. A schematic representation of both the design and mesh parameters is present in Figure 40.

Due to the large amount of possible combinations to be tested, an iterative approach was adopted, focusing on optimising the height and angle first, considering them as primary input parameters, and afterwards analysing one other considered as secondary, the length. Also a qualitative assessment of the added cost per bit comparing it to the already commercialised corresponding tool was done considering the volume changes in each design point.

The output parameter stresses were obtained through the solution's tab option for localised stress probing, applying this tool in the contact surfaces where CZM was applied. There, maximum principal stresses (σ_1) were measured to understand the severity of the load, as well as evaluate their directions and concentrations through vectorial analysis. Other than that, the normal (σ) and shear (τ) components of the stresses felt in the adhesive layer were extracted from local referential systems to better understand the mode mixicity felt by the adhesive layer.

5 Practical implementation and validation methods

This section describes the the process of implementing adhesive bonding in the production of edge milling tools. The main objective of this study was to assess the possibility of manufacturing a milling tool recurring to PCD inserts and an aluminium body.

Nevertheless, due to some performance and manufacturing concerns in relation to the use of aluminium, a more common steel body tool was also tested to compare results. This is important since many other products where steel use is indispensable could also benefit from this process exchange.

5.1 Induction cure cycle

Since induction was the current heating process used in brazed tool production, one of the main premises of this work was to keep it as the adhesive curing methodology. Induction brazing is characterised as a thermal joining process in which the PCD insert and the steel body are joined together by a pure silver filler heated up to 961.78°C by an induction coil. Steel is used originally due its ferromagnetic properties, which increase the effectiveness of the induction heating phenomenon, and its relatively low thermal conductivity for a metal, that reduces the heat diffusion effect out of the localised heating zone, making the filler achieve its melting point in just a few seconds. This method provides reliability, resistance and high productivity.

On the other hand, aluminium - the innovative body material under study - is non ferromagnetic, solely allowing induction heating by eddy currents. This makes the process less effective due to the decreased heating by joule effect as well as a quicker heat dissipation since aluminium more thermally conductive than steel.

In order to maintain similar production rates a curing time threshold was set at 15 seconds. This said two curing cycles could be implemented, a full cure or a pre-cure cycle under the time limit proposed.

Table 13: Known curing parameters of the adhesive chosen for the study.

Temperature/°C	Time/min
130	75
150	40
180	15

Looking at Table 13, it was possible to establish that the adhesive is only capable of fully curing at a temperature - $T_{full\ c}$ - higher than 180°C for the proposed time

frame - $t_{full\ c} > 15s$. A schematic representation of this cure cycle is presented in Figure 42.

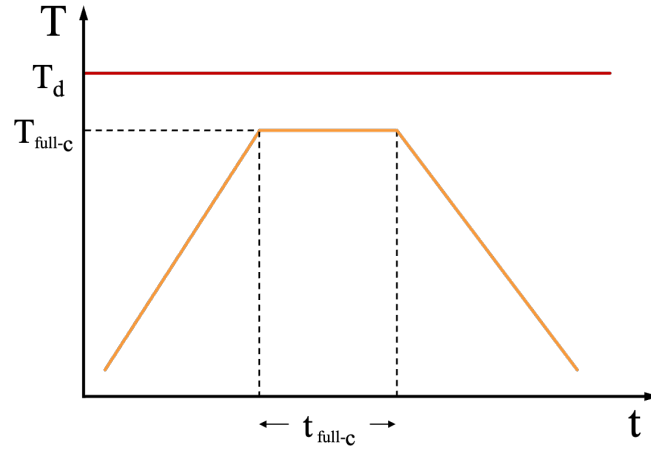


Figure 42: Full-cure cycle.

As for the pre-cure method it could be implemented at lower temperatures - $T_{pre\ c}$ -, under similar curing times - $t_{pre\ c}$ -, and finalised with a long - t_c - oven curing cycle at low temperature - T_c . A schematic representation of this cure cycle is presented in Figure 43.

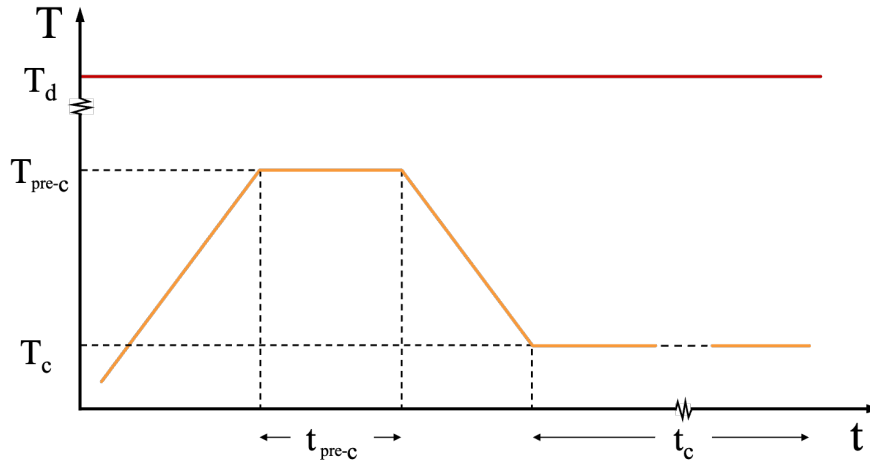


Figure 43: Pre-cure plus oven cure cycle.

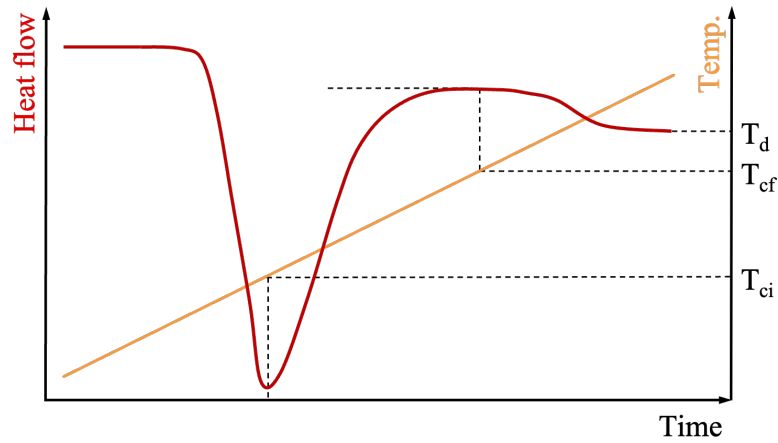
5.1.1 Differential scanning calorimetry tests

Differential scanning calorimetry tests is a thermoanalytical technique commonly used to study the thermal behaviour of polymers, in which the difference in the amount of heat required to increase the temperature of a sample in relation to a reference is measured. Several tests were performed using the adhesive in study, to better understand its polymerisation process at different temperatures and assess

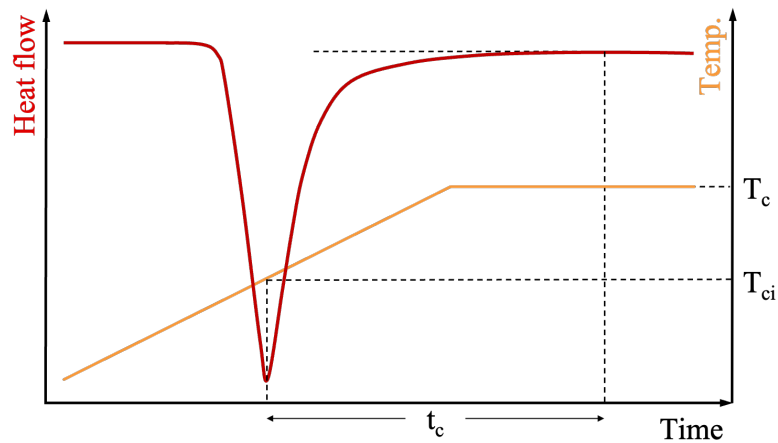
the possibility of the application of either a quick full-cure or pre-cure followed by a longer cure stage at lower temperature.

Two types of tests were performed, a continuous ramp and several isothermal cure stages to access the curing times at different temperatures.

As for the interpretation of these tests both situations are schematically represented in Figure 44. In both cases, after the initial constant stage of heat flow the curve suddenly drops to a minimum value, which represents the temperature at which the adhesive reticulation begins - T_{ci} . Afterwards, the heat flow begins to increase until it stabilises once more, finalising the adhesive polymerisation - T_{cf} . In the case of the continuous ramp, the heat flow will decrease once again until it reaches the degradation temperature - T_d - destabilising its behaviour after this point, making so that for safety reasons the cure temperature should be considerably lower than this value.



(a) Ramp DSC test.



(b) Isothermal DSC test.

Figure 44: Differential scanning calorimetry test curves.

It was important to note that all of the DSC tests performed do not correspond

to the real cure cycles, which are subjected to much higher heat rates, limiting the direct comparison between both conditions making so that they only serves as an auxiliary support for the definition of the cure cycles. This said, the cure times examined during this study only contemplate the point at which the isothermal stage was reached ignoring the cycle's heat ramp.

5.2 Prototype manufacturing

The manufacturing methodology was based on the present induction heating method, re-purposing the braze temperature control units currently used to control the adhesive's curing cycle. The setup used was comprised of a high frequency generator, CEIA Power Cube[®] 64/900 with a maximum power output of 5.6 kW; a heating head with a water cooled inductor; a foot start/stop switch; a temperature measuring sensor with laser assisted positioning, CEIA SH15/SLE-550-D1 pyrometer with a temperature range of 80°C to 700°C; and a master control unit, CEIA Master Controller V3+ capable of adjusting the isothermic cure temperature and settling time, the emissivity of the pyrometer, as well as setting the maximum power output of the generator controlling its values based on the temperature readings to maintain a constant temperature stage.

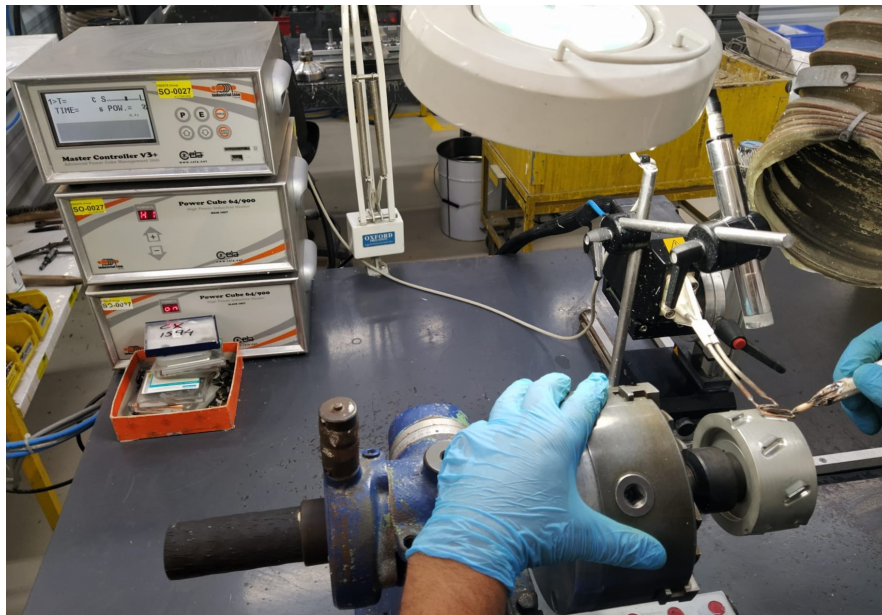
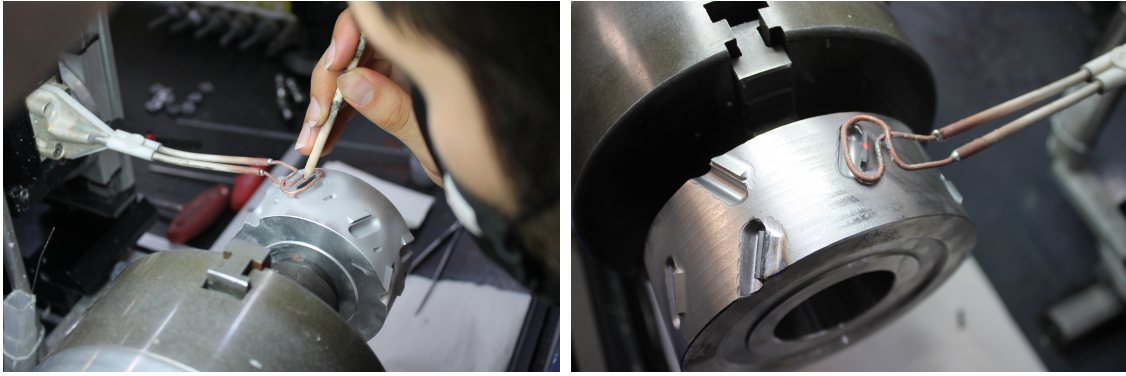


Figure 45: Prototype manufacturing setup at FREZITE.

The procedure followed was similar to the ones used in the experimental study, surface treatment and cleaning, positioning the body part in its rotational clamping support, applying the adhesive, positioning the PCD adherend, and curing them under appropriate temperature and pressure condition. Being these last two delivered by the power supply controller through an induction coil, and a manual ceramic or steel/rubber pointer, which can be seen in Figure 46.



(a) Aluminium prototype manufacturing. (b) Steel prototype manufacturing.

Figure 46: Induction cured prototype manufacturing.

5.3 Work temperature

Since work temperatures were reported, in previous studies described at Subsection 2.3, as a liability for adhesive bonded tools some steps were taken to determine if this was a relevant factor in the current study. Using an infrared thermal camera, Fluke Ti25 IR Fusion Technology, work temperature values were measured while cutting common wood raw materials, such as MFC (melamine faced chipboard) and MDF (medium density fiberboard). The test should be performed both with the original configuration as well as the adhesive bonded prototype to precisely assess differences. And, even though this considers only the temperature around the cutting area in a rotating tool, which does not represent the real temperature at the tool cutting inserts, it serves as a basis to evaluate the possibility of thermal degradation problems related to long work stages at severe enough temperatures to damage the adhesive properties.

Nevertheless, considering that contrarily to previous studies, where metals were machined by stationary cemented carbide lathe steel tools, whose heat dissipation mechanism in dry processes is only conduction, thermal degradation in this type of milling tool is predicted to have no relevance. All this due to the use of hard materials with low friction coefficients - like polycrystalline diamond (PCD) inserts - that decrease cutting edge temperatures, coupled with aluminium bodies with much higher thermal conductivity, rotational velocity that promotes heat dissipation by means of convection, and softer workpiece materials that produce less heat during chip creation.

5.4 Woodworking tool safety validation

5.4.1 EDM sharpening

With the introduction of harder materials new erosion processes started to be used for tool sharpening, like electrical discharge machining (EDM), or laser based

processes, that remove material by localized "melt and blow" operations at very high temperatures.

EDM is used to machine strong and hard materials based on their electrical properties since it works on the basis of a spark formation process between two electrodes, the tool-electrode and the workpiece-electrode, immersed in a dielectric fluid (commonly hydrocarbon oils). A high frequency pulsed circuit induces a voltage between both electrodes causing dielectric break down of the liquid, producing an electrical arc that melts material from both electrodes at their spark contact points. After the spark ceases to exist, the surrounding liquid fills the space carrying away the molten material as solidified particles.

Since this study considered the specific use of EDM as a sharpening process for milling tool production and adhesive materials are considered electrical insulators, certain considerations based on increasing the adhesive layer's electrical conductivity were studied. In [45], König reported that many different classes of materials such as hardened steels, carbides, ceramics, and other materials could be EDM machined if they offered 0.01 Scm^{-1} of electrical conductivity (σ), as shown in Figure 47. Since then many new materials can be machined by an EDM process, via sacrificial layers or doping, where the introduction of powdered conductive elements such as graphite, copper and aluminium [20], proved effective in improving the electrical conductivity of epoxy resins.

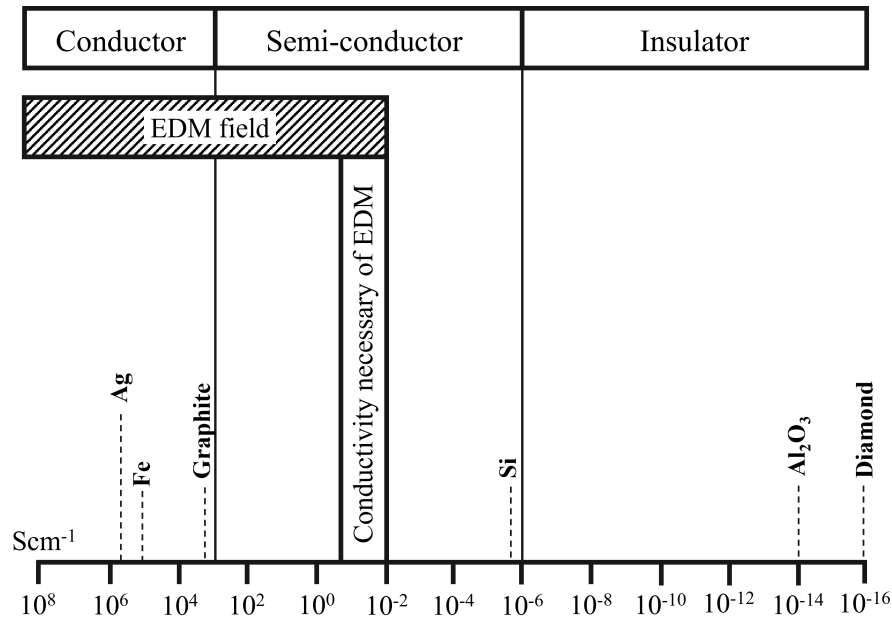


Figure 47: Electrical conductivity necessary for EDM. Adapted from [45].

This said, by analysing the electrical resistivity - $\rho = 1/\sigma$ - of all the materials at play, present in Table 14, it was possible to assess that, even tough the adhesive used is doped with aluminium powder to improve its electrical properties, in this case was not enough for sharpening bonded milling tools with EDM.

Table 14: Electrical properties of the materials used in this study.

Electrical property	Adhesive	PCD	WC	Aluminium	Spheres
$\rho / \Omega\text{m}$	$> 1 \cdot 10^{13}$	$1 \cdot 10^{13}$	$2 \cdot 10^{-5}$	$5.26 \cdot 10^{-6}$	$1.59 \cdot 10^{-6}$

Therefore, by adding a certain volume percentage of conductive spheres to the adhesive used, as previously detailed, it was possible to promote the existence of a stable closed loop between the body and the tool-electrode, improving the quality of the sharpening process, as presented in Figure 48.

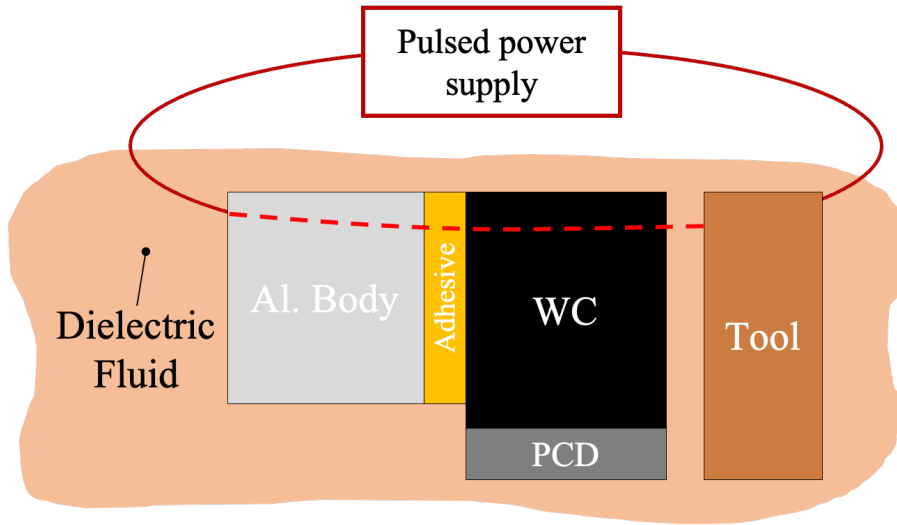


Figure 48: Schematic representation of EDM sharpening process.

5.4.2 EN 847 safety standard

As previously stated, the safety requirements for wood milling tools are set by the EN 847 standard, where in the specific case of adhesive bonded milling tools the validation method comprises of either a stress calculation or a centrifugal test against fracture, since in the case of woodworking milling tools the centrifugal stresses are the most severe ones as previously seen in Subsection 2.1.3.

Considering the centrifugal test as the validation method, the specimen used had the largest cutting diameter and width available in catalogue. During the overspeed condition type test, at a rotational test speed of $\eta_p = 2 \cdot \eta_{max}$ [η_p in rpm], if no fracture is verified in the bonded areas the test is considered valid.

The edge milling tool models considered in this work had standard catalogue diameters of 100 mm, 125 mm and 180 mm, with fixed width for each diameter. In terms of rotational velocity, calculation were made considering the typical and maximum peripheral cutting velocity's common for these tool models, using the

following equation:

$$\eta = \frac{v_c \cdot 60 \cdot 1000}{\pi \cdot d}, \quad [rpm] \quad (23)$$

whose values are represented in Table 15.

Table 15: Corresponding rotational speeds considering two peripheral cutting speed states, typical and maximum, for three standardised tool diameters.

Speed state	v_c / ms^{-1}	d / mm	η / rpm	η_p / rpm
Typical	70	100	13000	26000
		125	10000	20000
		180	7400	14800
Maximum	90	100	17000	34000
		125	13000	26000
		180	9500	19000

The tests were performed at FREZITE[®] Woodworking Tools (Trofa, Portugal), with an in-house overspeed testing machine, whose maximum rotational velocity is 21500 rpm.

6 Summary of the appended papers

Paper A - Experimental study on aluminium to WC/PCD adhesive bonding for milling tools

This paper studies an adhesive bonding process between aluminium and WC/PCD, using an electrically conductive structural adhesive with conductive spheres as the filler. Bulk tensile tests, thick adherend shear tests (TAST), double cantilever beam (DCB) tests and end notched fracture (ENF) tests were performed to mechanically characterise the adhesive. The joining process was studied using small-scale single lap joint (SLJ) specimens, testing the effect of the spheres on the mechanical and electrical properties of the adhesive, as well as the need for surface treatments. It was found that with an increase in the V% of spheres both the electrical resistance and the strength decreased, making the 5% sphere configuration a good compromise between all properties. Lastly, the previously detailed full characterisation of the adhesive was performed for the 5% sphere content, showing a reduction in fracture toughness, as expected.

Paper B - Numerical optimisation of bonded joints for the manufacture of edge milling tools

In this work, a numerical model was developed, able to predict the stresses generated due to centrifugal forces and determine the performance of the joint, using cohesive zone models (CZM). Recurring to the ANSYS's contact debonding based mechanism, a CAD model was adapted. A parametric design simulation was performed considering three geometrical input parameters, as well as evaluating the stresses generated in the adhesive layer as the output parameter, using a simplified single bit model of the full milling tool under an overspeed loading condition established by the EN 847-1 standard. The developed model highlighted the large safety factor present in the original model and allowed to optimise some of the key design parameters, minimising tool costs and ensuring maximum performance.

Paper C - Practical implementation and validation of a novel process for manufacturing milling tools using adhesive bonding

This paper is dedicated to proposing an alternative to the common brazed milling tool construction using a bonded configuration. The induction curing process was firstly studied, recurring to differential scanning calorimetry (DSC) tests, assessing two possibilities, an induction pre-cure followed by an oven curing or a faster induction full cure. The cure cycle was set and single lap joint (SLJ) tests were performed to validate joint strength. The electrical conductivity was validated by applying the EDM sharpening process to the prototypes. As for the safety requirements, the test condition used was the one set by the EN 847-1 standard, where a rotational speed test is performed at overspeed condition and the specimen is considered to have passed if no failure occurs. Although important differences in behaviour between the bonded and the brazed joints were identified, the proposed bonded joint was found to be suitable for practical implementation.

7 Conclusion

7.1 Conclusions

To validate the applicability of adhesive bonding on the industrial production of milling tools, a study on the bonding process between aluminium and WC/PCD was performed. This entailed the selection of suitable substrate surface treatments, selecting the adhesive and characterising it for an optimised content of conductive spheres, necessary to create electrical conductivity for the EDM process.

Afterwards, a numerical model of the bonded tool was developed and loaded to conditions consistent with those predicated by the EN 847 standard, using a cohesive zone model to model the performance of the bonded joint. The tool geometry was optimised by a parametric design simulation performed using Ansys® Workbench™.

And finally, validating this process on a practical level producing several prototypes for both steel and aluminium body solutions, with a properly defined induction cure cycles. For validation purposes, EDM sharpening as well as overspeed tests in accordance to the EN 847 standard were performed. This work led to the following conclusions:

- Adhesive bonding between aluminium and WC/PCD is possible, when proper surface treatments are applied;
- Bonded tools showed lower cohesive resistance, when compared to brazed ones;
- The numerical model allowed to determine that no failure occurs in the joint under overspeed conditions, with a high safety factor;
- Tools with aluminium bodies, unlike those using steel, were very challenging to cure with induction based process;
- The doped adhesive exhibited good performance, increasing the electrical conductivity of the adhesive layer for EDM sharpening, with a limited penalty to its mechanical properties;
- Steel bonded tools were fully validated presenting themselves as a robust solution for the milling tool sector.

Overall, this work proved that aluminium to WC/PCD bonding is possible, while highlighting the large safety factor present in the tested bonded tools, allowing for a highly durable and resistant milling tool. Although a few differences in behaviour between brazed and bonded tool were identified, the proposed configurations were found to be suitable for practical implementation. Nonetheless, the challenges found

during this work show there are still many avenues of improvement that can increase process efficiency in an industrial environment.

7.2 Future work

In future studies, on adhesive bonding applied to the milling tool industry, different cure processes should be studied, especially for tools with aluminium body, focusing the research on making this process more industrially productive. Such processes can include UV light pre-curing, the inclusion of steel spheres on induction based pre-curing processes to improve the heat flow from within the adhesive layer, and new inductor coil shapes with higher magnetic field intensity that penetrate more easily on the adhesive layer with a much more localised heating effect, requiring less time to cure with less heat dissipated in the process.

Furthermore, the use of adhesives in the milling tool sector can be expanded for many other specific applications, where brazing is not adequate. Examples of these applications are inserts with large dimension, tools which are highly susceptible to thermal buckling, metal milling tools, among many other tool types whose production can easily be automated, e.g. saws.

Finally, long term durability studies on fatigue, creep and chemical/thermal degradation should be considered, as well as new ways to improve adhesive's electrical and thermal conductivity. All these could open new pathways for the implementation of adhesive bonding in more branches of the tooling industry.

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Appendices

A Paper A

Experimental study on aluminium to WC/PCD adhesive bonding for milling tools

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Nowadays the use of adhesive joining processes is deeply embedded in the modern automotive and aeronautical industries as an alternative to the more common mechanical joining options. However, amongst other industrial sectors, such as the milling tool sector, it is still a quite recent and unexplored technology. This sector is, however, starting to look at adhesive bonding as a substitute for the more common brazing process. This work studies an adhesive bonding process between aluminium (AW 7075 T6) and WC/PCD (CTB010), materials used in a common woodworking edge milling tool, using an electrically conductive structural adhesive with conductive microspheres as the filler.

Using bulk tensile tests, thick adherend shear tests (TAST), double cantilever beam (DCB) tests and end notched fracture (ENF) the adhesive was mechanically characterised. The joining process was studied using small-scale single lap joint (SLJ) specimens manufactured using three configurations: neat state, 5% and 10% volume of spheres, in order to understand in a wider spectrum the effect of the spheres on the mechanical and electrical properties. The assessment of the electrical conductivity of the adhesive layer was done by measuring the specimen's electrical resistance with the 4 probe method and comparing it to a specimen manufactured with the original brazing process. The need for surface treatments was evaluated by measuring the surface energy of both substrates, and then validated by performing the SLJ tensile tests, verifying the type of failure that occurred, and reiterating the process applying the proper solutions.

It was found that with an increase in the V% of spheres both the electrical resistance and the strength decreased, making the 10% configuration not worth the small increase in electrical conductivity for the extra decrease in strength, and since the neat state did not ensure low electrical resistance at the test thickness all the results point towards the 5% sphere content as a good compromise between both mechanical and electrical properties. The 5% sphere configuration is the one chosen for the next steps of this case study. To finalise, the previously detailed characterisation of the adhesive was performed for the 5% sphere content, showing a reduction in fracture toughness, as expected.

A.1 Introduction

The application of adhesive bonding in the milling tool industry is still, after more than 40 years of study, not the norm. And, even though a limited number of studies have been carried out since the 1980's demonstrating the clear advantages brought by their use, over the years this process was not able to be fully industrialised. Certain production and performance concerns created resistance for the industrial environment to adopt this manufacturing processes, and with constant improvements in classical joining processes, brazing and mechanical fastening, which got more efficient - i.e. better induction based temperature control systems, harder materials, among others - the diminishing investment into research projects slowed its proliferation.

In 1989, Darwish and Davies [1], implemented operating conditions into the study of adhesive bonding for metal cutting tools, showing improved vibration damping over brazed tools and work temperature as a critical factor for the performance of bonded tools, proposing that heat cured toughened epoxy resins should be the best choice for these applications. Up until then it was known that the brazing process had a high reject percentage of 10 to 20% during production of cemented carbide tools due to thermal micro cracking in the inserts [2–4]. Adhesive bonding introduced it self as a solution to economically improve the production cycle, but also reduced cutting forces, lowered tool wear and, in accordance with future studies, improved surface quality [1, 5–7], all considered as a consequence of the damping effect provided by the adhesive.

However, the thermal insulation created by the adhesive layer was reported, in several studies, as an issue for both the adhesive and insert [1], due to lower heat dissipation at the cutting edge increasing the tools temperature compared with braze-joined or mechanically clamped systems. As a solution, the introduction of conductive elements into the adhesive - e.g. aluminium, copper, graphite, among others - was reported to improve both electrical [8] and thermal [9–11] conductivity's, and often even having a strengthening effect up until a certain critical weight percentage.

Nowadays, and focusing on the woodworking milling tool industry, with the evolution of the adhesive manufacturers using fillers (conductive metallic powders) in commercial products, harder materials using polycrystalline diamond (PCD) inserts with low friction coefficient to decrease cutting edge temperatures, and the tendency of the markets in using lighter tools made with low weight alloys such as aluminium, it appears that some of the concerns of the past that might have a better chance of being solved today.

In the present study the bonding process between aluminium and WC/PCD was evaluated, contrarily to most previous studies which analysed metal machining steel/carbide tools. Firstly, a heat cured epoxy adhesive will be characterised

in terms of strength and fracture envelope, while also being used to analyse the bonding process between aluminium and WC/PCD considering surface treatments, strength and fracture modes, as well as evaluating the electrical resistance of the adhesive layer by means of optimising a conductive filler content, comparing it with the original brazed configuration, in order to maintain the use of EDM insert sharpening.

A.2 Experimental details

In this section, a detailed description of both the materials used as and the manufacturing and testing is provided.

In order to fully characterise the adhesive's cohesive law, tensile, TAST, DCB and ENF specimens were manufactured and tested, to determine tensile and shear properties, as well as the energy release rates in mode I and mode II, respectively. Firstly, these tests were carried out in the neat state and after the bonding process an additional study was made with the respective optimised amount of spheres.

For the evaluation of the aluminium to WC/PCD adhesive bonding process, SLJ specimens were used, allowing to test the cohesive behaviour, the need for possible surface treatments, and also the electrical conductivity of the joint.

A.2.1 Braze-joining adhesive substitute

The adhesive chosen for this work was a one-part, heat-cured epoxy resin compatible suitable for induction curing that can be used as alternative to riveting, welding and brazing in high stress applications, with the particularity of having improved conductivity properties due to a aluminium filler. The cure cycle used in this work was the same suggested by manufacturer in the respective data sheet, consisting of a stage at 150°C for 40 minutes, Figure 1.

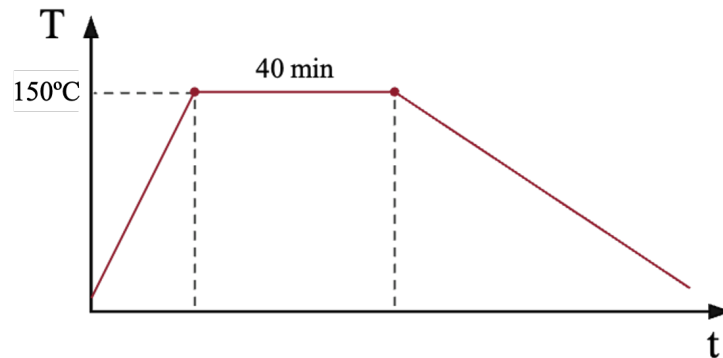


Figure 1: Cure cycle of the adhesive under study.

In addition to the use of this adhesive, an additive will also be studied, more

precisely conductive microspheres, whose use will control two parameters: adhesive layer thickness and electrical conductivity.

A.2.2 Specimen fabrication

Tensile specimens

Tensile specimens were machined from 2 mm thick cured adhesive plates, manufactured following the French standard NF T 76-142 [12]. First the steel mould was cleaned, degreased and a demoulding agent was applied to all surfaces in possible contact with the adhesive. The uncured adhesive was then applied within a silicone rubber frame, positioned inside the mould, used to restrict the adhesive and creating hydrostatic pressure that prevents the presence of voids as well as promoting a smooth surface finish. Both temperature and pressure conditions were tailored to guarantee a proper cure cycle of the adhesive. Finally, the specimens were then machined following the British BS 2782 [13] standard, with the geometrical configuration presented in Figure 2.

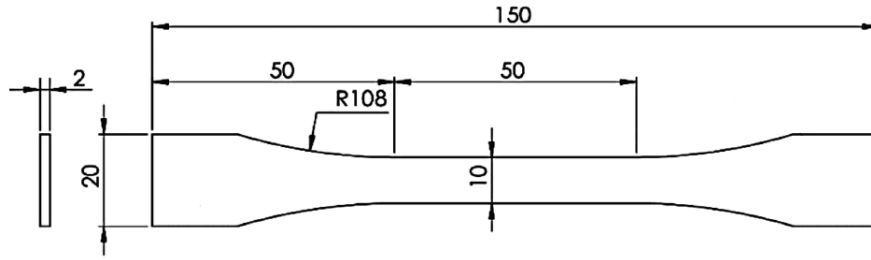
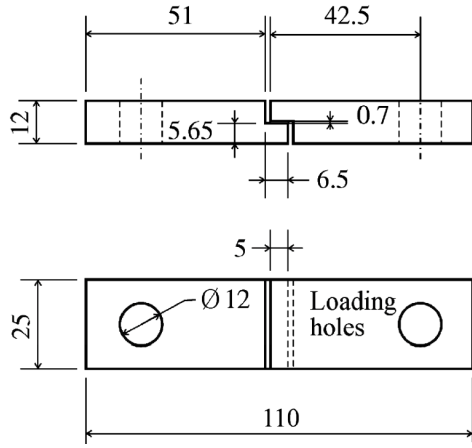


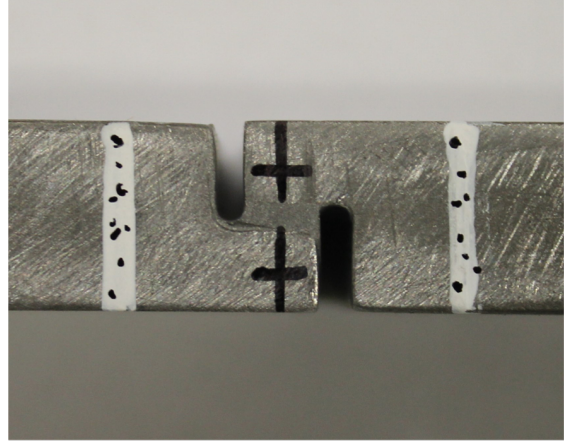
Figure 2: Technical drawing of tensile specimens' geometry, according to BS 2782 [13], dimensions in millimetres.

TAST specimens

TAST specimens were manufactured following the standard ISO 11003-2:2019 [14]. Using thick steel substrates, an adhesive joint was created with a bondline thickness of 0.7 mm and an overlap of 5 mm, as presented in Figure 3a. All substrates were grit blasted and degreased with acetone in the bonding areas to guarantee good adhesion. Calibrated tape, 1.5 mm thick, was inserted between the adherends to restrict the adhesive to the designated bondline area. To ensure the proper cure of the adhesive, all specimens were subjected to pressure and temperature using a hot plate press. To enhance the quality of the measurements made using image correlation, all specimens were painted with a high contrast auxiliary dotted pattern - Figure 3b.



(a) TAST specimen's geometry.



(b) High contrast auxiliary pattern.

Figure 3: Representation of TAST specimen, dimensions in millimetres.

DCB specimens

DCB specimens, Figure 4, were manufactured following the relevant standard [15], using hard steel adherends to prevent plastic deformation. Prior to the application of the adhesive, all substrates were grit blasted and degreased with acetone, to ensure good adhesion. The initial crack length, a_0 , was set to 45 mm and the crack itself was induced by a sharp razor blade, 0.1 mm thick, positioned in the mid-thickness of the bondline. The 0.2 mm adhesive layer thickness was ensured recurring to calibrated tapes. The adhesive was then cured under appropriate temperature and pressure conditions.

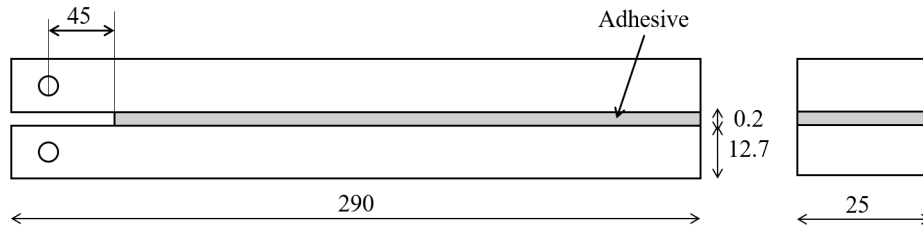


Figure 4: Representation of DCB specimens' geometry, dimensions in millimetres.

ENF specimens

The specimens used for the ENF tests have the same geometry as those traditionally used for DCB tests, Figure 4. Accordingly, all the main manufacturing procedures were similar to the previously described DCB specimens.

After curing, a small pre-crack was created, in mode I, by loading the specimen up until crack propagation was detected, measuring the new initial crack length, a_0 . This procedure is used to promote stable crack propagation during the test.

SLJ specimens

Materials For the study of the aluminium to WC/PCD adhesive joint, single lap joint specimens were used, adopting a specially designed adherent geometry. Due to the cost and flexural fragility of the PCD material, small scale specimens were manufactured considering both of the criterion above and also a proper aluminium thickness to prevent its yielding.

For the aluminium and WC/PCD substrates, a water-jet cut AW7075-T6 aluminium plate and a laser cut standardised CTB010 synthetic diamond grade wafer were used, respectively. Going forward, for simplicity reasons the tungsten carbide (WC)/polycrystalline diamond (PCD) material will be called only PCD, which is its commercial nomenclature, however it is important to state that this is a hybrid material and the adhesive will be adhering to the WC side.

Specimen design In terms of joint configuration, the adhesive layer thickness was fixed at 0.15 mm, in order to ensure that the sphere diameter controls the thickness, and both the adhesive layer overlap length and width were set as 12.5 mm and 8 mm, respectively. All other dimensions were determined taking into consideration the requirements specified above, as well as being able to be properly mounted on a in-house designed friction-based fixture system. With the rough geometry set, some additional features had to be added, such as a hole for the fixation alignment pins and in the case of the aluminium a milled surface in the region of the overlap length in order to establish the same surface conditions as those of the real milling tool holding sockets. The final dimensions of each substrate are as shown in Figure 5.

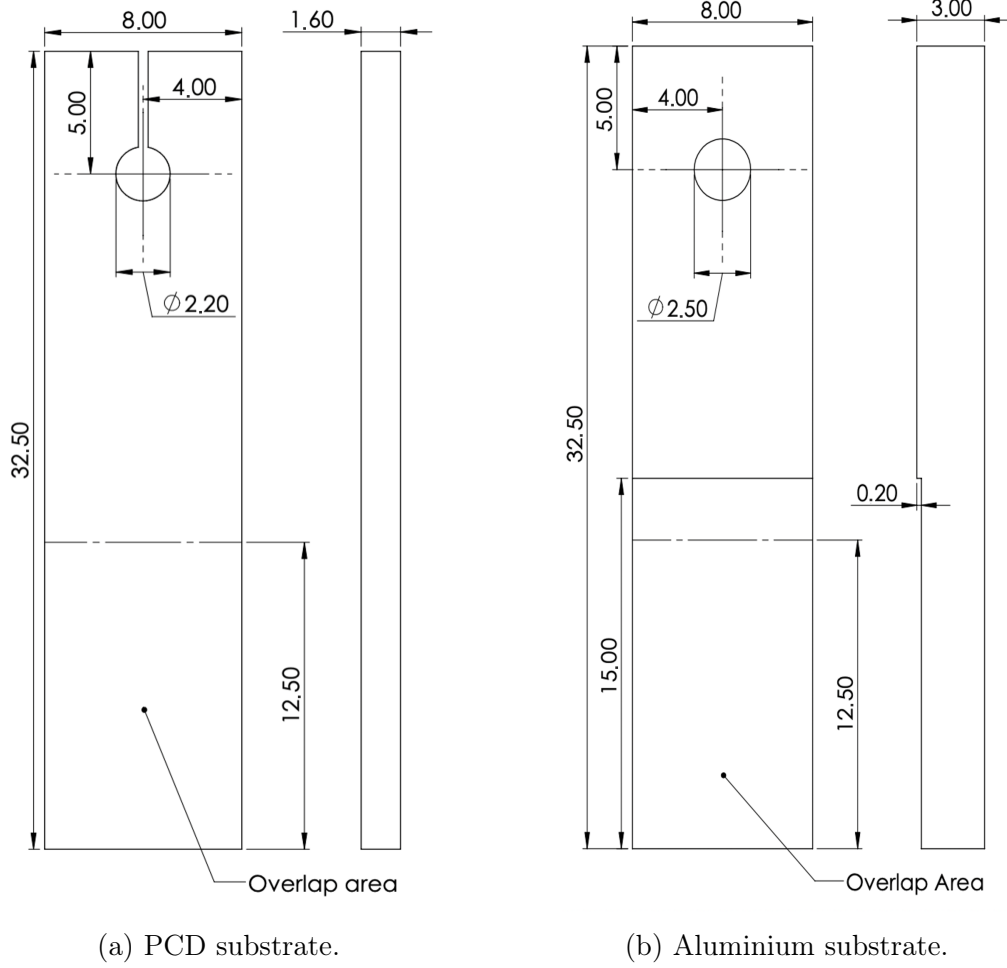


Figure 5: Technical drawings of the SLJ substrates, dimensions in millimetres.

Surface treatments To ensure a good level of adhesion to the substrates and identify the possible need for surface treatments, the surface energy of the substrates was measured through a contact angle test using an optical contact angle tensiometer.

Using the relations between surface free energies of a solid-liquid contact - Figure 6 - represented by the well-known Young equation [16]:

$$\gamma_S = \gamma_L \cos \theta + \gamma_{SL} \quad (1)$$

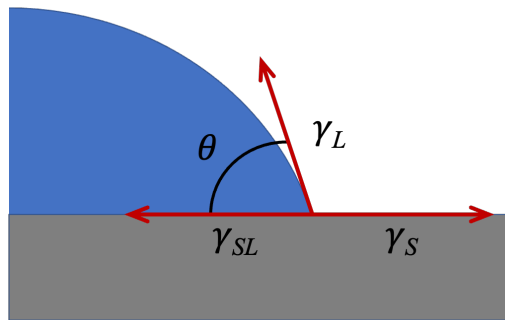


Figure 6: Contact angle at a solid-liquid-gas contact line. Adapted from [16].

and applying to it the model developed by Owens, Wendt, Rabel and Kaelble (OWRK model) [17]:

$$\gamma_{SL} = \gamma_S + \gamma_L - 2\sqrt{\gamma_S^d \gamma_L^d} - 2\sqrt{\gamma_S^p \gamma_L^p} \quad (2)$$

it is possible to calculate the solids' surface free energy, γ^S , by measuring the contact angles stabilised by three different liquids, whose disperse and polar surface energies are well known, fitting the results into a linear regression ($y = a \cdot x + b$) and extracting the disperse and polar components of the surface energy from the following expression:

$$\frac{\gamma_L(1 + \cos \theta)}{2\sqrt{\gamma_L^d}} = \sqrt{\gamma_S^p} \cdot \left[\frac{\sqrt{\gamma_L^p}}{\sqrt{\gamma_L^d}} \right] + \sqrt{\gamma_S^d} \implies \gamma_S = a^2 + b^2 \quad (3)$$

The three liquids used were water, etilenoglicol and n-hexadecane.

Fillers The adhesive under study is doped with a conductive additive, more precisely aluminium powder, however, the addition of another conductive filler will be studied to improve the electrical properties of the adhesive layer as well as controlling the adhesive layer thickness, similarly to the practical scenario of the production of milling tools. Three configurations were tested: neat adhesive (0% volume of spheres), adhesive plus 5% volume of spheres and adhesive plus 10% volume of spheres.

Manufacturing These specimens were manufactured using the already mentioned substrates, applying the surface treatments planed by the surface energy test results. Spacers were used to ensure an uniform pressure distribution and therefore guarantee the same adhesive thickness of 0.15 mm throughout the whole overlap length.

In addition, a braze-joined SLJ specimen was manufactured in the original configuration (steel/PCD) with a pure silver brazing metal. This specimen will serve as a baseline reference for the SLJ specimen tests.

A.2.3 Mechanical testing procedures

All the tests were performed using a universal testing machine, more specifically the INSTRON[®] 3367 whose load cell is capable of measuring up to 30 kN. The tensile and shear strength properties were determined at the loading rate of 1 mm·min⁻¹. Mode I and II fracture properties were determined for quasi-static conditions, 0.2 mm·min⁻¹. And the SLJ bonding tests were determined once again at a loading rate of 1 mm·min⁻¹.

Finally, for each specimens type at least three specimens were tested and its data treated.

Tensile tests

These were tested under tensile loads up until failure, Figure 7. The load displacement ($P-\delta$) curves were acquired using a load cell and an extensometer, respectively. Stress-strain curve were generated allowing the determination of the Young's modulus and tensile strength.

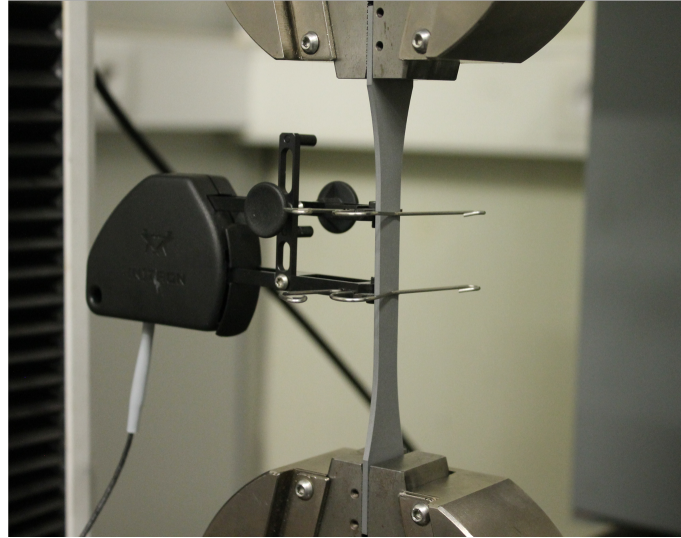


Figure 7: Bulk specimen testing setup.

TAST

Both the shear strength and modulus were obtained using thick adherend shear tests by analysing their stress-strain curves. For the data treatment, both the load and displacement were measured, being the last recorded using a camera setup - Figure 8 - coupled with a digital image correlation analysis enhanced by the previously mentioned pattern.

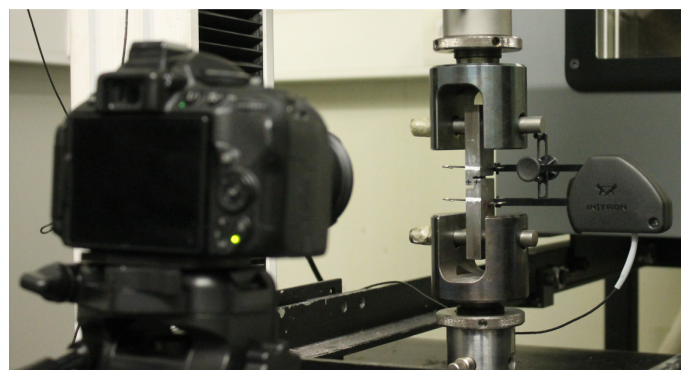


Figure 8: TAST specimen testing setup.

DCB tests

Critical energy release rate in mode I was determined using DCB tests, Figure 9, by propagating a crack in mode I up until failure, as can be seen in Figure 10. Due to the relative fragility of the adhesive used there was no need to open pre-cracks by loading the specimens prior to testing, which in certain cases help to promote a more stable crack propagation as well as a sharper pre-crack. The load displacement curves were recorded and their data treated.

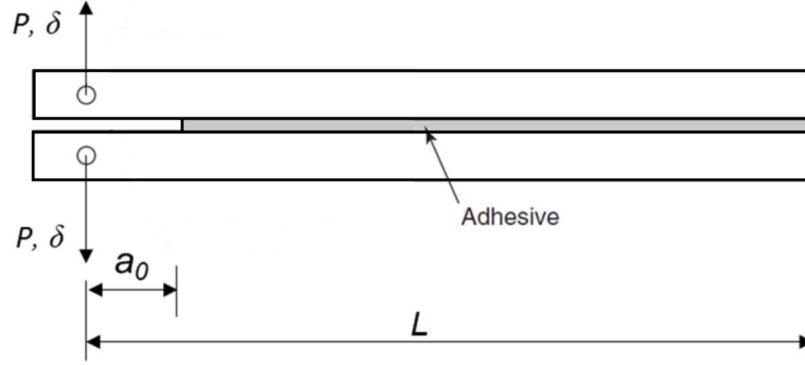


Figure 9: Representation of DCB test, dimensions in millimetres.

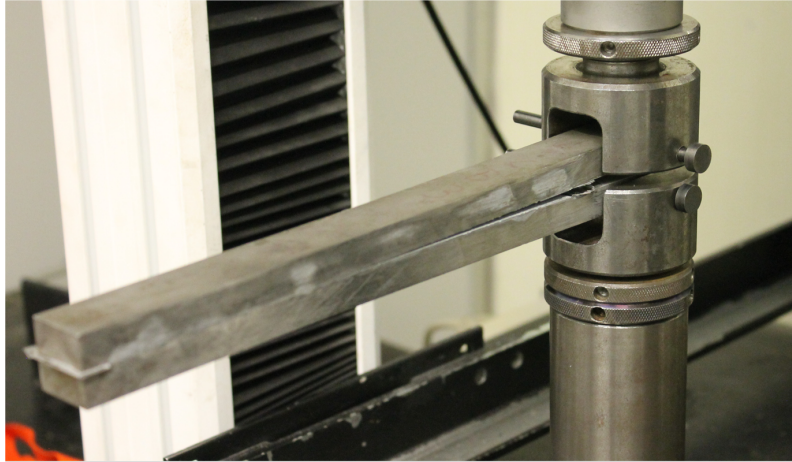


Figure 10: DCB specimen testing setup.

Energy release rate in mode I was determined using the compliance based beam method (CBBM), a data reduction scheme that has the advantage of not needing the exact crack length determination as well as taking into account the fracture process zone [18]. Considering this method, fracture energy is given by [18]:

$$G_I = \frac{6P^2}{b^2h} \left(\frac{2a_{eq}^2}{h^2E_f} + \frac{1}{5G_{13}} \right) \quad (4)$$

where P is the load applied, b the specimen width, h the thickness of the substrates, G_{13} their shear modulus, a_{eq} the equivalent crack length and E_f the corrected flexural

modulus, needed since this method does not take into account stress concentration and the substrates' rotation near the crack tip [18].

ENF tests

The fracture toughness in mode II was determined using ENF tests, Figure 11.

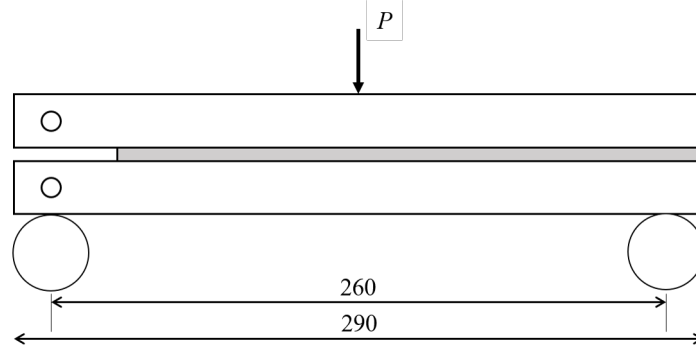


Figure 11: Schematic representation of ENF test, dimensions in millimetres.

Prior to testing, all blades were removed and a folded Teflon sheet, with oil inside it acting as a lubricant, was placed between the adherends, in the pre-crack region, to prevent the appearance of friction during the test, as can be seen in Figure 12.

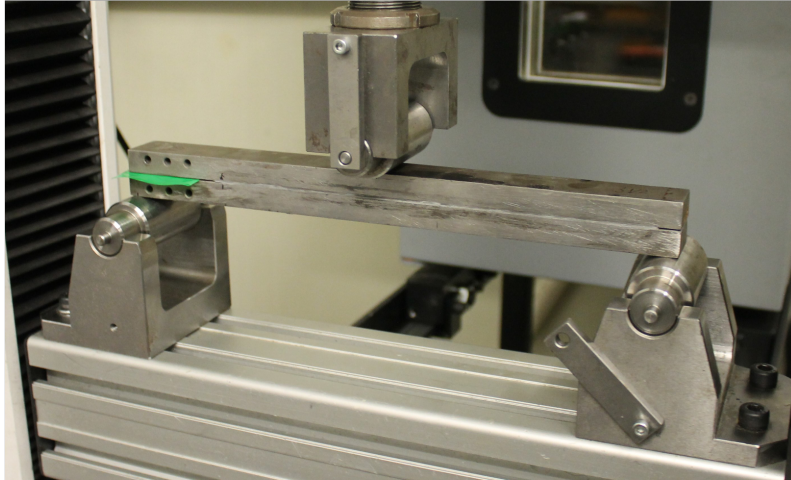


Figure 12: ENF specimen testing setup.

Load and displacement were recorded for each test, and the fracture energy was determined using the same data reduction scheme as before - CBBM. The energy release rate, in mode II, is given by [19]:

$$G_{II} = \frac{9P^2 a_{eq}^2}{16b^2 E h^3} \quad (5)$$

being P the load, a_{eq} the length of the equivalent crack, b the specimen width, E_f the corrected flexural modulus of the substrates and h their thickness.

SLJ tests

All SLJ specimens were tested under tensile loads using a dimensionally compatible friction based clamping apparatus as presented in Figure 13. Due to the poor performance of PCD under flexural stresses and the small dimensions of the specimens, to improve fixation and prevent undesired flexural stresses, tabs will be used during the SLJ tests. The positioning of both the specimens and the tabs was ensured by small alignment pins.

The tensile tests were performed as seen in Figure 13, where both load and displacement data was recorded and the fracture surfaces analysed to access their failure mode.

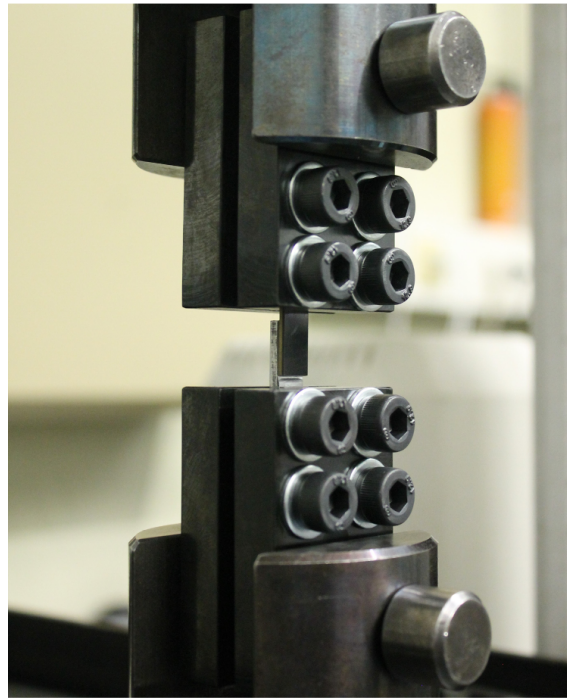


Figure 13: Complete SLJ testing setup, shown a test.

A.2.4 Electrical conductivity tests

To measure the electrical conductivity of the adhesive layer the previously described SLJ specimens were used prior to performing the tensile tests. The method used was a simple electrical resistance measurement, recurring to a multimeter capable of performing the 4 probe method, to compare the differences between the original brazed PCD/steel configuration against the adhesive joined PCD/aluminium setup with and without spheres, finding an optimal percentage to ensure that both the electrical and mechanical properties of the adhesive layer are as close as possible to the original brazed joint.

A.3 Experimental results and discussion

A.3.1 Neat adhesive characterisation

Tensile tests

The stress, σ , strain, ε , curves obtained for the tensile tests are illustrated by a representative curve shown in Figure 14, for the neat state.

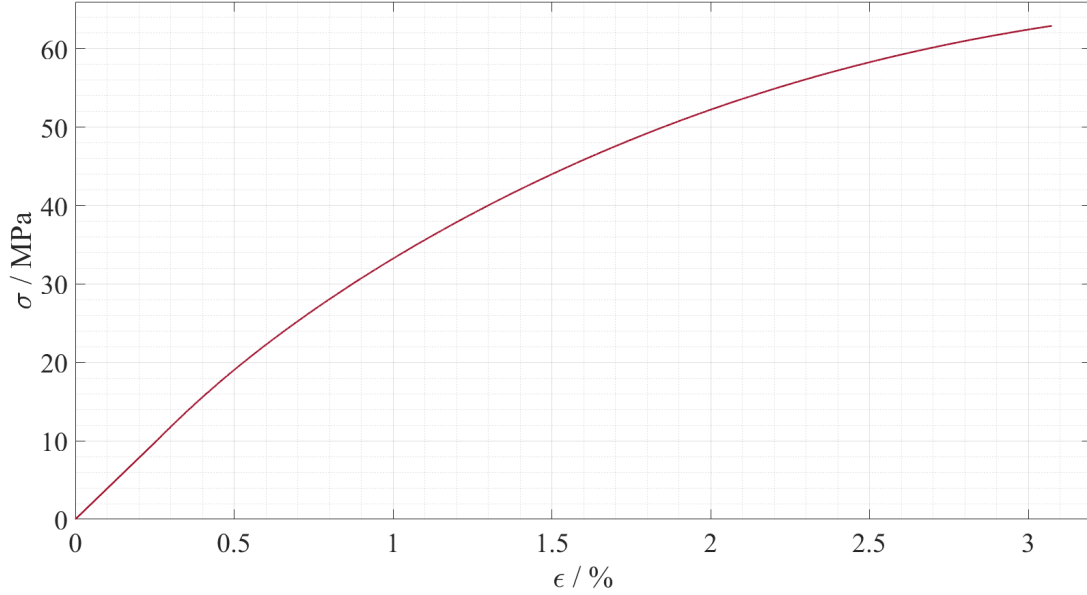


Figure 14: Representative stress-strain curve for Bulk specimens in the neat state.

Both the Young's modulus, E , and fracture tensile stress, σ_f , were extracted from the curves, whose values can be seen in Table 1.

Table 1: Young modulus, E , and maximum tensile stress, σ_f , for the Bulk specimens tested in neat state.

Configuration	E / MPa	σ_f / MPa
Adhesive neat	3880.5 ± 50.0	65.6 ± 3.8
Datasheet	3800	64
Relative error (%)	2.1%	2.5%

Comparing the results of these tests with the theoretical values supplied in the datasheet of the adhesive, limited deviations were found which validate the properties shown by the manufacturer as well as the quality of the adhesive batch used.

TAST

TAST were performed to determine shear modulus, G , and the ultimate shear stress, τ_f . The stress, τ , strain, γ , curve types obtained are shown by a representative curve presented in Figure 15, for the neat state.

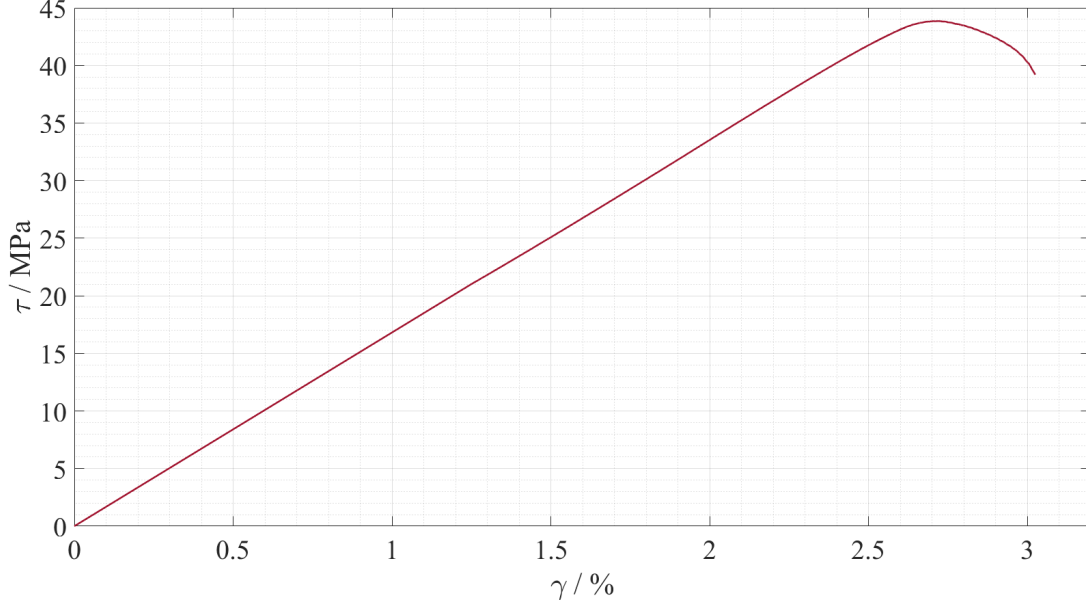


Figure 15: Representative stress-strain curve for TAST specimens in the neat state.

The apparent perfectly linear behaviour presented in the previous curve results from the method used to measure the displacements necessary to determine the shear modulus, nevertheless a more pronounced viscoelastic behaviour is expected from this type of material.

As for the values of both shear modulus and maximum stress obtained for all the testing conditions they can be found in Table 2.

Table 2: Shear modulus, G , and maximum shear stress, τ_f , for the TAST specimens tested in neat state.

Configuration	G / MPa	τ_f / MPa
Adhesive neat	1446.9 ± 148.1	41.6 ± 3.9
Datasheet - Al/Al SLJ	—	33

Since the values presented in the adhesive's datasheet do not represent the same type of test - i.e. SLJ aluminium specimens - which suffer from much higher peel stresses than the ones used to obtain the shear properties of the adhesive, the only relevance of the theoretical values is to establish a minimum threshold strength limit for the results of the TAST tests.

Both results present agreeable values, being the shear stress higher than that of the manufacturer SLJ tests, and the shear modulus returns a Poisson's ratio value of 0.34, expected for these types of materials.

DCB tests

Fracture energy in mode I was determined using DCB tests. The load displacement (P - δ) curves recorded from the universal testing machine can be seen in Figure 16, for the neat state.

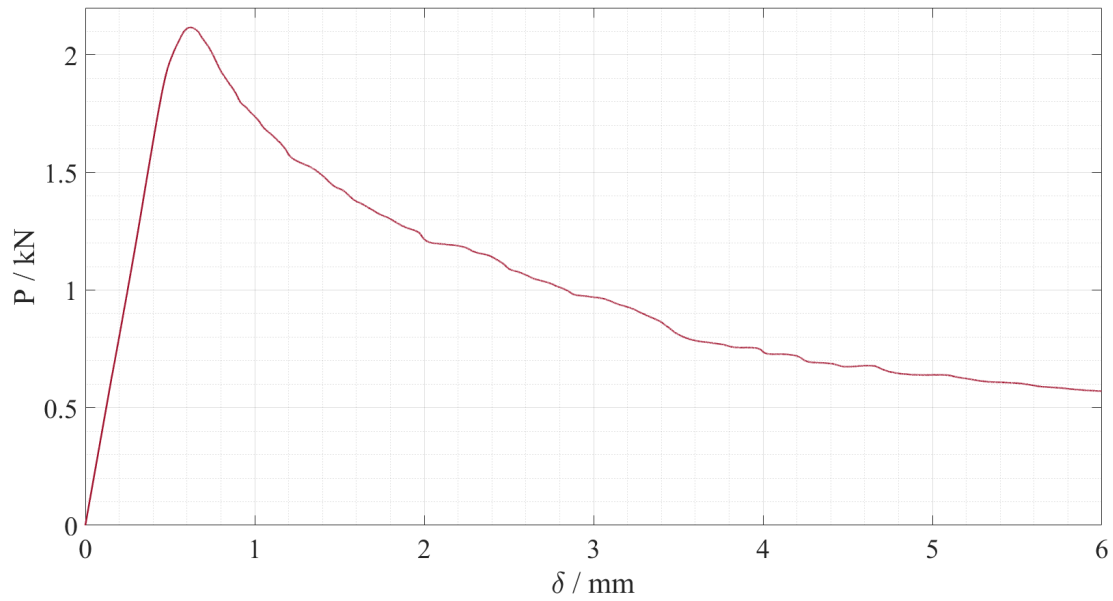


Figure 16: Representative P - δ curve for DCB specimens in the neat state.

Based on the load displacement curves, and using CBBM, the respective R-curves were determined, and consequently the critical energy release rate in mode I was obtained, Figure 17, for the neat state.

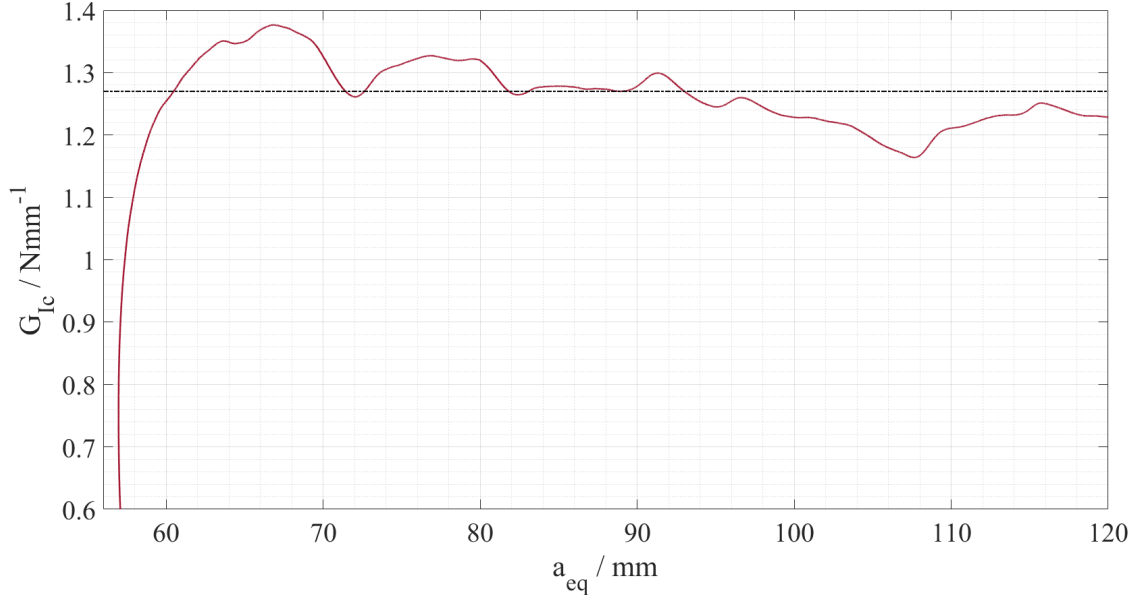


Figure 17: Representative R-curve for DCB specimens in the neat state.

A representative fracture surface can be seen in Figure 18, exhibiting the fully cohesive failure in the adhesive encountered for all specimens under study. This fracture surface presents some adhesive flow over the blade the tip, which occurred during specimen manufacturing due to the fluidity of the adhesive used. This phenomenon was not recurrent, nevertheless it is not desired and the cured adhesive was removed carefully prior to testing with a thin serrated blade in order to avoid damaging the bonded area.

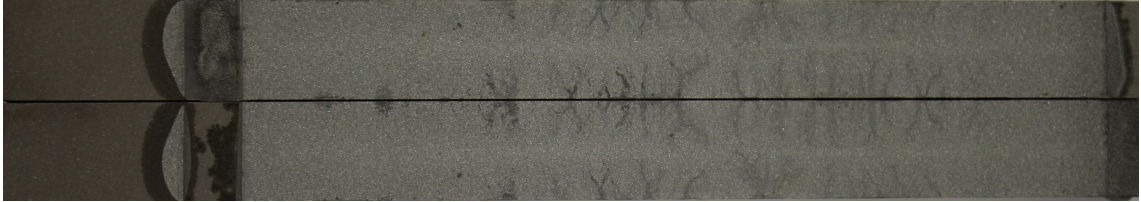


Figure 18: Representative fracture surface for DCB specimens in the neat state.

A summary of all the results obtained can be seen in Table 3.

Table 3: Mode I critical energy release rate, G_{IC} , for the neat adhesive.

Configuration	$G_{IC} / \text{N}\cdot\text{mm}^{-1}$
Adhesive neat	1.27 ± 0.05

The values obtained show that this is a tough adhesive under mode I loading, compared to other similar epoxy-based adhesives, getting close to the values obtained by certain toughened epoxies, even though this adhesive is not classified as such.

ENF tests

Fracture energy in mode II was determined using ENF tests. The load displacement (P - δ) curves recorded from the universal testing machine can be seen in Figure 19, for the neat state.

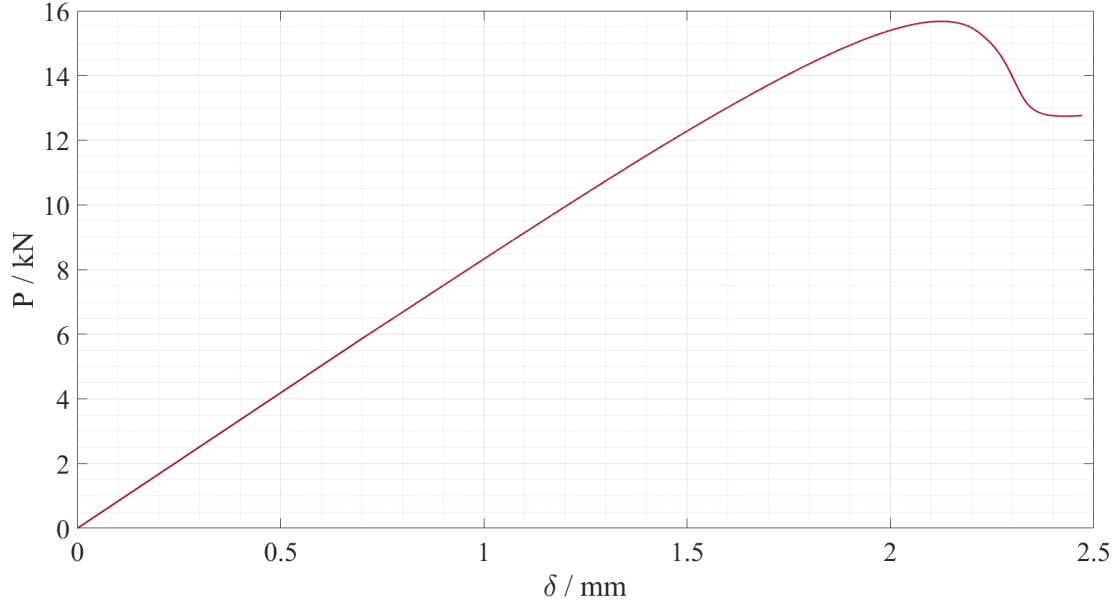


Figure 19: Representative P - δ curve for ENF specimens in the neat state.

Once again based on the load displacement curves, and using CBBM, the respective R-curves were determined, and consequently the critical energy release rate in mode II was obtained, Figure 20, for the neat state.

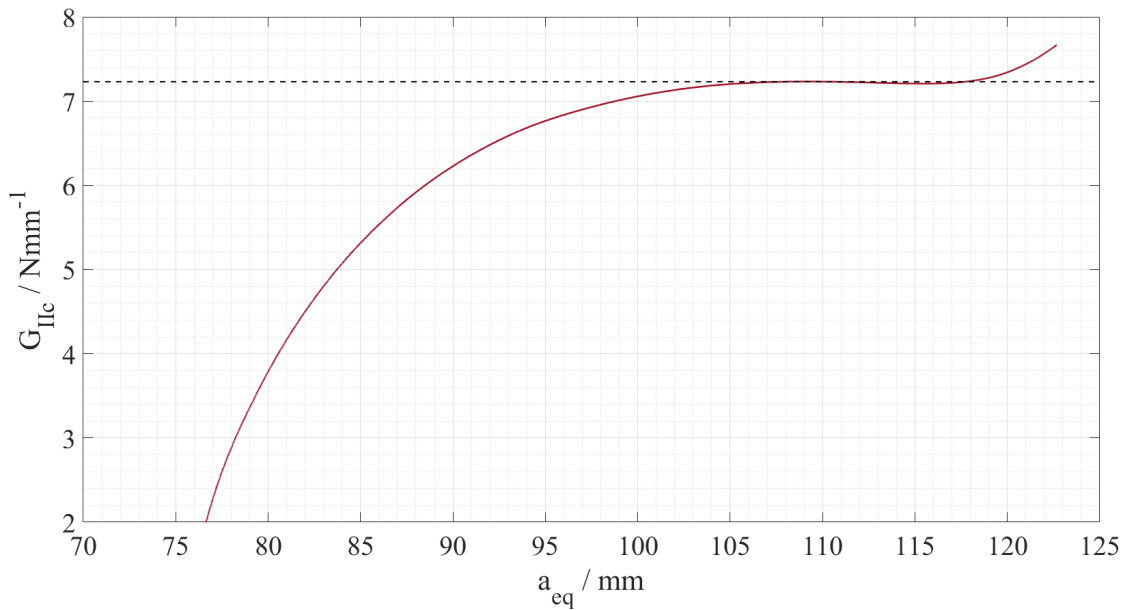


Figure 20: Representative R-curve for ENF specimens in the neat state.

A representative fracture surface of the ENF test can be seen in Figure 18, exhibiting fully cohesive failure in the adhesive. In this particular test type it is possible to distinguish the mode I pre-crack and the subsequent mode II crack propagation up until the middle of the specimen.



f

Figure 21: Representative fracture surface for ENF specimens in the neat state.

The resultant summary for energy release rate in mode II, G_{IIC} , of all specimens can be seen in Table 4.

Table 4: Critical energy release rate in mode II, G_{IIC} , of the neat adhesive.

Configuration	$G_{IIC} / \text{N}\cdot\text{mm}^{-1}$
Adhesive neat	7.22 ± 0.33

Once more the values obtained under mode II loading are typical of a tough adhesive, compared to other epoxy-based adhesives. Again, these values are also close to those shown by common toughened epoxies.

Property summary

Comparing the obtained properties with other common structural adhesives such as the Huntsman Araldite AV138 and Nagase-Chemtex XN1244, whose properties can be seen at Table 5, it is clear that the adhesive used in this study presents strength properties of a non-toughened epoxy adhesive with a fracture toughness that is closer to the values obtained for a toughened epoxy, even though it is not characterised as such. These properties are suitable for application in the milling tool industry, with good strength and stiffness, improved electrical properties due to a aluminium filler, and excellent toughness, thought to be related to the addition of the ductile aluminium powder.

Table 5: Property comparison between common epoxy structural adhesives, [20], against the neat adhesive in study.

Property	AV 138	XN1244	Studied adhesive
E/MPa	4590	5972	3880.5
σ_f /MPa	41.0	68.2	65.6
G/MPa	1559	2150	1446.9
τ_f /MPa	30.2	32	41.6
G_{Ic} /N·mm ⁻¹	0.35	0.47	1.27
G_{IIc} /N·mm ⁻¹	4.91	2.20	7.22

A.3.2 Aluminium to WC/PCD bonding

Surface treatments

Analysing the contact angle measurements in the as supplied state, Figure 22a, insufficient values of surface energy were obtained - Table 6 -, not suitable for good interfacial bonding between the adhesive and substrates. This behaviour was expected due to the fact that, for the PCD, hydrocarbon oils and other contaminants are part of the production process. These are difficult to remove with weak reagents. In the case of aluminium, the low adhesion in an untreated state is widely reported.

Accordingly, proper surface treatments had to be applied to the substrates in order to increase the surface energy values. For the PCD substrate a 4 step treatment was used, starting with a ultrasound solvent bath followed by two grades of grit blasting. This process was concluded with a second ultrasound bath. The aluminium adherends were anodised using phosphoric acid anodization (PAA) as specified in the ASTM-D3933 standard [21].

After both surface treatments were completed, the contact angles were measured once again, Figure 22a, and the surface energies of both substrates calculated - Table 6 -, presenting much higher values that are conducive for proper interfacial bonding.

Table 6: Substrate surface energy values pre and post surface treatments.

Substrate	γ_S supplied / mJmm ⁻²	Surface treatment	γ_S treated / mJmm ⁻²
PCD	32.47	Ultrasound bath	47.13
		+ Grit blasting	
Aluminium	26.98	Anodization	51.06

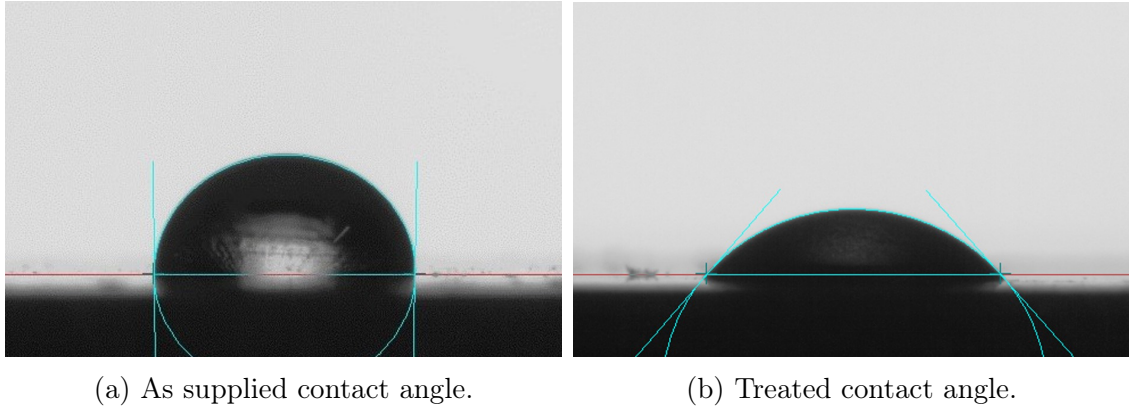


Figure 22: Representative water contact angle measurements for PCD substrates, in the as supplied and treated states.

Electrical conductivity tests

This test presented slight variations in resistance values, considered to be a product of the random spheres distribution, noticeably affecting the measurements depending on the contact points chosen and small geometrical variations during manufacturing that, due to the dimensional scale of the specimens used, resulted in the nonexistence of the electrical bridge effect created by the conductive spheres in certain locations of the overlap area. From all the tests performed, only the more consistent value ranges are presented in Table 7.

Table 7: Electrical resistance values, for the brazed and all adhesive bonded SLJ configurations.

Substrates	Configuration	R / Ω
Steel/PCD	Braze-joined	2 to 30
Aluminium/PCD	Adhesive neat	0.3×10^6 to 12×10^6
Aluminium/PCD	Adhesive + 5% spheres	4 to 340
Aluminium/PCD	Adhesive + 10% spheres	0.8 to 220

Taking into consideration the results from the original brazed configuration, the neat adhesive showed improved behaviour compared to common epoxy adhesives, nevertheless, the values measured still do not allow EDM sharpening. As for the two doped configurations, both presented significant improvements in the resistance values, producing the desired improvement in electrical conductivity of the adhesive layer.

SLJ tests

During tensile testing of the SLJ specimens, load displacement (P - δ) curves were recorded from the universal testing machine.

Considering the maximum shear stress obtained from the TAST specimen and the joint overlap area, a maximum threshold value - Table 8 - was set for the loads supported by the SLJ specimens as if the adhesive fully worked under shear, which is represented has a horizontal dashed line in the following load-displacement curves. Furthermore, a curve corresponding to the results of a steel/PCD brazed SLJ configuration was introduced in all the plots to serve as a visual basis for comparison between brazed and adhesive bonded joints. However, it is important to note that that the brazed P - δ curve does not correspond to a cohesive failure of the brazing element but to the failure of the PCD substrate, due to high flexural stresses.

Table 8: Maximum theoretical load sustained by the SLJ specimens.

Shear stress	Overlap area	$P_{max\ th}$
41.6 MPa	$12.5 \cdot 8\text{ mm}^2$	4.16 kN

Starting with the neat adhesive configuration the P - δ curves are presented in Figure 23, and a representative fracture surface in Figure 24.

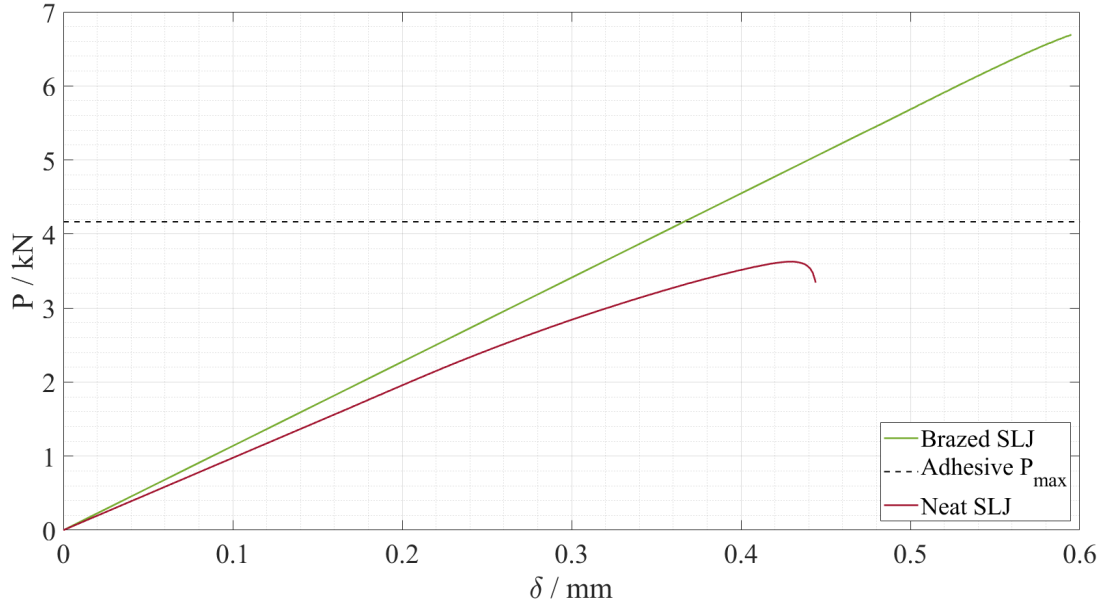


Figure 23: P - δ curves for SLJ specimens, braze-joined versus neat adhesive configuration.



Figure 24: Representative fracture surface for SLJ specimens in the neat state.

The mean load values obtained in this configuration were the highest from all the configurations tested, however, most fracture surfaces showed partial adhesive failure mostly in the aluminium, meaning that the interfacial adhesion is still weaker than that of the adhesive cohesive bonds. Since these specimens are uneven both in thickness and stiffness of each substrate the stress distribution will be affected, however, the exact behaviour of stress distribution is not yet clear. Studies on this topic show differences in the stress distribution of both dissimilar thickness and stiffness specimens, presenting an expected tendency for higher peel and shear stress values at the end of the thicker adherend and at the end of the less stiff adherend - [22, 23] - implying opposite effects that can balance themselves, making it difficult to assess the expected behaviour in this specific case.

For the 5% spheres content configuration the P - δ curves are presented in Figure 25, and a representative fracture surface in Figure 26.

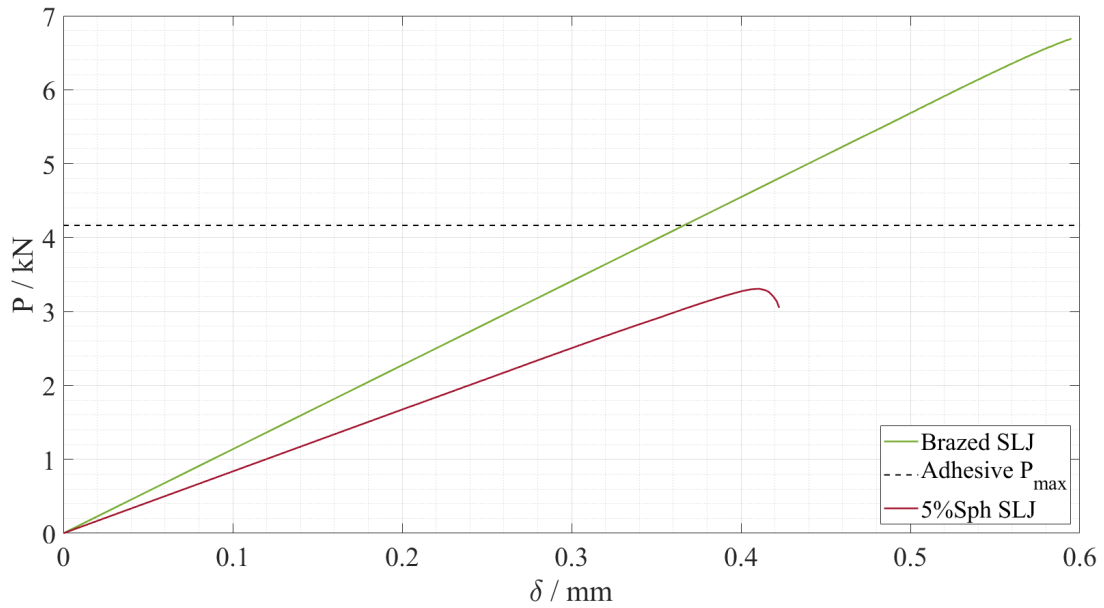


Figure 25: P - δ curves for SLJ specimens, braze-jointed versus 5% sphere configuration.



Figure 26: Representative fracture surface for SLJ specimens with 5% sphere content.

With 5% sphere content, the specimens started to show improved fracture behaviour with 100% cohesive failure, however mean load values dropped by approximately 6% compared to the neat adhesive.

Finally the 10% spheres content configuration the P - δ curves are presented in Figure 27, and a representative fracture surface in Figure 28.

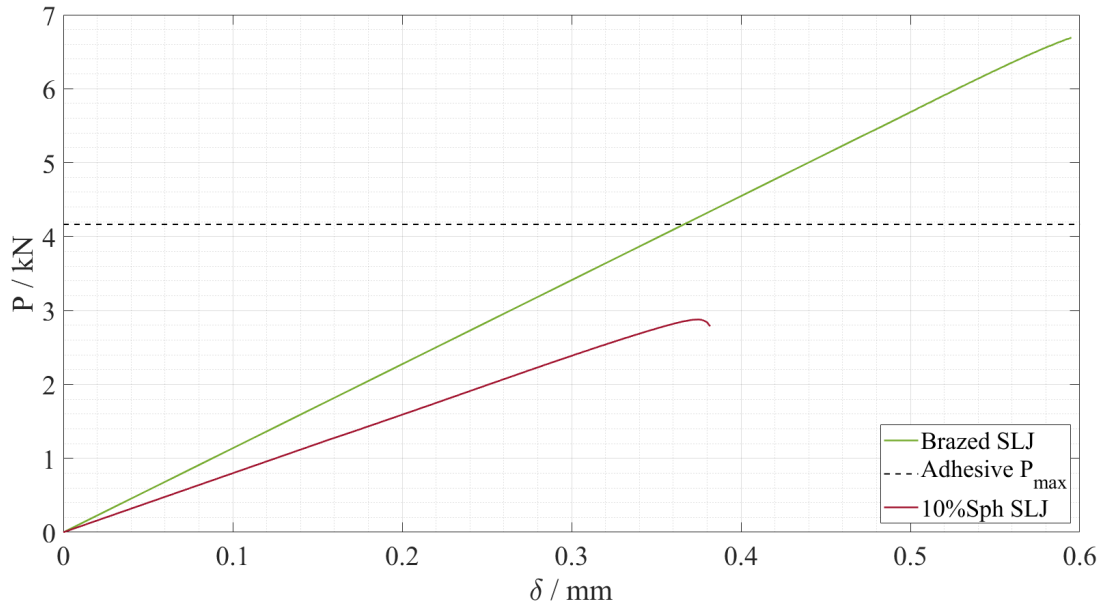


Figure 27: P - δ curves for SLJ specimens, braze-jointed versus 10% sphere configuration.



Figure 28: Representative fracture surface for SLJ specimens with 10% sphere content.

Once again, but with 10% spheres content, specimens showed 100% cohesive failure, however mean load values decreased even more showing approximately 17% of reduction in terms of load resistance.

The previous plots clearly demonstrate the strength and compliance differences between the braze and bonded joint. At a first glance, the limited performance of

the bonded joint might seem to preclude its use in milling tools, however, most of these applications rely on designs with extremely high safety factors, which provides a margin for the implementation of a joining solutions with lower overall strength but that can still provide other decisive advantages.

As a summary of the results obtained in all test configurations the maximum load values are displayed in Table 9.

Table 9: Maximum load values, of the SLJ specimens in each configuration.

Configuration	P_{max} / kN
Adhesive neat	3.383 ± 0.188
Adhesive + 5% spheres	3.168 ± 0.178
Adhesive + 10% spheres	2.808 ± 0.196

The decrease in strength with the addition of higher volumes of spheres is supported by the data shown in Figure 29.

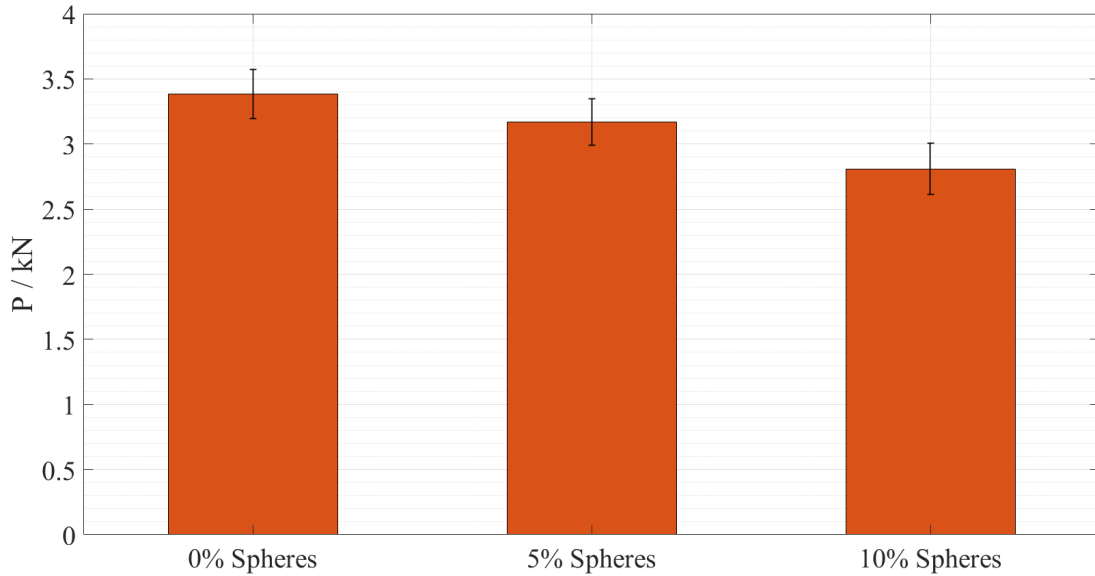


Figure 29: Statistical trend of the maximum load with each configuration.

A.3.3 Adhesive recharacterisation with optimised sphere content

Considering the small difference in terms of electrical resistance between the 5% and 10% volume of spheres, and taking into account that the resistance variation between the neat and 10% spheres content more than triples in relation to the same comparison with the 5% spheres configuration. Thus, the 5% configuration

presented it self as the best choice for the final adhesive configuration and has been recharacterised. The results of this process are shown in this subsection.

Tensile tests and TAST

When considering the curing process of the specimens with 5% of spheres content, concerns related with the spheres settling process appeared, since when applying the Stokes law to calculate the settling velocity a high value was obtained for the current manufacturing time frame. Therefore, neither tensile nor TAST specimens with 5% spheres content were manufactured and tested, due to concerns related with non uniformity of the sphere distribution in these specimens which rely in relatively thick adhesive layers, limiting the correct correlation between the experimental results and the expected behaviour of the ideal specimens.

Table 10: Relevant properties for the settling velocity of the conductive spheres in the adhesive under study.

Material	ρ / $\text{g}\cdot\text{cm}^{-3}$	μ / $\text{Pa}\cdot\text{s}$	d / μm
Adhesive	1.42	140	—
Conductive spheres	2.52	—	150

The settling velocity was calculated using the relevant proprieties presented in Table 10 through Equation 6, resulting in the following value for the settling velocity:

$$V_t = \frac{g \cdot d^2 (\rho_{sph} - \rho_{adh})}{18 \cdot \mu} = 0.006 \text{ mm min}^{-1} \quad (6)$$

As previously said this value of settling velocity was considered to high for the current cure cycle and respective specimen type, not allowing for a uniform sphere distribution, making so that both tensile and TAST specimen with this optimised were not manufactured.

DCB tests

Fracture energy in mode I was determined using DCB tests. The load displacement (P- δ) curves recorded for the universal testing machines can be seen in Figure 30, for the 5% sphere configuration.

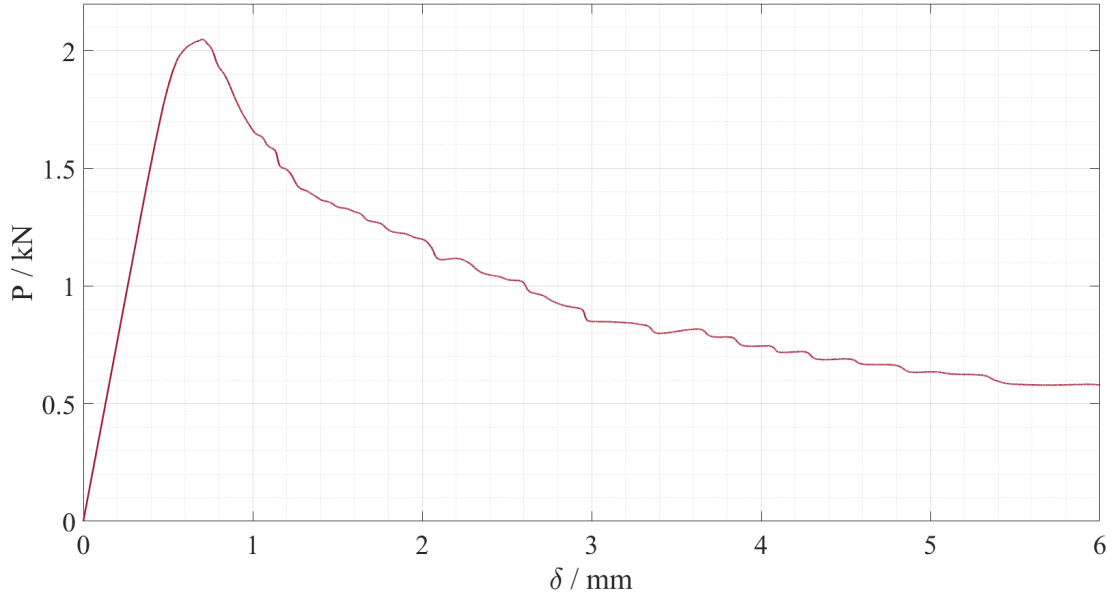


Figure 30: Representative P - δ curve for DCB specimens in the 5% sphere configuration.

Based on the load displacement curves, and using CBBM, each the respective R-curve was determined, and consequently the critical energy release rate in mode I was obtained, Figure 31, for the 5% sphere configuration.

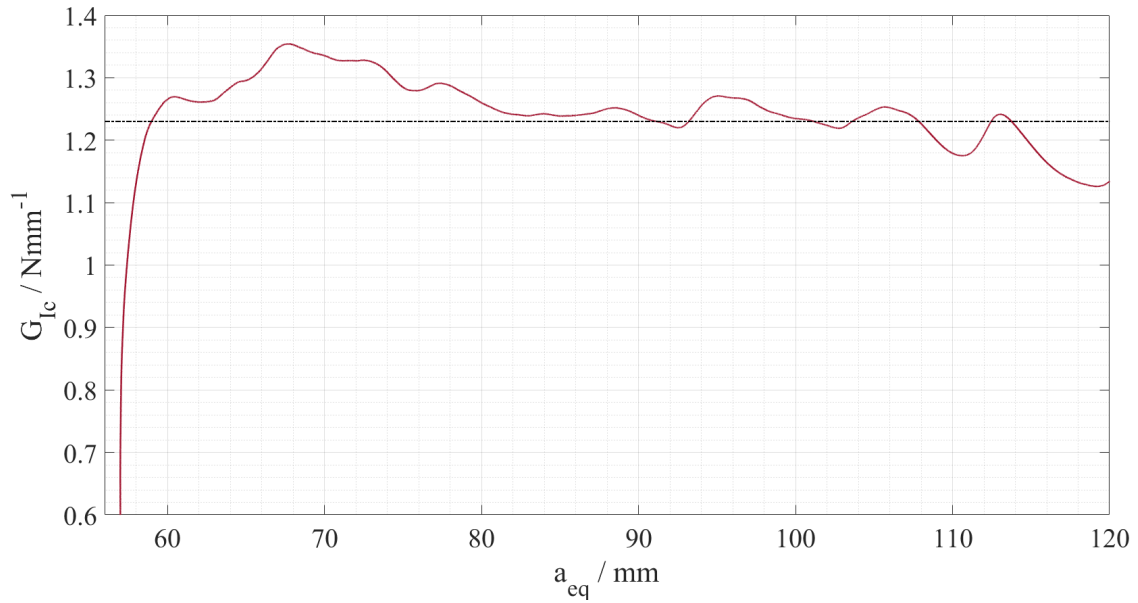


Figure 31: Representative R-curve for DCB specimens with 5% sphere content.

A representative fracture surface of a DCB test can be seen in Figure 32, exhibiting fully cohesive failure in the adhesive, as all specimens did.

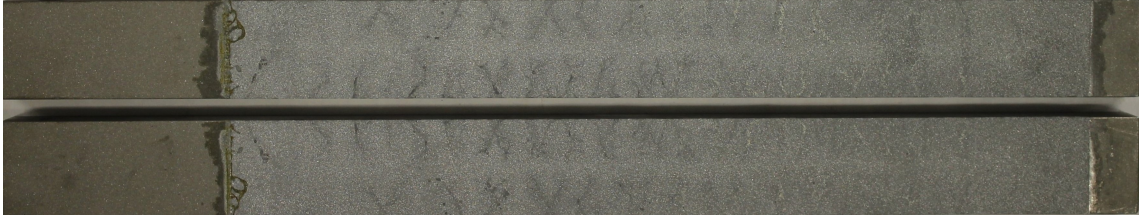


Figure 32: Representative fracture surface for DCB specimens with 5% sphere content.

The summary of the results obtained for all tests can be seen in Table 11.

Table 11: Mode I critical energy release rate, G_{IC} , for the 5% sphere configuration.

Configuration	$G_{IC} / \text{N}\cdot\text{mm}^{-1}$
Adhesive + 5% spheres	1.23 ± 0.03

Comparatively to the previous neat tests the addition of 5% volume of spheres only decreased the fracture toughness, G_{IC} , by about 3.15%, continuing to present a good behaviour under mode I crack propagation.

ENF tests

Fracture energy in mode II was determined using ENF tests. The load displacement (P - δ) curves recorded for the universal testing machines can be seen in Figure 33, for the 5% sphere configuration.

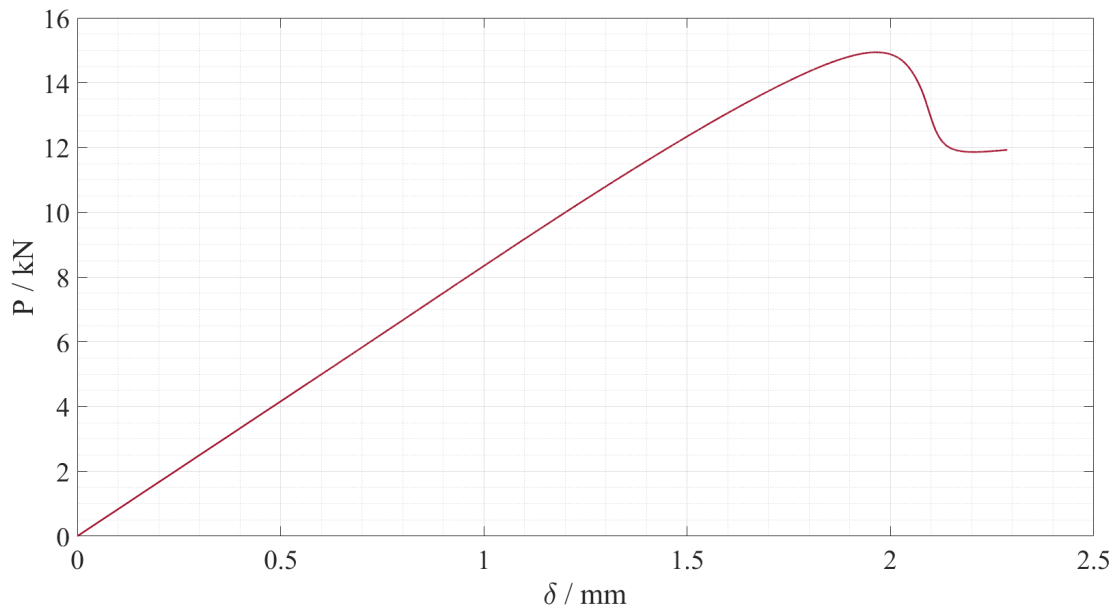


Figure 33: Representative P - δ curve for ENF specimens with 5% sphere content.

Once again based on the load displacement curves, and using CBBM, each respective R-curve was determined, and consequently the critical energy release rate in mode II was obtained, Figure 34, for the 5% sphere configuration.

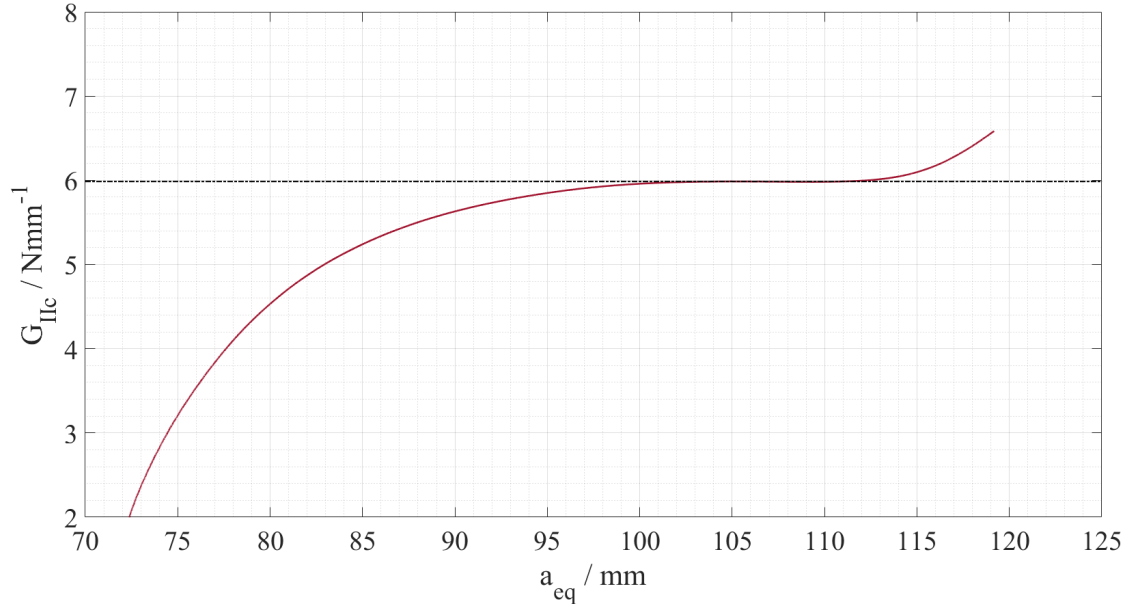


Figure 34: Representative R-curve for ENF specimens with 5% sphere content.

A representative fracture surface of a ENF test can be seen in Figure 35, exhibiting fully cohesive failure in the adhesive, as all specimens did. In this particular test type it is possible to distinguish the mode I pre-crack and the subsequent mode II crack propagation up until the middle of the specimen, even though this visual effect was less pronounced in this configuration.



Figure 35: Representative fracture surface for ENF specimens with 5% sphere content.

The summary of all results for energy release rate in mode II, G_{IIC} , can be seen in Table 12.

Table 12: Critical energy release rate in mode II, G_{IIc} , of the adhesive with 5% sphere content.

Configuration	G_{IIc} / N·mm ⁻¹
Adhesive + 5% spheres	6.17 ± 0.27

By adding 5% volume of spheres, the decrease in fracture toughness, G_{IIC} , was higher, by about 14.5%, showing a higher sensibility to mode II propagation but still continuing to present a high level of resistance to mode II crack propagation.

A.3.4 Conclusions

This study had as its main objective the study of the bonding process between aluminium and WC/PCD. For that purpose, the adhesive chosen was fully characterised, both in the neat state and with an optimised sphere content. The bonding process was evaluated to determine the need for surface treatments, adhesive layer electrical resistance, strength and fracture behaviour, from which the following conclusions were taken:

- From all the properties studied, the chosen adhesive stood out in terms of toughness, since the values obtained were comparable to those of a toughened epoxy, even though it is not classified as such;
- Both of the materials used require proper surface treatments in order to attain a good level of adhesion and avoid interfacial failures;
- By increasing the V% of spheres in the adhesive layer its electrical conductivity improved when compared to the neat state, but the measured conductivity values were much less uniform than those obtained for the brazed joint, with a large dependence on the location of the measurement points;
- Both the joint's resistance and compliance decreased for higher spheres content. However, the fracture behaviour changed from partially adhesive to fully cohesive;
- Fracture toughness decreased for 5% of spheres content, but remained within the range of tough adhesive;
- Joint level testing demonstrated that bonded tools will have lower cohesive resistance when compared to brazed ones, implying a possible need for tool redesign.

Overall, this work successfully demonstrate that aluminium to WC/PCD bonding is possible with proper surface treatments, recommending a 5% volume of conductive spheres configuration as the best balance between mechanical performance and electrical properties.

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B Paper B

Numerical optimisation of bonded joints for the manufacture of edge milling tools

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Edge milling tools for processing wood are currently assembled using brazing or a mechanical joining process, connecting the cutting insert to the tool body. However, the demand for lighter tools has led to a growing interest in changing the joining process from brazing to adhesive bonding, as this methodology allows for the use of lighter tool bodies, machined from aluminium alloys. The design of these tools and its bonded connections benefits from the creation of numerical models, able to predict the stresses generated due to centrifugal forces and determine the performance of the joint. In this work, models using cohesive zone modelling (CZM) were created, allowing to predict the mechanical performance of this type of joint. Since the CZM approach used in ANSYS® Mechanical™ is based on a contact debonding mechanism, the CAD model had to be adapted to allow this simulation. Considering a single bit simplification of the full milling tool, the model was modified in order to be comprised of four components, an aluminium body, the WC/PCD insert and two separate adhesive joints per insert, one at the bottom and another at the back of the bit, each divided into two separate layers to allow the contact debonding mechanism.

To optimise the joint geometry, a parametric design simulation was performed using the simplified single bit model of the full milling tool. This numerical simulation considered three different geometrical input parameters, the bit's height, holding notch angle and length, and evaluated the stresses generated as the output parameter/criterion. Due to the large amount of possible combinations, an iterative approach was adopted, focusing on optimising the height and angle first, considering them as primary input parameters and afterwards analysing another parameter considered as secondary, the length. The added cost per bit comparing it to the already commercialised corresponding tool was also analysed qualitatively. The loading condition used was based on the overspeed test, required by the EN 847-1 standard.

The developed model highlighted the large safety factor present in the original, base-line design, demonstrating that adhesive bonding can lead to a highly durable and resistant milling tool. The developed model also allowed to optimise some of the key design parameters, while providing paths for minimising the tool's manufacturing cost and ensuring maximum performance.

B.1 Introduction

Edge milling tools for processing wood are composed of a solid body to which a varied number of inserts (or bits) is connected. The inserts are composed of a very hard material, highly sharpened and are responsible for performing the cutting action. Currently, these inserts are joined to the body via a brazing or a mechanical joining process, however, the demand for lighter tools has led to a growing interest in changing the joining process from brazing to adhesive bonding, as this methodology can facilitate the use of lighter tool bodies, machined from aluminium alloys. In current industrial practice, the design of these tools is carried out with the assistance of numerical models, able to determine the stresses generated on the tool components and evaluate joint performance.

Most of the numerical models developed for adhesive bonding in the machining tool industry focus either on their thermal behaviour [1–3] or the workpiece surface roughness [4]. However, most of the tests used to assess the strength of the bonded joints are experimental in nature [5] and do not employ numerical modelling.

The concept of a cohesive zone model (CZM), originally proposed by Barenblatt [6] and Dugdale [7], evolved during the past few years into a robust method that allows the modelling of non-linear processes while avoiding stress singularities, dispensing the existence of pre-cracks and the need for user interference for its propagation to occur [8]. Since then, it has been mostly used to simulate adhesive and composite failure under static, dynamic and cyclic loading conditions. Although the use of CZM to analyse the strength of milling tools has not been extensively documented, it is an important tool to accurately simulate the adhesive's behaviour in the creation of a novel generation of bonded edge milling tools. Furthermore, the tools using numerical construction are highly over-engineered, having room for geometrical optimisation.

In the Ansys[®] Mechanical[™] FEA software, cohesive zone models (CZM) make use of contact elements to establish contact debonding, in which two surfaces are bonded with a layer of CZM elements. This material's behaviour is based on damage mechanics, taking into account continuum and fracture mechanics, to study damage initiation and propagation, respectively. Cohesive zone models are typically based on elements with no thickness, which establish the connection between two solid surfaces and are modelled by damage variables that, after a stress criterion is satisfied, are used to simulate material degradation by applying a softening process based on a fracture energy criterion, up until failure occurs.

Debonding allows three modes of separation, mode I (debonding for normal separation), mode II (debonding for tangential separation), and mixed mode (debonding for normal and tangential separation) where a power law defines the mode mixity of the loading conditions, as seen in Equation 1.

$$\left(\frac{G_I}{G_{Ic}}\right)^{\frac{\alpha}{2}} + \left(\frac{G_{II}}{G_{IIc}}\right)^{\frac{\alpha}{2}} = 1 \quad (1)$$

The behaviour of the adhesive is then simulated using suitable traction-separation laws. These can be shown as a graphical representation of the adhesive properties - Figure 1.

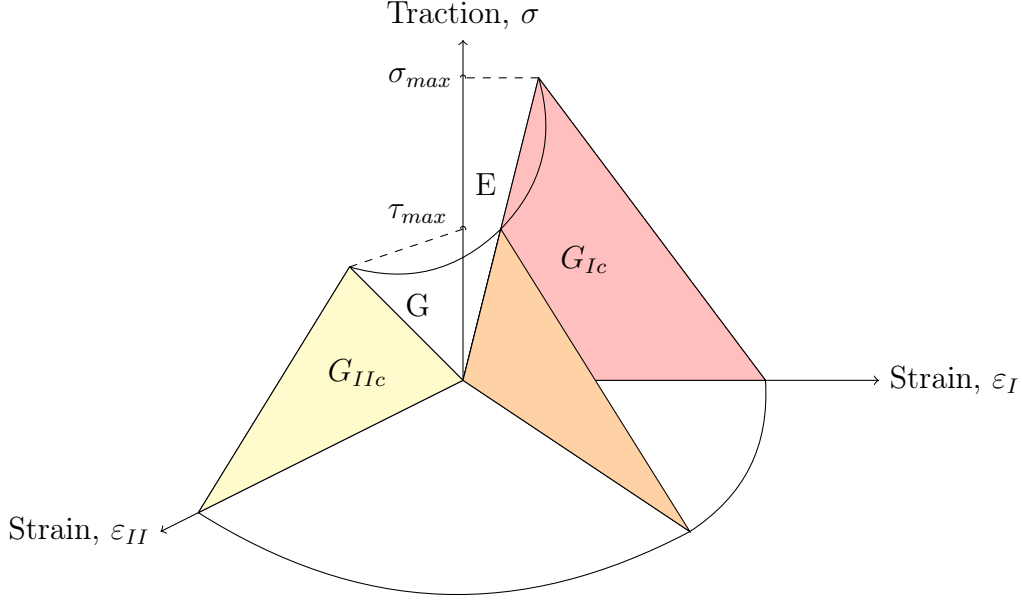


Figure 1: Schematic 3D representation of mode mixicity for triangular traction-separation laws between pure mode I (red), pure mode II (yellow).

Since most loading conditions result in CZMs loaded under mixed mode conditions, a bilinear material behaviour based on the model proposed by Alfano and Crisfield [9], can be defined using the following properties: normal, E , and tangential, G , stiffness's; maximum stresses under normal, σ_{max} , and tangential, τ_{max} , loading; and critical fracture energies in mode I, G_{Ic} , and mode II, G_{IIc} .

The following work consists of a numerical study of a milling tool constructed using PCD inserts bonded to an aluminium body, through a parametric simulation on Ansys[®] Workbench[™]. The model used simulated the adhesive layers recurring to the CZM approach. Three geometrical parameters were analysed and optimised studying their effect on the stresses felt by the adhesive layer, achieving the best compromise between performance, cost and manufacturing concerns.

B.2 Numerical model

A static structural parametric analysis of a milling tool was initially performed using the ANSYS[®] Workbench[™] 2021 R1 commercial software, using mainly the Mechanical[™] application. The following block diagram ruled this parametric simulation, Figure 37.

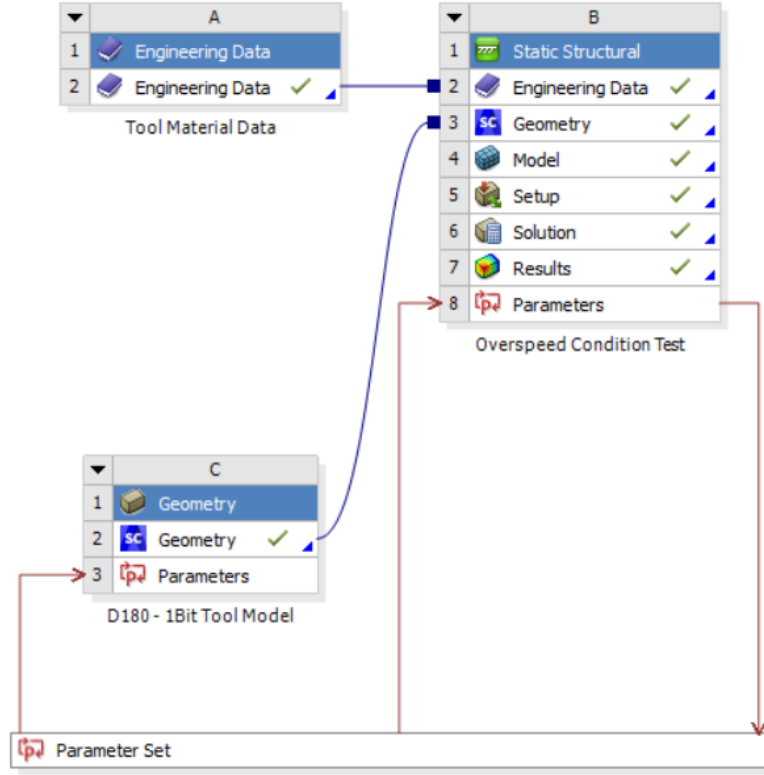


Figure 2: Block structure of the ANSYS® Workbench™ software, for a parametric simulation.

Materials

The materials used in this simulation follow those listed in the work of Correia, [10], where aluminium to PCD adhesive bonding was studied. Both the aluminium (AW7075-T6) and the PCD (CTB010) were considered to have an elastic, isotropic behaviour, fully defined by the Young's modulus and the Poisson's ratio. The material's density was also introduced in the model in order to account for the inertial loads.

Due to the complexity of the geometry, both adhesive layers were loaded in mixed mode in a condition between pure mode I and pure mode II. Therefore, the adhesive follows a mixed mode CZM behaviour with fracture-energy based debonding. The value for the artificial damping coefficient - η - used was 1×10^{-5} s, tangential slip under compression - β - was not considered, and the power law exponent - α - was kept at the default value of 2, corresponding to a linear behaviour. The adhesive's density was also considered, allowing to simulate the inertial behaviour of the tool.

All of the material properties used are displayed at Table 1.

Table 1: Input properties of the materials used in the numerical study.

Type	Property	Adhesive	Aluminium	PCD
Inertial	ρ / gcm^{-3}	1.47	2.80	4.08
Elastic	E / MPa	3880.5	71000	1000000
	ν / —	—	0.33	0.10
	G / MPa	1446.9	—	—
Cohesive	σ_f / MPa	65.6	—	—
	τ_f / MPa	41.6	—	—
	G_{Ic} / Jmm^{-2}	1.23	—	—
	G_{IIc} / Jmm^{-2}	6.17	—	—

Geometry

The milling tool model, with a nominal diameter of 180mm, was created by considering that all inserts are located at the same distance from the rotational axis, being subjected to the same inertial loads, therefore simplifying the model to a single bit configuration - Figure 3. The model considers an aluminium body of 180 mm of nominal diameter, the PCD bit and two separate adhesive joints, one at the base and another at the back of the insert, each divided into two separate layers to allow contact debonding. The design parameters - holding notch's height (H), base angle (θ) and length (L) - were parametrically embedded in the model allowing geometry changes within the stipulated ranges, being their original values 2mm, 15° and 14mm, respectively.

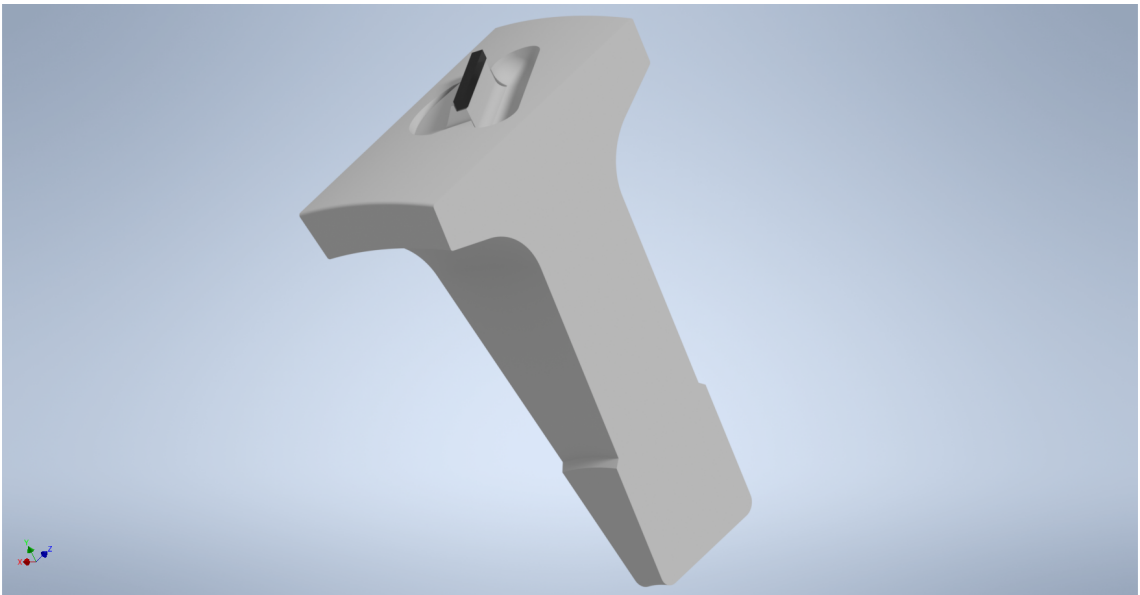


Figure 3: One bit partial edge milling tool 3D model obtained with Autodesk Inventor®.

Connections

Proper connections were established between the adherend-adhesive interfaces - bonded contact pair with the augmented Lagrange formulation method - and the adhesive layer's halves - bonded with the pure penalty formulation method.

Mesh

Suitable meshes were applied to the adherends and adhesive - Figure 40 - each with its own mesh parameters, divided into the vertical (w_V) and horizontal (w_H) width directions, as well as the length's (l). All the adherends and adhesive edges parallel to one of the specified directions were meshed with same number of divisions, corresponding to the regions near the adherend-adhesive interfaces.

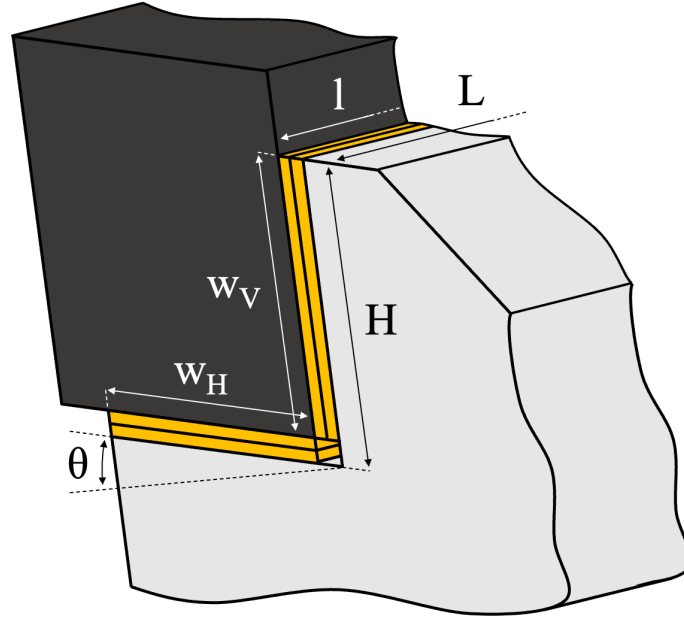


Figure 4: Schematic representation of both the geometrical and mesh input parameters used in the simulation.

A regular mesh was generated in the proximity of the adhesive layers, resorting to both face meshing and edge sizing on the adherends and adhesive layers. The sizing commands were based on a biased number of divisions with factors of 5 for vertical and horizontal directions, and 10 for the length's. An example of type of meshing used can be seen in Figure 5.

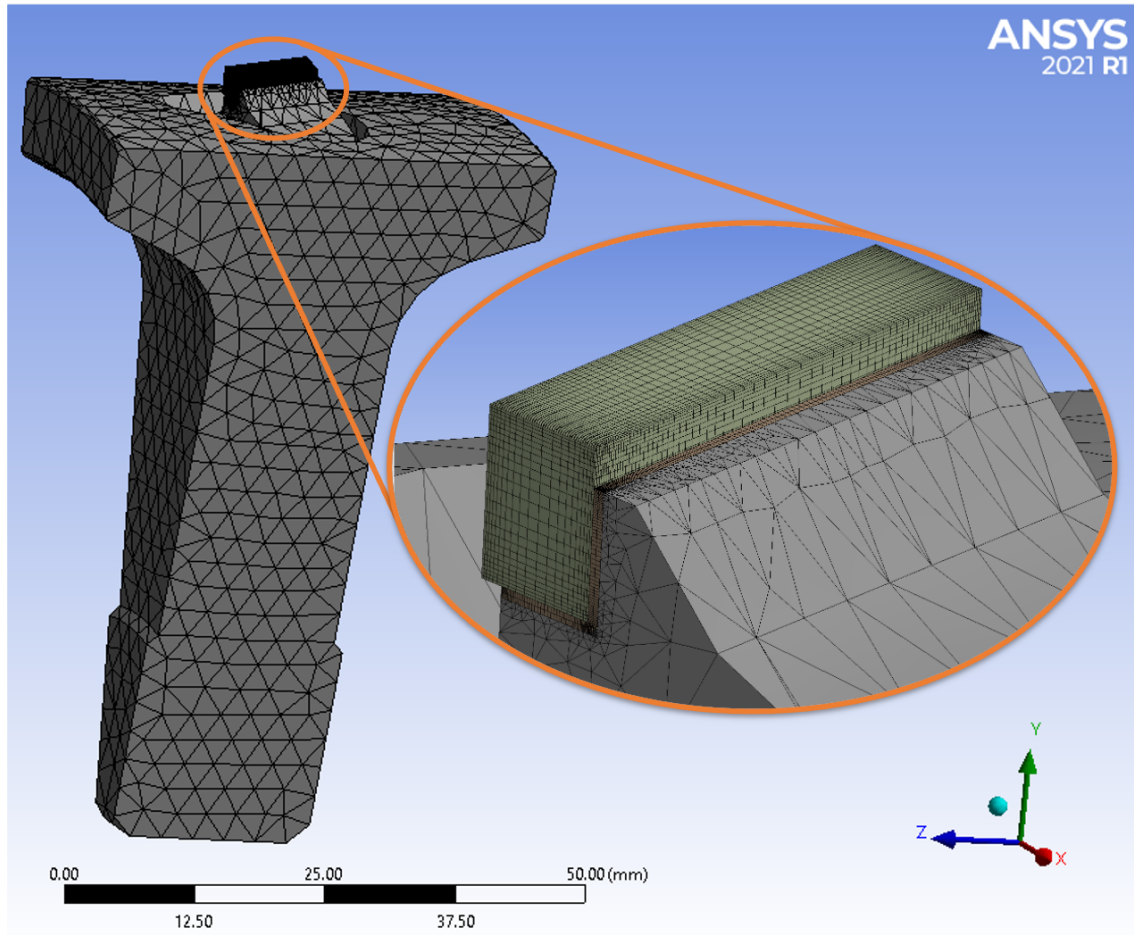


Figure 5: Representative model mesh used in ANSYS® Mechanical™ for the parametric analysis.

The elements used were 8-node linear 3-D structural solid elements - SOLID185 - for the regular solid bodies (adhesive and PCD insert), and 4-node linear 3-D structural solid elements - SOLID285 - for the irregular aluminium body. And for all the bonded connections, 8-node linear 3-D surface-to-surface contact/target element pairs were used - CONTA174/TARGE170.

The mesh convergence was evaluated taking into consideration the influence of both the adherends and the adhesive mesh refinement in separate. The final converged mesh density was maintained throughout all of the parametric design points.

Loading and boundary conditions

In woodworking tools, the most severe stresses acting on the tools bonded layer are due to centrifugal loads. Considering the safety validation test defined by the EN 847 standard, an overspeed loading condition was set to 19000 rpm in accordance to the tool's diameter 180mm and maximum work peripheral cutting velocity allowed of 90 ms^{-1} .

To facilitate the model convergence, the load step was subdivided into small time increments with a minimum and maximum time steps of $5 \times 10^{-4} \text{ s}$ and $1 \times 10^{-2} \text{ s}$,

respectively.

The boundary conditions consisted of a cylindrical support at the tool's shaft hole, where radial, tangential and axial movements were set as fixed, and a radial symmetry condition, created by restricting displacement in the normal direction to each symmetry face.

Parametric simulation

To optimise the joint geometry, a parametric design simulation was performed using the previously defined model. This numerical simulation considered 3 geometrical input parameters, the holding notch's height (H), base angle (θ) and length (L), and evaluated the generated stresses as the output parameter/criterion.

The stresses were obtained through localised maximum stress probing in the contact surfaces where CZM was applied. There, the maximum principal stresses (σ_1) were measured to evaluate the severity, direction and disposition of the stresses through vectorial analysis. Other than that, the normal (σ) and tangential (τ) components of the stresses generated in the adhesive layer were extracted from local referential systems to better understand the mode mixicity felt by the adhesive layer.

Due to the large amount of possible combinations under analysis, an iterative approach was adopted, focusing on optimising the height and angle first, considering them as primary input parameters, and afterwards analysing another parameter considered as secondary, the length. Also the added cost per bit due to the changes in geometry was qualitatively analysed.

A summary of the input parameter ranges can be seen in Table 2, as well as the used output parameters.

Table 2: Parametric analysis details.

Parameter	Analysis	Parameter	Range	Step
Input	Primary	Support height (H/mm)	[1.0; 3.0]	0.5
		Base angle ($\theta/^\circ$)	[0; 30]	15
	Secondary	Bit length (L/mm)	[8; 16]	2
Output	Quantitative	Stress _{Back layer} (σ_1, σ, τ /MPa)	-	-
		Stress _{Base layer} (σ_1, σ, τ /MPa)	-	-
	Qualitative	Bit price (BP/€)	-	-

B.3 Numerical results and discussion

B.3.1 Primary parametric simulation

For the presented primary design analysis, five height (H) and three angle (θ) values were evaluated, resulting in 15 design points. The maximum principal stresses obtained from each one are presented in Figure 6, as for the normal and tangential components the values retrieved from the simulation are shown in Figure 7.

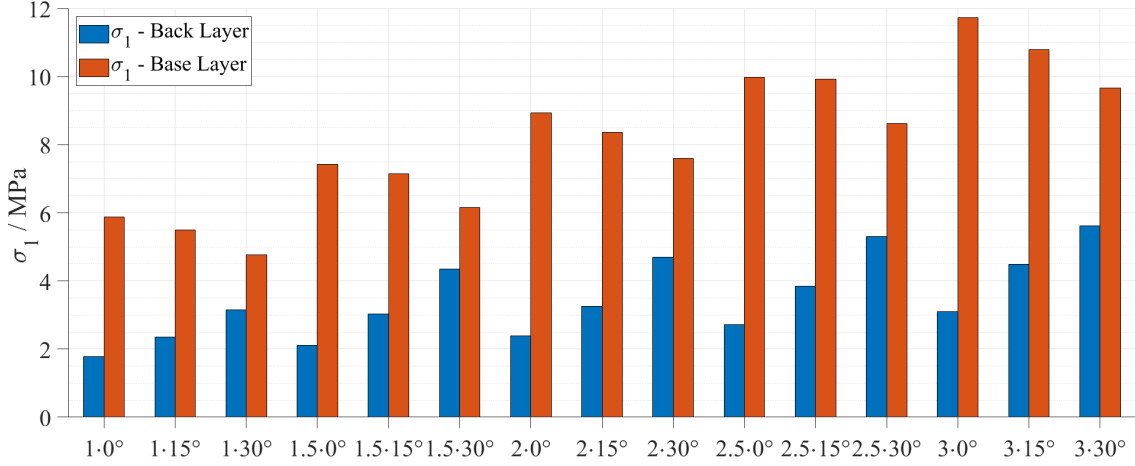


Figure 6: Parametric design results for the maximum principal stresses as a function of the height, H, and angle, θ .

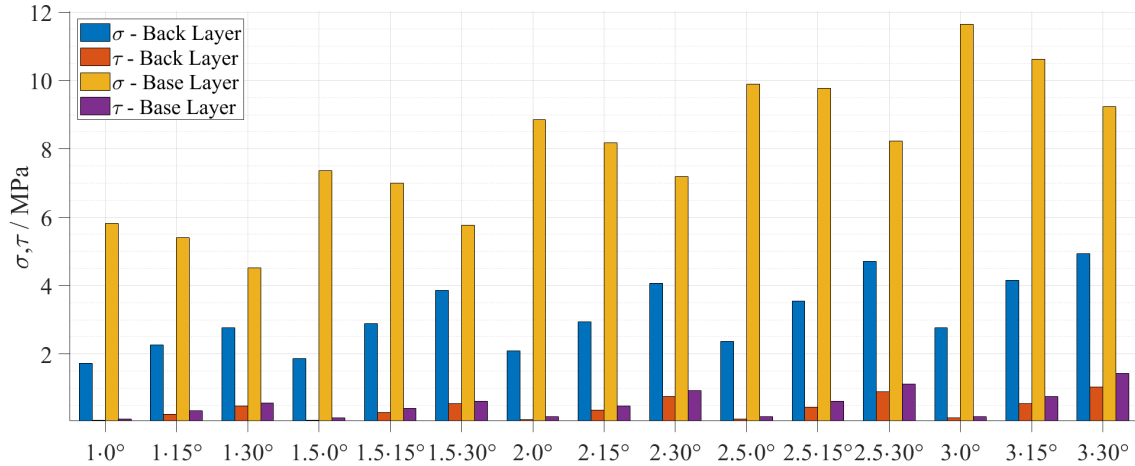


Figure 7: Parametric design results for the normal and tangential stresses as a function of the height, H, and angle, θ .

Analysing both the maximum principal stresses and respective component values, it was possible to understand that increasing the holding notch's height does not improve the joint behaviour, since the plot shows that all of the stresses progressively increased for each respective three design points. This was due to the

fact that the heavier the bit gets the higher are the stresses imposed to the adhesive joint, especially in the base layer that has shown itself as the main load support of the bonded tool for this loading condition. Therefore, as for the H value, the previous statements showed that this parameter could only be maintained or reduced, allowing to improve the inserts performance as well as reducing material costs.

Another phenomenon showed by this initial model was the effect of the base angle, acting as a maximum principal stress regularisation factor that relieves the stresses on the more critical base layer, transferring part of the inertial load to the back layer. An analysis of the normal and shear stresses, shows an inverse behaviour as the angle increases, where the normal stresses become progressively closer and both shear stresses increased slightly, presenting a well defined shift in the joint's behaviour. In the end, for this parameter it became clear that increasing θ was the best option for improving the models performance.

Taking into consideration the industrial requirements of these milling tools - enough height is need to allow several sharpening sweeps as well as a sufficiently high frontal area to be able to use a high precision touch probe to calibrate the positioning of the insert prior to the EDM sharpening process - the height and base angle chosen for proceeding into the second stage of this design test were, 2mm and 30° , respectively.

B.3.2 Secondary parametric simulation

Following the final configuration for the primary parametric simulation, the results of the secondary study on both the maximum principal stresses, and the normal and tangential components are presented in Figure 8 and 9, respectively.

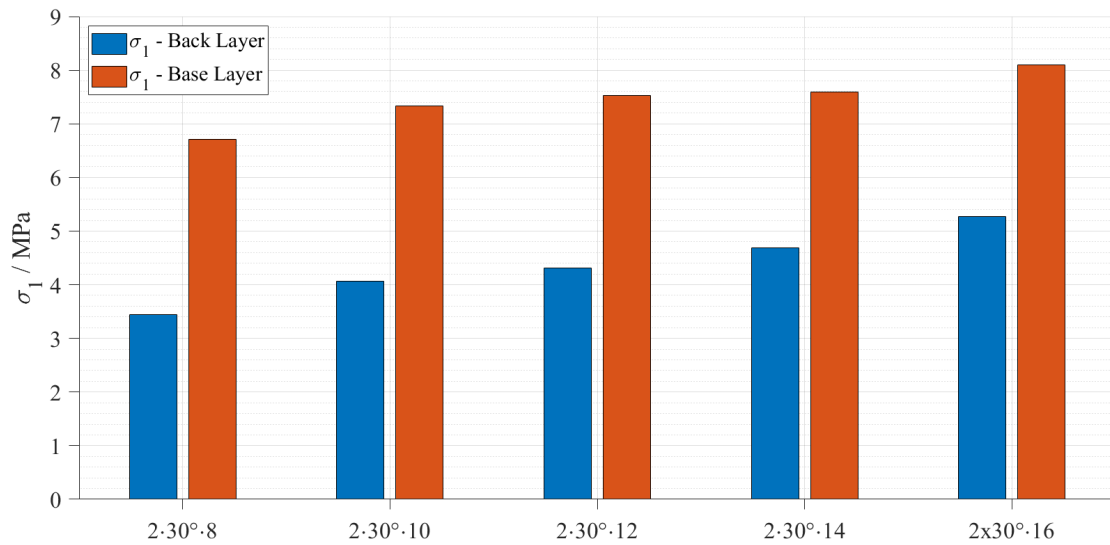


Figure 8: Parametric design results for the maximum principal stresses as a function of the length, L.

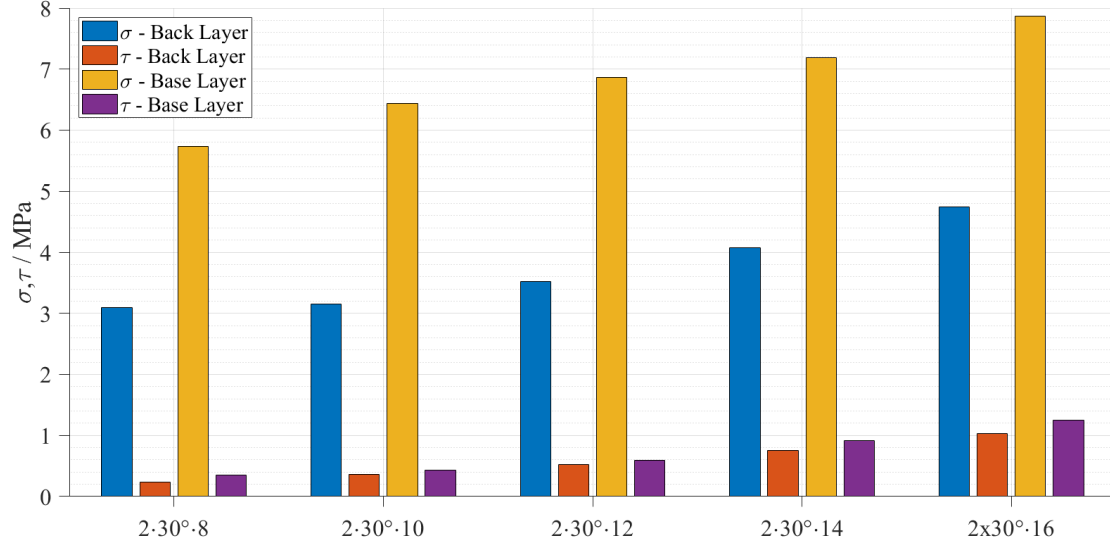


Figure 9: Parametric design results for the normal and tangential stresses as a function of the length, L .

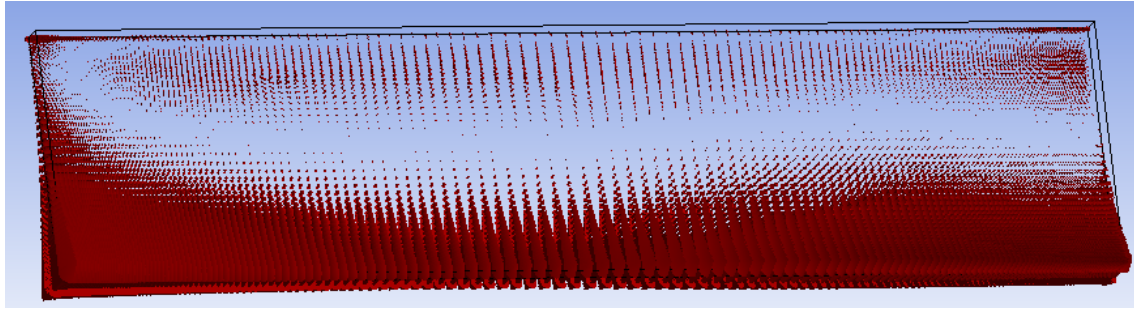
When comparing results for this model, as expected, the variation in the maximum principal stress was directly correlated with the bit's weight, since a larger bit length increases the weight, resulting in higher centrifugal loads. A similar behaviour was found for both the normal and shear components and, therefore, no relevant statistically trend was identified by this secondary study.

The model clearly shows that reducing the bit's length improves the stresses generated in the adhesive and, also importantly, reduces the tool's cost. However, large reductions in length might imply additional tool redesigns, in order to either maintain or change the tools width due to incompatibilities in the bit's cutting edge superposition, which ultimately, might require the addition of extra bits and costs.

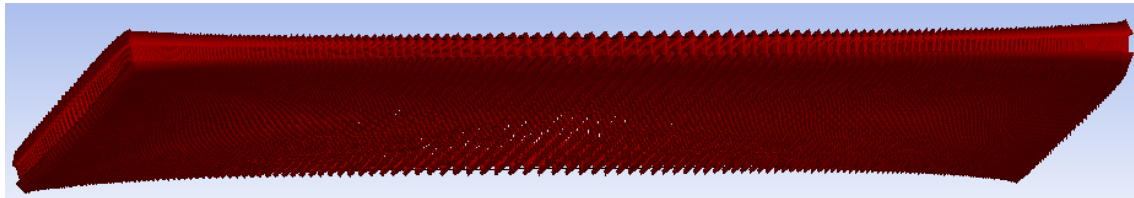
Therefore, the length of the bit was maintained at 14mm, thus defining the possible geometrical optimisations as changes in the base angle.

B.3.3 Stress distribution analysis

To better understand why the most severe stress components were normal in orientation, especially in the back layer, and to visually evaluate the stress distributions in the adhesive instead of only the maximum values, representative vectorial plots for each layer are presented in Figure 10.



(a) Back layer.



(b) Base layer.

Figure 10: Representative vectorial scheme of the maximum principal stress for both adhesive layers.

Analysing the effect of inertial loads on the maximum principal stresses measured in the back layer - Figure 10a - it was possible to determine that only the bottom half of the adhesive layer is being heavily loaded, more precisely through normal stresses. This phenomenon can be justified by the holding notch's back angle, that, as seen in Figure 11, does not follow the centrifugal force's direction creating an effective lever at the back adhesive layer's highest point, forcing the bit to rotate on itself. This rotation creates a torque that intensifies the normal stresses at the bottom of the back adhesive layer, validating the previously described behaviour.

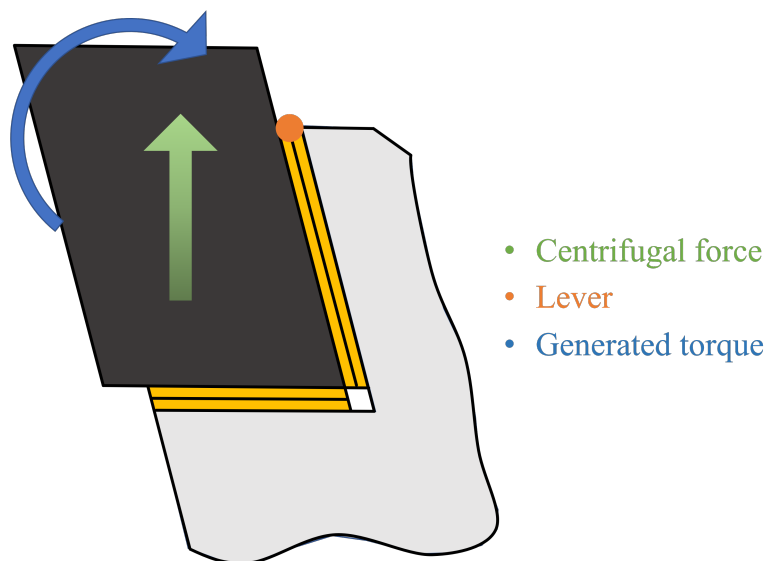


Figure 11: Schematic representation of the insert's inertially induced torque.

As for the base layer - Figure 10b - it becomes evident that the whole adhesive is being mostly subjected to normal stresses, since the centrifugal force acts almost perpendicularly to the adhesive layer. Nevertheless, the previous conclusions taken from the primary analysis - where by increasing the base angle the performance of the joint is improved - can be justified, not only by change in the angular difference between the centrifugal load and the base layer - increasing the shear stress component - but also by improving the counteracting effect on the previously reported insert rotation - where the base layer mechanically supports part of the generated load by the torque - proving the previously reported regularisation behaviour in the primary analysis.

Although these stress distributions varied for different design points, the same main behaviour was detected in all of them.

B.3.4 Validation of joint cohesion under overspeed condition using CZM

Besides being used for the stress analysis, the CZM elements were used to directly determine if the two adhesive layers present in the optimised joint configuration suffered damage when subjected to the overspeed condition. To this end, the loads acting on the adhesive layers were reported as a function of the rotational velocity of the complete tool and, simultaneously, the level of damage on the bonded layer was monitored. These results are reported in Figure 12

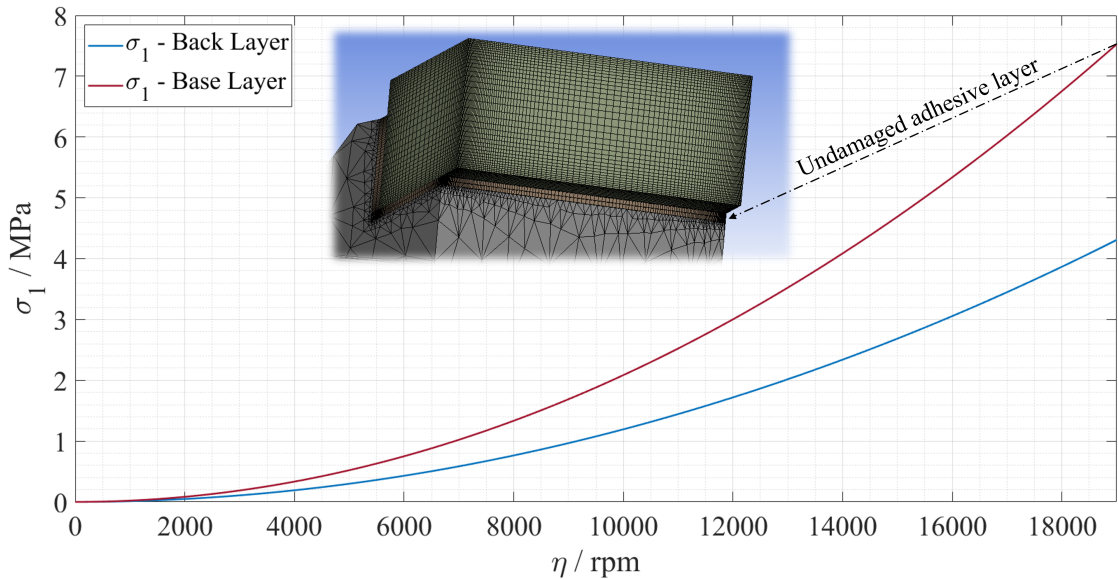


Figure 12: Stresses acting on the adhesive layers as function of the rotational speed of the tool. Undamaged state of the adhesive layer in the overspeed condition (inset).

As reported before, the results clearly indicated that the bottom adhesive layer is loaded more severely during the test, mainly under peeling, mode I loads, directly resulting from the centrifugal loads created during the overspeed condition. There is

no indication of failure or damage in the adhesive layer for this configuration, which is expectable, since the stresses acting on this layer are well below of the peak tensile and shear stresses supported by the adhesive. This modelling approach showed that both adhesive layers have sufficient strength to support the loads associated to the overspeed testing, thus validating the design. The numerical determination of the ultimate failure load of the adhesive layer was also attempted using this model. However, the model suffered from severe convergence issues at rotational speeds much higher than those associated to the overspeed condition, which precluded the estimation of a theoretical limit for the tool strength.

B.3.5 Safety factor

Considering the respective maximum principal stresses of the final configuration, it is possible to calculate a safety factor based on the Rankin criterion, also called maximum principal stress criterion, considering that the material fails if σ_1 is higher than the ultimate tensile strength of a bulk tensile test specimen, specified in Table 1. The safety factors for both layers are displayed in Table 3.

Table 3: Safety factors for the final configuration considering the Rankin criterion.

Parameter	σ_1 / MPa	Safety factor
Base	7.59	8.6
Back	4.69	14

From these values it is possible to see a highly over-engineered joint, which corroborated the previous statement that no adhesive damage or failure is estimated in this model for the loading condition used.

B.3.6 Conclusions

With the purpose of understanding the stresses to which the adhesive joint was subjected to in service conditions, as well as optimising the tool's geometry, a parametric design simulation was carried out using Ansys[®] Workbench[™]. Three geometrical parameters were optimised, taking into account the stresses generated in the adhesive layer, as well as a qualitative evaluation of the tools cost. From this study the following conclusion were drawn:

- The main stresses acting on the adhesive layer are normal stresses;
- Both the height and length increases the stresses acting on the joint, mainly due to the fact these represent an important increase of the weight of the inserts;

- The angle θ was the most relevant design parameter, allowing the uniformisation of the normal stresses and imposing improved shear behaviour;
- For the overspeed rotational speed considered no failure was detected, irrespective of the joint configuration, since the inertial loads still represent low values, demonstrating the suitability of this joining technique for the practical application.

The developed model allowed to optimise some of the key parameters, providing paths for minimising the tool's manufacturing cost while ensuring adequate performance. A large safety factor was also found to be present in this bonded tool design which, although below that of a brazed configuration, still allows for the production of a highly durable and resistant milling tool.

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C Paper C

Practical implementation and validation of a novel process for manufacturing milling tools using adhesive bonding

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Although adhesive bonding is widely used in diverse applications, from aerospace structures to electronic assembly, its application in the production of edge milling tools is still quite limited. Nonetheless, the inherent advantages of adhesive bonding do have the potential to represent a valid alternative to the brazed construction used in these tools. To this end, the adhesive joint must fulfil three main requirements. The first is ensuring that applicable safety standards are respected, the second guarantee enough electrical conductivity in the joint to be compatible with an electrical discharge machining (EDM) sharpening process and finally the possibility of using an induction based cure process, increasing the flexibility of the production not recurring to templates for each tool model produced.

In order to validate the practical applicability of this joining process, the cure cycle was firstly studied, considering two possibilities, a safer induction pre-cure followed by a longer oven cure at low temperature to finalise the cure process or a full cure at high temperature using only induction which was not documented for the adhesive used. To characterise the adhesive polymerisation at different temperatures several differential scanning calorimetry (DSC) tests were performed, one continuous ramp up until degradation and three isothermal tests at different temperatures.

The electrical conductivity of this adhesive joint was validated in the real milling tool joint by applying the EDM sharpening process. As for the safety requirements, the test condition used was the one set by the EN 847-1 standard where a rotational speed test is performed at an overspeed condition validating its performance if no joint failure occurs.

The results of these tests allowed to fully determine the performance of the bonded tool, allowing its performance to be compared with that of the original brazed configuration. Although important differences in behaviour between the bonded and the brazed joints were identified, the proposed bonded joint was found to be suitable for practical implementation.

C.1 Introduction

Even though a limited number of studies have been carried out since the 1980's on the use of adhesive bonding as a tool joining process, these have mainly devoted to the determination of its effects on tool wear and surface quality of metalworking lathe tools, [1–3], or the tool's thermal behaviour during work [4–8]. In the milling tool sector, especially for wood applications, the use of adhesive bonding is still relatively unexplored, but there is a growing interest in using adhesive bonding as a substitute for the current braze-joined and mechanically fastened processes. With the market's preference for lightweight tools, which require less power to operate and create less stresses in the milling machine, the design of bonded milling tools with aluminium bodies is a key research subject.

Being induction the heating process used currently used in the manufacture of brazed tools, one of the main premises of this work was to ensure that it could also be adopted as the adhesive curing methodology, avoiding the need for costly equipment changes. With a very high heating efficiency for both the WC/PCD and steel materials, achieving the desired temperatures in just a few seconds, steel tool prototypes should be able to cure quickly and uniformly under induction heating, since both of the adherends provide proper heat transfer conditions, as depicted by Figure 1a.

On the other hand, aluminium - an innovative body material for this type of tool - cannot be inductively heated as efficiently as steel, since it does not possess ferromagnetic properties, solely allowing induction heating via the effect of Eddy's current, making the process less effective due to the decreased heating by joule effect as well as a quicker heat dissipation since aluminium is more thermally conductive than steel. This fact creates challenges in the process, leading to non-uniform curing, as it can be seen in Figure 1b.

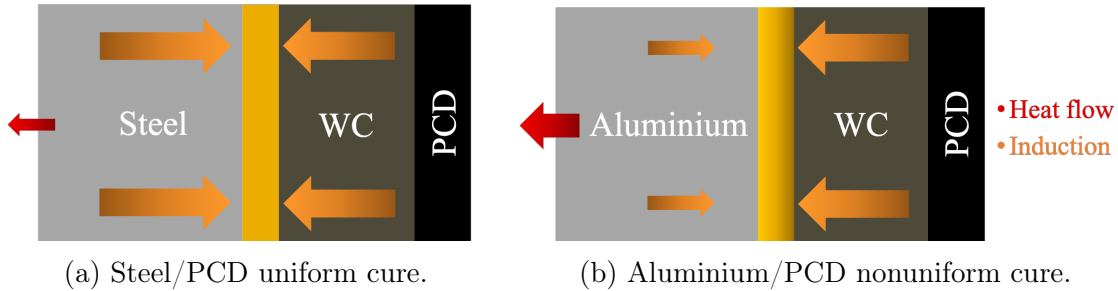


Figure 1: Schematic representation of the induction cure process in terms of heat fluxes supplied by the coil, in orange, and diffused by the body, in red.

Another common concern is the long term reliability of the bonded tools, related to the thermally insulating effect of the adhesive layer. This was reported as a liability for both the adhesive and the insert [4, 9], due to thermal degradation concerns. With lower heat dissipation through the tool's body, the inserts tempera-

ture increases when compared with braze-joined or mechanically clamped systems. As a solution, the introduction of conductive elements was reported to improve the thermal conductivity of the adhesive layer [5, 6, 8].

In [10], König reported that many different classes of materials such as hardened steels, carbides and ceramics could be electric discharge machined (EDM) if they offered 0.01 Scm^{-1} of electrical conductivity (σ), as shown in Figure 2.

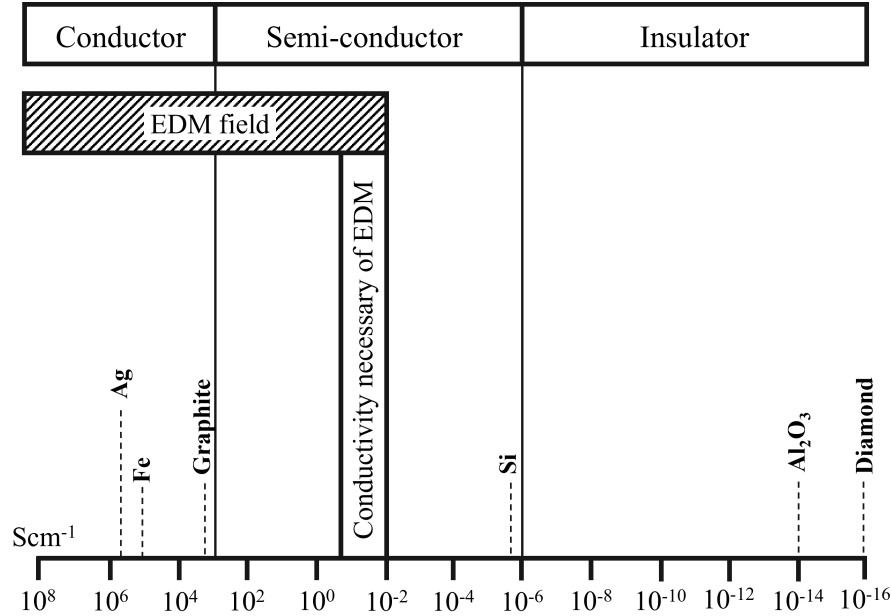


Figure 2: Electrical conductivity necessary for EDM. Adapted from [10].

However, not all materials are sufficiently electrically conductive, especially adhesives, so certain methods are used to overcome this issue, such as adhesive doping. In which introducing conductive elements as a filler - i.e. aluminium, copper and graphite powders [11], or conductive spheres [12] - proved effective in improving the electrical conductivity of epoxy resins.

Therefore, following the procedure proposed by Correia, [12], where an aluminium doped epoxy resin is mixed with conductive spheres, it is possible to achieve similar layer electrical resistance to that of a brazed joint, promoting the existence of a stable closed loop - Figure 3 - between the body and the tool-electrode, improving the quality of the sharpening process.

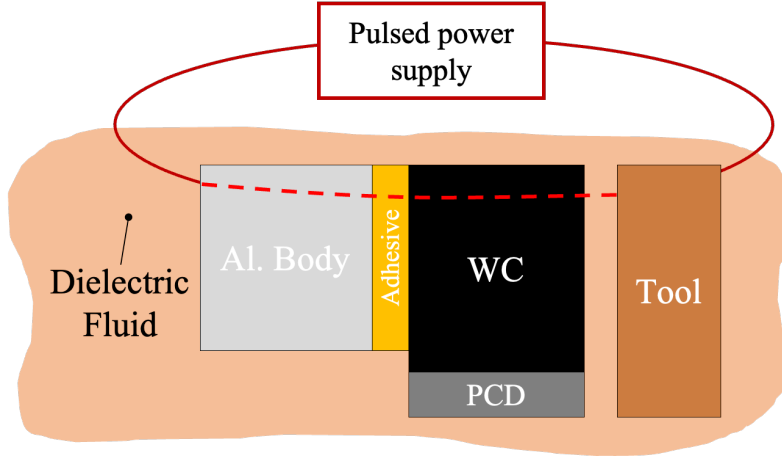


Figure 3: Schematic representation of EDM sharpening process.

The present work consists of a feasibility study on a novel milling tool concept, constructed using PCD inserts bonded to the body materials. This type of bonded construction also has the potential to be used in other applications, such as tools with large inserts or geometries highly susceptible to thermal buckling, composed of various body materials. Aluminium and steel body tools were both manufactured, representing different construction methodologies. Initially, the induction cure cycle was defined and studied using differential scanning calorimetry tests. Aluminium and steel prototypes were then manufactured, using an induction curing setup. Finally, the prototypes were properly tested for EDM sharpening and to ensure work safety.

C.2 Experimental details

The body and insert materials used in this material are part of edge milling tool models already commercially available and were supplied by FREZITE® Woodworking Tools. The adherends treatments, adhesive used and conductive filler percentages followed the work presented by Correia in [12]. The manufacturing and validation procedures were performed at FREZITE® Woodworking Tools.

C.2.1 Induction cure cycle

In order to maintain production rates compatible with an industrial process, a maximum curing time threshold was set to under a minute. Two different approaches were established, one seeking to obtain a full cure under the time limit proposed by the company while the other only seeks to obtain a pre-cured state to be finalised in a posterior manufacturing step.

Taking into account the curing data supplied by the adhesive's manufacturer, the use of a full-cure process is only possible at a temperatures - $T_{full\ c}$ - higher than

180°C for the proposed time frame - $t_{\text{full-c}}$. A schematic representation of this cure cycle is presented in Figure 4.

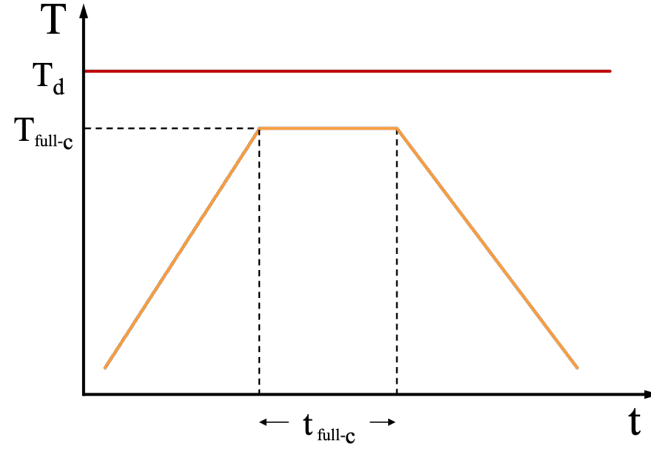


Figure 4: Full-cure cycle scheme.

The pre-cure method can be implemented at lower temperatures - $T_{\text{pre-c}}$ - under similar curing times - $t_{\text{pre-c}}$ - since in this process the adhesive is only partially cured to establish enough cohesive strength to maintain the inserts in place. Afterwards to finalise the cure, a longer stage - t_c - can be established in an oven relying on low temperatures - T_c . A schematic representation of this cure cycle is presented in Figure 5.

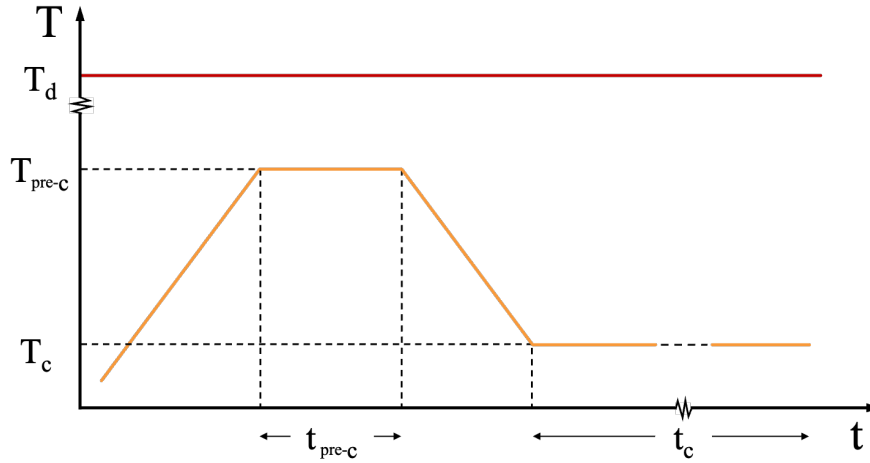


Figure 5: Pre-cure plus oven cure cycle scheme.

Differential scanning calorimetry tests

Differential scanning calorimetry tests were performed using the adhesive chosen for this study to better understand its polymerisation process at different temperatures, and assess the possibility of the application of either a quick full-cure or

a pre-cure followed by a longer cure stage at lower temperature. All tests were performed at a heating rate of 20°C per minute.

Two types of tests will be performed, a continuous ramp and several isothermal cure stages to determine the curing times at different temperatures. The isothermal cure cycles will be performed within the temperatures at which the adhesive reticulation begins and finishes. After reaching the isothermal stage, the cure time will be analysed up until the DSC curve stabilises, finalising the adhesive polymerisation process. In the case of the continuous ramp, the heat flow will decrease once again until it reaches the degradation temperature - T_d - with the adhesive becoming damaged after this point is reached.

The cure times examined during this study will only contemplate the point at which the isothermal stage is reached, ignoring the cycle's heat ramp.

As a result from these tests, the adhesive's degradation temperature was accurately determined, to prevent the use of a cure temperature too close to this point, and cure cycles will be defined for subsequent practical testing. All sudden irregular curve oscillations should be discarded since they were caused by current peaks.

C.2.2 Manufacturing procedures

The manufacturing methodology was based on the present induction heating method, repurposing the braze temperature control units currently used to control the adhesive's curing cycle. The setup used is comprised of a high frequency generator, with a maximum power output of 5.6 kW; a heating head with a water cooled inductor; a foot start/stop switch; a pyrometer with laser assisted positioning, with a temperature range of 80°C to 700°C; and a master control unit, capable of adjusting the isothermic cure temperature - T_c - and settling time - t_c -, the emissivity of the pyrometer, as well as defining the percentage of the maximum power output supplied by the generator, controlling its values based on the temperature readings to maintain a constant temperature stage.

The manufacturing procedure started with surface treatment, where the PCD inserts were degreased in an ultrasound solvent bath, followed by two stages of grit blasting. After grit blasting the substrates were cleaned again in a ultrasound bath. All of the steel bodies were only grit blasted (St-Gr). As for the aluminium adherends, different paths were tested, following three types of surface treatment configurations: initially the substrates were only anodised (Al-An), as proposed by Correia [12], although in this case a sulphuric acid anodisation was selected in order to match current processes used in this industrial environment; however, two other methods were tested during the development of this solution, a grit blasted plus anodised prototype (Al-Gr+An) and a solely grit blasted prototype (Al-Gr).

The positioning of the tool's body was done with a rotational clamping support, to move the insert's groove into position freely. Then after application of the

adhesive, the PCD insert was positioned in place, and cured under appropriate temperature and pressure condition. The temperature induced by the coil was governed by the power supply controller, while pressure was manually applied with a ceramic pointer, both of which can be seen in Figure 6a.



(a) Aluminium prototype manufacturing. (b) Steel prototype manufacturing.

Figure 6: Induction cured prototype manufacturing.

Manufacturing started with a smaller diameter of 100mm, to assess in a smaller scale the different cure cycle possibilities and to fine tune the induction based manufacturing procedure. Tools with 180mm of diameter were later produced, representing the final prototypes to whom all the validation methods would be applied.

All prototypes were addressed by a code comprised of the diameter of the prototype (100mm or 180mm), body material (steel or aluminium) and surface treatments (grit blast or anodization) in the described order, e.g. 180Al-Gr+An.

C.2.3 Work temperature

Using a Fluke Ti25 infrared thermal camera, typical work temperature values were determined using a brazed tool while cutting common wood raw materials, such as MFC (melamine faced chipboard) and MDF (medium density fiberboard). Although this test determines only the temperature around the cutting area in a rotating tool, which does not represent the real temperature at the tool cutting edges, it serves as a basis to assess the possibility of temperature degradation issues related to long work stages at severe enough temperatures to damage both the insert's and adhesive's properties.

C.2.4 Woodworking tool validation methodologies

Electric discharge machining (EDM) sharpening tests

The sharpening tests are used to evaluate if the bonded joint is to close the circuit between the workpiece and the tool-electrode performing the EDM sharpening

process. This process is implemented by the industrial partner in commercial EDM machines.

This process is performed in a liquid work environment, arising the possibility that chemical degradation could also be of relevance. However, since the fluid used was a hydrocarbon based dielectric fluids, and looking at the chemical medium influence in shear strength under compression detailed in the adhesive's datasheet, chemical degradation should not be a concern since it is unaffected by oils and petroleum based work mediums.

EN 847 standard safety tests

The safety requirements for wood milling tools are set by the EN 847 standard, part 1 [13], where in the specific case of adhesive bonded milling tools, the safety validation method includes a centrifugal test until failure, since in the case of wood-working milling tools the centrifugal stresses are the most severe ones.

The test specimen should have the largest cutting diameter and width available in catalogue. During the overspeed test, at a rotational test speed of $\eta_p = 2 \cdot \eta$, if no failure is verified in the bonded areas the specimen is considered to have been successfully validated [13].

The edge milling tool models considered in this work have standard diameters of 100 mm and 180 mm, with fixed width for each diameter. In terms of rotational velocity, calculation were made considering the typical and maximum peripheral cutting velocity's - v_c - common for these tool models, using the following equation:

$$\eta = \frac{v_c \cdot 60 \cdot 1000}{\pi \cdot d}, \quad [rpm] \quad (1)$$

whose values are represented in Table 1.

Table 1: Overspeed values considering two peripheral cutting speed states, for the two standardised diameters used in prototype manufacturing.

Speed state	v_c / ms^{-1}	d / mm	η / rpm	η_p / rpm
Typical	70	100	13000	26000
		180	7400	14800
Maximum	90	100	17000	34000
		180	9500	19000

The prototype's overspeed rotational velocity is firstly set to the standard service condition, validating its use, and if no problems arise by that stage, it advances to

the next speed level, validating the maximum cutting velocity condition. Since the overspeed testing machine used has a maximum rotational velocity of 21500 rpm, only the prototypes manufactured with 180 mm can be fully validated.

C.3 Experimental results and discussion

C.3.1 Differential scanning calorimetry tests

Applying a continuous heating ramp up until 400°C the DSC plot shown in Figure 7 was obtained, three main results can be obtained. First, the temperature at which polymerisation begins is close to 150°C, the cure process under continuous heating ends at 230°C, and the degradation temperature is at 290°C - as stated in the adhesive's datasheet.

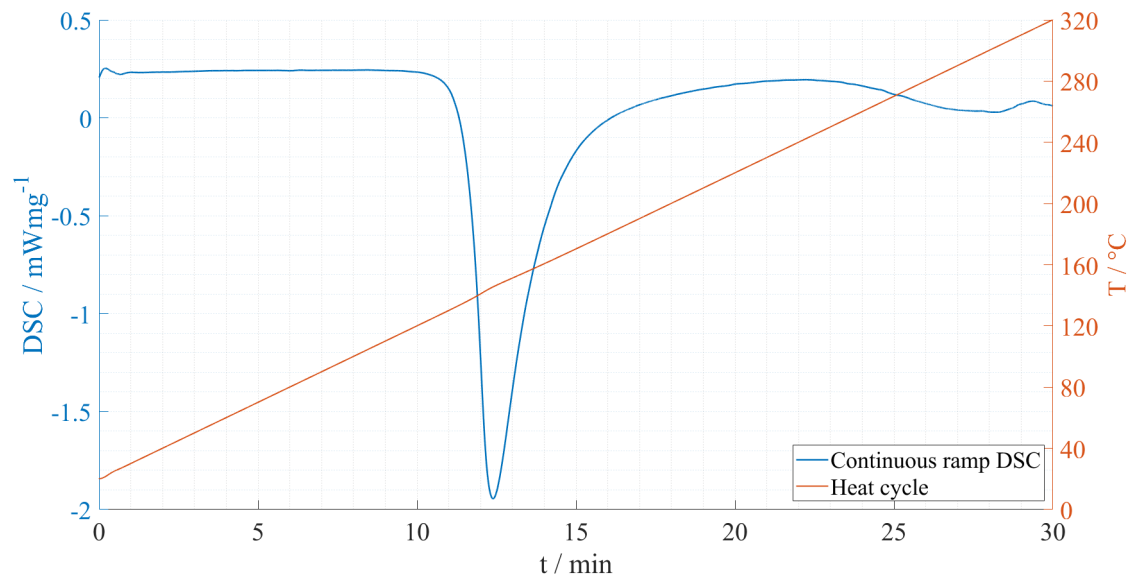


Figure 7: Differential scanning calorimetry results for a continuous ramp heating cycle.

Based on the information obtained from the previous curve, three isothermal tests were carried out at 220°C, 150°C and 180°C.

Starting with the study of the full-cure cycle, an isothermal heat stage at 220°C was performed, whose results are presented in Figure 8. The main conclusion taken from this test was that for this temperature a full cure would not be possible in under a minute, considering differences in thermal conductivity associated to the aluminium prototypes and possible thermal inertia effects. Even though higher cure temperatures could be used, for safety reasons the cure temperature cannot be higher than 230°C. Furthermore, to achieve these temperatures within the desired time, very high heat rates would be necessary, necessitating very high powered equipment and with high likelihood of damaging the adhesive layer and other components of the tool.

Thus, the pursue of a full-cure cycle was abandoned going forward. Nevertheless, this analysis determined that a quick pre-cure cycle at this temperature could be successfully established.

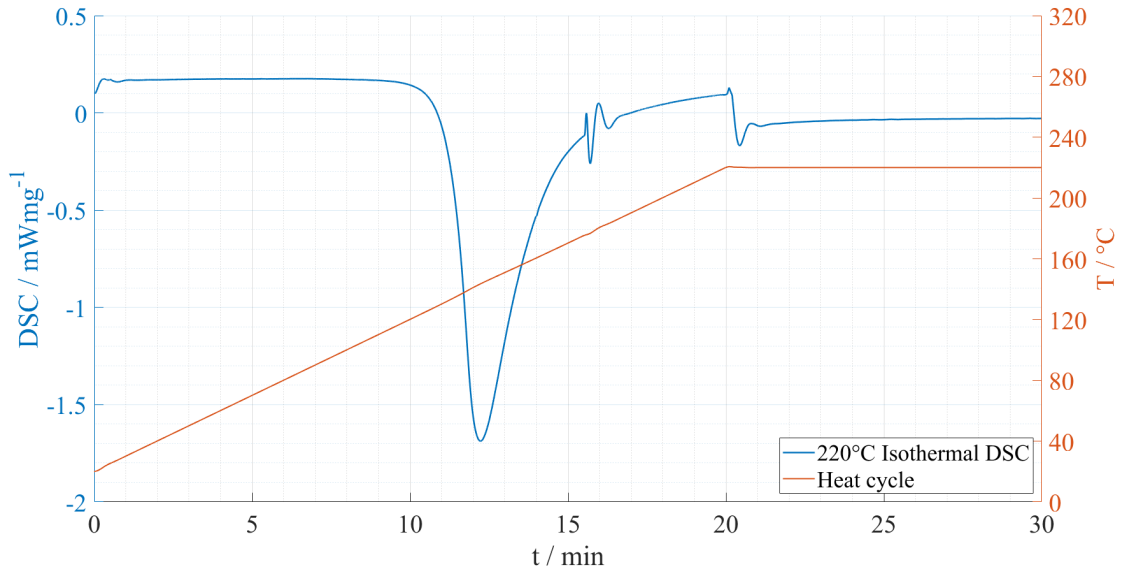


Figure 8: Differential scanning calorimetry results for an isothermal heating cycle at 220°C.

For the pre-cure cycle study two other isothermal tests were carried out at 150°C and 180°C, whose results are presented in Figure 9 and 10, respectively.

Considering the 150°C stage, it is possible to extrapolate from the DSC curve that more than 3 minutes are necessary to obtain a suitable pre-cured state, which is not compatible with the manufacturing time frame previously established. Consequently, this temperature was removed from the pre-cure cycle possibilities.

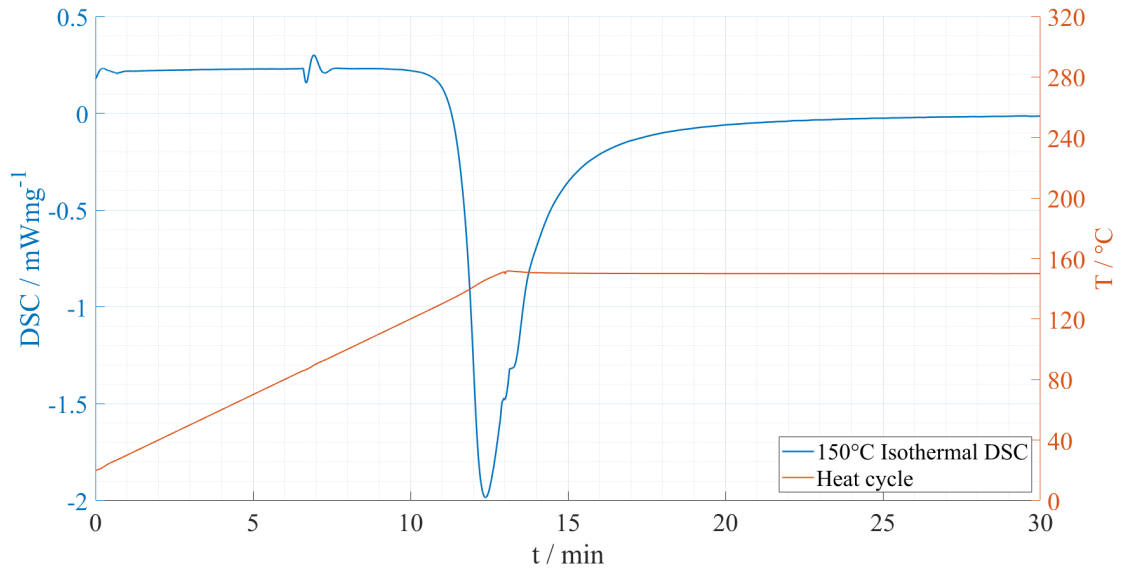


Figure 9: Differential scanning calorimetry results for an isothermal heating cycle at 150°C.

As for the cure stage at 180°C, contrarily to the previous test, when the isothermal temperature is reached the curve is almost stabilized, which make this cure cycle suitable for use in pre-curing.

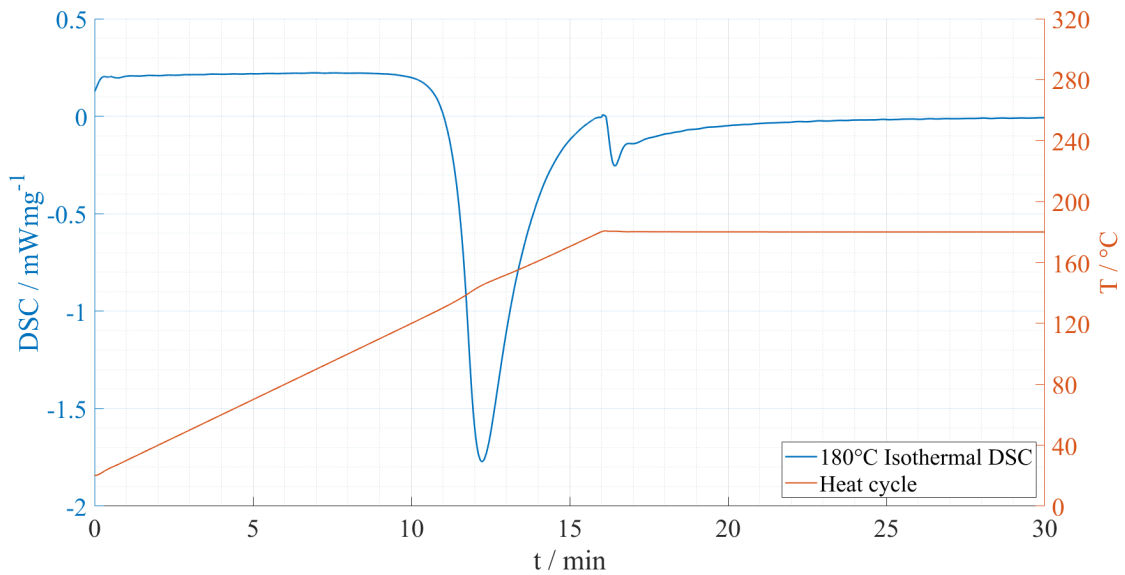


Figure 10: Differential scanning calorimetry results for an isothermal heating cycle at 180°C.

All results considered, the full cure cycle was discarded and a few pre-cure cycles were selected for testing in the manufacturing stage, namely the 180°C and 220°C pre-cure cycles.

C.3.2 Prototype manufacturing

Testing all the pre-cure cycles in the 100St-Gr prototypes demonstrated the need for a slow heat ramp, considering the lowest power output possible, to prevent a severe expansion effect. This effect was found for the 220°C cure temperature, making so that the only cure cycle possible for steel tools was the gentler isothermal stage at 180°C, with low power output. A 180St-Gr prototype was manufactured at this temperature for the final validation tests.

When performing the same tests for the 100Al-An, 100Al-Gr+An and 100Al-Gr prototype configurations this did not occur, mainly due to the low induction heating efficiency and high thermal diffusivity of the aluminium body. In this case, for all cycles a higher power output was necessary to improve the pre-cure performance, however the previously detected expansion effect did not appear in any of the cure stages for aluminium. This said, the selected cure cycle would simply translate into a specific curing time. Because productivity is one of the main requirements of this study added to the fastest cycle - the 220°C isothermal cure stage - a few steps were taken to improve the manufacturing time of these prototypes. Since the 100mm prototypes showed curing issues for the current adopted manufacturing process, no 180mm diameter aluminium tool configurations were manufactured, as the steps taken to improve the curing process on the aluminium adherend did not work either properly nor efficiently for the highest diameter.

The final prototype configurations finished their curing process through a longer cure stage at lower temperatures, and then proceeded to the validation stage where the following configurations were tested: 100Al-An, 100Al-Gr+An, 100Al-Gr and 180St-Gr.

C.3.3 Work temperature

The work temperature values measured using a infrared thermal camera showed low temperature readings, presented in Figure 11.

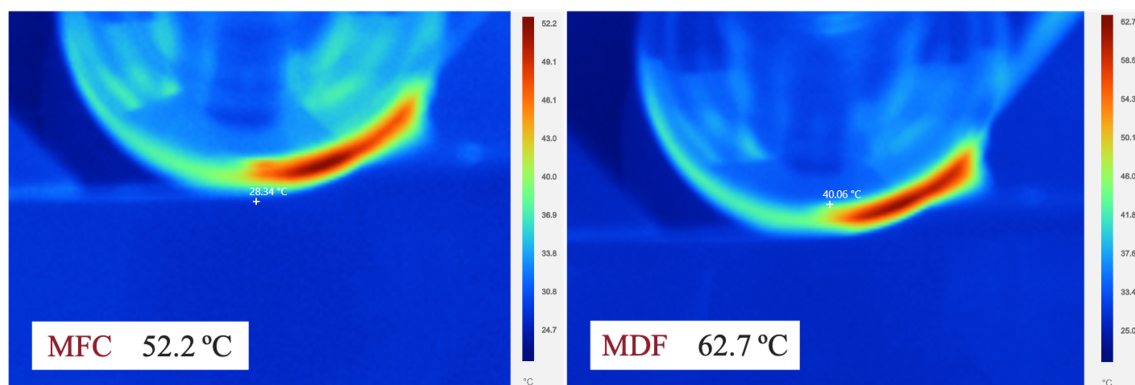


Figure 11: Thermal imagery of two woodworking scenarios, wood agglomerate to the left and MDF to the right.

Taking into consideration that in this application the use of hard materials with very low friction coefficients - such as polycrystalline diamond (PCD) inserts - to decrease cutting edge temperatures, coupled with aluminium bodies with much higher thermal conductivity, rotational velocity that promotes heat dissipation by means of convection, and softer workpiece materials that produce less heat during chip creation, it is possible to safely consider that thermal degradation of both the insert and adhesive will not be a relevant factor in woodworking adhesive bonded milling tools.

C.3.4 Woodworking tool validation tests

A summary of all the tests performed, both for EDM and overspeed, is presented in Table 2. The sharpening tests are evaluated on a Yes/No basis, and the safety requirements on the test velocity achieved in relation the overspeed condition as a percentage, to evaluate the results taking into consideration the test machine limitations, as well as the occurrence of joint failure evaluated with a binary Yes/No criterion.

Table 2: Summary of the validation test results for each prototype.

Prototype	EDM test	Overspeed test		Joint failure
	Yes/No	Typ. / η_p %	Max. / η_p %	Yes/No
100Al-An	N	82	63	N
100Al-Gr+An	N	82	63	N
100Al-Gr	Y	82	63	N
180St-Gr	Y	100	100	N

Both aluminium anodised prototypes - 100Al-An and 100Al-Gr+An - failed in the sharpening tests due to an insulation effect of the present anodisation layer, which for the previous bonding study [12], did not present a problem when measuring the bonded layer resistance. This might be due to the fact that different anodisation processes were used in each study, possibly changing the amount of influence that the anodisation layer had on the electrical properties. Nevertheless, both the 100Al-Gr and 180St-Gr prototypes were successfully sharpened via EDM, validating the use of this adhesive configuration in terms of electrical conductivity in industrial conditions.

From all the aluminium prototypes manufactured, with 100 mm in diameter, none were tested for the predicted overspeed conditions due to the machine's speed limitation. Nevertheless, all achieved the maximum speed supported by the machine without failure, corresponding to a rotational speed safety factor of 1.65 and 1.26

for the typical (26000 rpm) and maximum (34000 rpm) states, respectively, slightly short of the coefficient of safety of 2 required by the standard. As for the 180St-Gr prototype all overspeed states were achieved without any sign of fracture, both in typical (14800 rpm) and maximum (19000 rpm) conditions, fully validating this configuration for the safety requirements set by the EN 847 standard.

C.3.5 Conclusions

The main purpose of this work was to validate the application of adhesive bonding in the production of milling tools. A suitable induction cure cycle was studied, first in a laboratorial setting with DSC analysis and then practically during manufacturing of the prototype configurations. Both steel and aluminium solutions were tested and different surface treatments tested. EDM sharpening tests were performed as well as overspeed tests in accordance to the EN 847 standard. This led to the following findings:

- Unlike the brazing process, bonded tools require a two step cure cycle starting with a quick pre-cured followed by a longer oven cure;
- Neither chemical nor thermal degradation seem problematic for both the production and work stages of wood milling tools;
- Aluminium tool bodies, contrarily to steel, posed challenges for curing the adhesive under an induction based process;
- The doped adhesive performed as expected, increasing the electrical conductivity of the adhesive layer, allowing EDM sharpening of the grit blasted prototypes;
- The anodising of aluminium precludes EDM sharpening and thus only laser based sharpening solutions can be implemented with this surface treatment;
- The only prototype that was fully validated was the steel configuration, showing that a few improvements in the manufacturing process are still needed to bond aluminium tools;
- Other adhesive fillers or pre-curing solutions might improve the productivity of this manufacturing process.

Although important differences in behaviour between brazed, steel bonded and aluminium bonded joints were identified, the proposed bonded tools were found to be suitable for practical implementation, even tough in the case of aluminium a few challenges must still be overcome. Still, this is still a relatively incipient process, with plenty of room for achieving greater efficiency, performance and productivity in an industrial environment.

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