META-L-BASED ADDITIVE MANUFACTURING
EVALUATION OF METALLIC PARTS PRODUCED WITH ADDITIVE MANUFACTURING TECHNOLOGY AT YAZAKI EUROPE LIMITED

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Dissertation submitted
at Faculdade de Engenharia da Universidade do Porto
to achieve Master Degree in Metallurgy and Materials Engineering

Dissertation under Supervision of
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## METAL-BASED ADDITIVE MANUFACTURING
**Evaluation of metallic parts produced with Additive Manufacturing Technology at YAZAKI Europe Limited**

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METAL-BASED ADDITIVE MANUFACTURING
Evaluation of metallic parts produced with Additive Manufacturing Technology at YAZAKI Europe Limited

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Twenty years from now you will be more disappointed by the things that you didn't do than by the ones you did do. So throw off the bowlines. Sail away from the safe harbor. Catch the trade winds in your sails. Explore. Dream. Discover.

Mark Twain

Discovery is seeing what everybody else has seen, and thinking what nobody else has thought.

Albert Szent-Gyorgyi
ABSTRACT

Metal-based Additive Manufacturing (MbAM) is an additive manufacturing process for the direct fabrication of prototypes, tools and fully functional parts. The MbAM equipment usually uses a high intensity laser beam that will completely melt the metal powder particles, according to a layer defined from a three-dimensional CAD model. There are several processes available, from different suppliers, and for this work the selected one was the Direct Metal Laser Sintering (DMLS), from EOS GmbH. DMLS is capable of producing high density parts, with mechanical properties similar to traditional manufacturing techniques and with cost control when complex geometry increases. DMLS can work with different materials, and in this cases it was used maraging steel (1.2709), an iron-nickel steel alloy with good mechanical properties, easily heat treatable using an age-hardening process which will enable superior hardness and strength.

The experimental investigation involved the analysis of maraging steel powder, microstructure of produced parts, mechanical properties and dimensional analysis. The results of experimental evaluation demonstrated that after age-hardening parts achieved the hardness pre-defined requirements, they also present, at the same time, a very high density. With this dissertation it is intended to bring knowledge about MbAM to YAZAKI to support future steps and decisions. The first chapter, Literature Revision, starts by presenting additive manufacturing, defining it and showing the path taken. After this, it is presented all the different process approaches to MbAM, benefits and limitations. It ends with the analysis of the equipment used in this work, EOS M 290, and properties of maraging steel. The second chapter, Experimental Procedure, mentions all the methods used, from parts manufacturing to post-processing operations (trimming, age-hardening) and analysis carried out (like hardness, SEM/EDS evaluations, tensile tests, among others). The results are presented and analyzed in chapter three, and conclusions are presented in chapter four. The report finishes with Future Steps chapter.
KEYWORDS

Additive Manufacturing, Metal-based Additive Manufacturing, Direct Metal Laser Sintering, Metals, Maraging Steel.
RESUMO

A manufatura aditiva de materiais metálicos (MbAM) é um processo de fabricação para a produção direta de protótipos, ferramentas e peças totalmente funcionais. O MbAM utiliza normalmente um laser de alta intensidade, que vai fundir completamente as partículas de pó metálico numa camada definida a partir do modelo tridimensional do software CAD. Existem vários processos disponíveis, de diferentes fornecedores, e para este trabalho foi seleccionado o Sinterização Direta de Metal a Laser (DMLS), da EOS GmbH. O DMLS é capaz de produzir peças de elevada densidade, com propriedades mecânicas semelhantes às técnicas de fabricação tradicionais e com controlo de custos, quando aumenta a complexidade geométrica. O DMLS pode fabricar peças em diferentes materiais, sendo que para este estudo foi usado um aço maraging (1.2709), aço ligado ao Ni-Co-Mo-Ti, com boas propriedades mecânicas, ao qual é possível aplicar tratamentos térmicos (endurecimento por envelhecimento), o que aumenta a dureza e resistência mecânica.

A investigação experimental envolveu a análise de pó metálico do aço maraging, a microestrutura das peças produzidas, propriedades mecânicas e análise dimensional. Os resultados da avaliação experimental demonstraram que após endurecimento por envelhecimento da liga, as peças produzidas alcançam a dureza pretendida nos pré-requisitos, apresentado também, ao mesmo tempo, uma elevada densidade. Esta dissertação tem como objectivo trazer conhecimento à YAZAKI sobre MbAM, para apoiar as decisões e ações futuras. O primeiro capítulo, Revisão de Literatura, começa por apresentar a manufatura aditiva, definindo-a e mostrando o caminho percorrido. De seguida são apresentadas as diferentes abordagens ao processo de MbAM, e aos benefícios e limitações. Termina com uma análise ao equipamento utilizado neste estudo, EOS M 290, e propriedades do aço maraging. O segundo capítulo, Procedimento Experimental, menciona todos os métodos usados, desde a produção até às operações de pós-processamento (desbaste, tratamentos térmicos) das peças e ensaios realizados (como dureza, observação SEM/EDS, ensaios de tração, entre outros). Os resultados são apresentados e analisados no capítulo três, e as conclusões
no capítulo quatro. O relatório termina com algumas sugestões para poder continuar o estudo futuramente.

**PALAVRAS-CHAVE**

Manufatura Aditiva, Manufatura Aditiva de Materiais Metálicos, Sinterização Direta de Metal a Laser, Metais, Aço Maraging.
Why Metal-based Additive Manufacturing in YAZAKI? YAZAKI is leader in wire harness business. We can only be different if we make things more efficiently and better, with a perceived quality from our customers, achieving what they desire. YAZAKI has a real and oriented focus to quality. Last year’s several awards, such as the automotive OEMs, and more recently - the European Award for Best Practices 2016, attributed by European Society for Quality Research (ESQR), completely demonstrate this orientation. As part of the New Technologies team in European Manufacturing Engineering department, a major part of my job is to consider where and how can we become more efficient, and also transform our business to be more profitable, maintaining the quality standards.

YAZAKI is a company where the consumption of metallic parts - used to enable the production of our products - is very high. Internally, there are many components, from upstream to downstream, that represent a significant amount of costs, not only due to the quantities used, but also due to the high rotation of product and engineering changes.

The core objective of evaluating the additive manufacturing for metallic components that YAZAKI is currently using is to determine if technology has potential to be introduced and used as an alternative to traditional processes. To evaluate the technology, some parts were selected, probably the most critical and demanding, to verify their feasibility and to trial in production conditions. YAZAKI has a real interest in this technology and the intent is to evaluate the advantages of using additive manufacturing and what will the company gain. YAZAKI intends to become more efficient, flexible and dynamic, more profitable and high detailed in customer focus level, by producing the core business component with low impact in finance, and fulfilling customer requirements and expectations.

This study, with all the dedicated time (professionally and personally), brought the desire to proceed with my studies to a PhD.

A great way to finish this is YAZAKI motto: One for All, All for One.
ACKNOWLEDGEMENTS

First, I would like to express my gratitude and appreciation to Jan, Andreas and Marco. When presenting a project like this, completely out of the box, the perfect reception does not always happen, and the receiver does not always embrace the full picture of what is being said. Since the moment I presented this project, you were by my side and endorsed it in a very enthusiastic way. I feel privileged for the trust you placed in me to manage this project, for your support in the darkest moments, and also the time and money invested. It is a lot easier to move a mountain when we have people by our side. Can we continue this?

My deepest gratitude to Professor Manuel Vieira, for accepting the supervision of my dissertation, for the patience and commitment he has shown all the time. For all the comments and advices given, all the time spent with travelling, analysis and project execution made possible to reach the end of this project. In my previous graduation (Licenciatura) you were one of the best examples I had, and I humbly appreciate and thank everything you have done for me.

I would also like to thank Claudia Lopes and José Ramiro, faculty staff, for all the support provided with specimens’ preparation, heat treatments, equipment explanation and analysis made during this project. You made this a lot easier. I cannot forget Inês and Tânia, forth year students in the Metallurgical and Materials Engineering master, for all the support given during the analysis.

I would also like to thank CINFU, especially to Fernando Barbosa, for the support provided in the tensile tests, as well as all the suggestions made for the future.

I cannot end the acknowledgments without thanking my family and friends. The biggest appreciation goes to my wife and mother, for all the support along the last couple of years, for your patience, love and trust in me. To my in-laws and closest friends, thank you so much for the encouragement. Pedro, thanks for all your inputs and different perspectives.

I thank God for the opportunity.
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ACRONYMS AND SYMBOLS

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<td>3D</td>
<td>Three-dimensional</td>
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<tr>
<td>AM</td>
<td>Additive Manufacturing</td>
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<td>ASTM</td>
<td>American Society for Testing and Materials</td>
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<td>CAD</td>
<td>Computer-aided Design</td>
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<tr>
<td>CNC</td>
<td>Computer Numerically Controlled</td>
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<td>DEMM</td>
<td>Department of Metallurgical and Materials Engineering</td>
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<td>DED</td>
<td>Direct Energy Deposition</td>
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<td>DLD</td>
<td>Direct Laser Deposition</td>
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<td>DMLS</td>
<td>Direct Metal Laser Sintering</td>
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<td>EDM</td>
<td>Electrical Discharge Machining</td>
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<td>EDS</td>
<td>Energy-dispersive X-ray Spectroscopy</td>
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<tr>
<td>EMEA</td>
<td>Region: Europe, the Middle East and Africa</td>
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<td>FESEM</td>
<td>Field Emission Scanning Electron Microscope</td>
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<td>FEUP</td>
<td>Faculdade de Engenharia da Universidade do Porto</td>
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<td>HIP</td>
<td>Hot Isostatic Pressing</td>
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<td>HRC</td>
<td>Rockwell C Hardness</td>
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<td>HV</td>
<td>Vickers Hardness</td>
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<td>LC</td>
<td>Laser Cusing</td>
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<td>IIoT</td>
<td>Industrial Internet of Things</td>
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<td>MbAM</td>
<td>Metal-based Additive Manufacturing</td>
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<td>PBF</td>
<td>Powder Bed Fusion</td>
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<td>RP</td>
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<td>SLM</td>
<td>Selective Laser Melting</td>
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<td>SM</td>
<td>Subtractive Manufacturing</td>
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<td>STL</td>
<td>Standard Tessellation Language</td>
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The success story of YAZAKI starts in 1929, in Japan, by Mr. Sadami YAZAKI. This long-established, family-owned company is, nowadays, the number one in the global automotive wiring harness market, and supplier of innovative solutions to all major car manufacturers worldwide. With global operations, YAZAKI Corporation (established in 1941) has more than 280,000 committed and highly motivated employees, at 478 locations, in 45 countries, to contribute to YAZAKI’s global success (following picture).

![YAZAKI Corporation location worldwide](image)

**Figure 1**: YAZAKI Corporation location worldwide [1]

In spite of the fact that YAZAKI started as automotive supplier, which is the core business, YAZAKI also has additional businesses in Energy System (electric wire, environmental systems, gas equipment, and transport systems) and New Businesses (paper, glass and food recycling and nursing care).

In the automotive business YAZAKI is divided in Electrical Distribution System (figure 2a), Components (figure 2b), Electronics and instrumentation (figure 2c) and High Voltage (figure 2d).
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Evaluation of metallic parts produced with Additive Manufacturing Technology at YAZAKI Europe Limited

In Europe, YAZAKI was established in 1980, as YAZAKI UK Limited, and in 1998 changed to YAZAKI Europe Limited.

YAZAKI Europe Limited is responsible for EMEA region, being present in 22 countries and 56 locations today, which will increase in the near future.

YAZAKI Saltano de Ovar, legal nomination of YAZAKI Portugal, in June 2016, has headcount of more than 2000 employees, splitted by Components Manufacturing, Electronics and Instrumentation, Wire Harness Manufacturing and Porto Technical Center.

As a curiosity, the first plant in YAZAKI’s European operation was in Vila Nova de Gaia (Porto District, Portugal), in current Salvador Caetano Group Headquarters.
LITERATURE REVIEW

1 ADDITIVE MANUFACTURING

1.1 DEFINITION

The term Rapid Prototyping (RP) is widely used in industry to describe a method for quickly creating a component, system or part representation, especially for complex products, to check and validate a development before final release or commercialization. Additive manufacturing (AM) was first developed for prototyping, and it was quickly understood its potential, transforming RP to be more effective, to be used from upstream to downstream, from development phase to customer [2]. AM also brought a new perception regarding the manufacturing of components with complex shapes and integrated parts, as will be seen in the following chapters [3].

What is additive manufacturing? One of the most consensual definitions for AM is from The American Society for Testing and Materials (ASTM International), which defines AM as a process of joining materials to make objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies [4].

Wohlers Report 2016 also defines AM as a process of joining materials to make parts from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing and formative methodologies; historical terms include additive fabrication, additive processes, additive techniques, additive layer manufacturing, layer manufacturing, solid freeform fabrication, and freeform fabrication [5].

In powder additive manufacturing, each layer has a finite thickness, due to limitations in equipment when handling powders, and on powder particle size, since it is not easy to get smaller size. The thinner each layer is, the closer the final part will be to the original 3D model data image (figure 3a), with better mechanical properties and surface roughness [2].
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Figure 3: Phases of additive manufacturing [6]
(1) Part 3D model; (2) Making of STL-model; (3) Making of one certain layer; (4) Part produced thru AM technology.

Additive Manufacturing equipment are able to build a 3D part by bonding materials layer by layer (layer example in figure 3c and figure 4), where each new layer of material is defined by the 3D model cross-sectional data. Usually, these models are in the form of 3D CAD data (Computer Aided Design) in the STL (Standard Tessellation Language) file format (figure 3b), and thru specific software - are “sliced” to adequate number of layers [7,8], as shown in following figure.

Figure 4: Phases of additive manufacturing [6]

AM technology is most commonly used for modeling, prototyping, and tooling, and it is changing manufacturing process as we know it, by applying this technology to the production of final products or parts that go into final products (figure 3d) [2]. This is happening mainly due to the personalization level required by customers, and also due to the better finishing of equipment available in the market.

AM cannot be considered a new technology, since the concept of AM was already being researched more than 50 years ago, and the first commercial systems were on the
market in the late 1980s, thru the stereolithography in 1987 and 1988, patented by Chuck Hull (3D Systems Inc). However, the main developments occurred, especially for polymeric materials, since 2010 [5].

AM processes are more and more considered as intrinsic parts of the product development process, since they are used to manufacture prototypes, tools and end products. AM is well known for engineering applications, continuing to gain relevance from architecture to medicine, archaeology, art, cartography, among others [9]. To achieve an effective joining in AM, one of the mandatory requirements is having an effective combination of the feedstock (or raw) material, and also a good energy delivery. ASTM recognizes as AM methods the material extrusion, material jetting, sheet lamination, VAT photopolymerisation, binder jetting, directed energy deposition (DED) and powder bed systems (also known by power bed fusion - PBF). Usually, each AM method is custom-made for building a specific type of material (e.g. ceramics, polymers, composites or metals) as the effective material deposition and joining can be unique [7].

Each AM process has specific features, like materials used, processing operations to build components and possible applications.

1.2 BACKGROUND, HISTORY AND EXPECTATIONS

AM is the opposite of subtractive manufacturing (SM), also known as conventional or traditional manufacturing. American Society for Testing and Materials (ASTM International) defines SM as making objects by removing of material (for example, milling, drilling, grinding, carving, etc.) from a bulk solid to leave a desired shape, as opposed to additive manufacturing [4]. In the SM, material is cut away from a solid block of material, shaping it to achieve the defined three-dimensional CAD component.

As mentioned before, AM is not a new subject, since it has been investigated/studied for more than 50 years. In the late 1960s, at Battelle Memorial Institute, was held the first attempt using lasers to create solid objects of photopolymers [10].
The first commercial equipment appeared in 1987 from 3D Systems, and was named *stereolithography* (SL). SL was a process that solidifies thin layers of ultraviolet light-sensitive liquid polymer using a laser [5,10].

After this point, big disputes were raised between AM equipment manufacturers (and competitors) related with patents start, with different equipment manufacturers fighting for their place in the market.

During the 1990s and 2000s, different technologies were released. In 1991 Stratasys launched fused deposition modeling (FDM), Cubital launched solid ground curing (SGC) and Helisys launched laminated object manufacturing (LOM). Selective laser sintering (SLS) was launched in 1992, and the interesting was that it was using the heat from a laser to melt powder materials. In 1997 AeroMet (subsidiary of MTS Systems Corp.) developed a process called laser additive manufacturing (LAM), that used a high-power laser and powdered titanium alloys [10].

In the first years of 2000s, different and new technologies were introduced, focusing also in new materials to be processed. Precision Optical Manufacturing presented direct metal deposition (DMD), a laser-cladding process that produces and repairs parts using metal powder. In 2001 Concept Laser GmbH introduced a new system that combined laser sintering, laser marking, and laser machining; in 2004 launched laser cusing\(^1\) melting machine, and in 2007 launched equipment to process reactive materials like aluminium and titanium alloys. Stratasys launched ABS plastic in 2002, and after that date several other polymeric materials were added to the list as able to be processed with AM technology [10].

Since 2010, AM technology got some notoriety, and to gain advantages against competitors, several acquisitions were made, for instance Stratasys and 3D Systems acquired several competitor companies, and also joint-ventures were signed (for instance in 2015 EOS and SLM Solutions agree a cross-license for Laser Sintering and Selective Laser Melting), which enabled a faster technology development and ended with some legal disputes about patents [11].

\(^1\) Cusing is made up of the letter C from Concept Laser and the word Fusing (complete melting).
AM techniques are a cost effective alternative to traditional manufacturing processes, such as injection molding, and also all subtractive processes, for medium sized batch production [12]. Several developments are still required in the AM technology, mainly in components finishing, to have smaller dependence on additional processes, for e.g. to improve surface, improve material properties, obtaining a wider acceptance by final customer (industrial or not).

Future potential is huge; according to Wohlers, expectation is that the AM growth will continue, to both products and services, as shown in the following chart [5].

![Wohler’s additive manufacturing forecast](chart)

The technology development, and how fast it will happen, depends on market acceptance and technology implementation; if more users accept this technology, OEM will make further investments to develop the technology.

1.3 **METAL-BASED ADDITIVE MANUFACTURING**

The capability of obtaining high performance metallic components with controllable microstructural and mechanical properties also shows a distinct difference from various AM processes [8]. The main metal-based additive manufacturing (MbAM) categories are the powder bed systems, powder feed systems, and wire feed systems [13,14].
Nowadays, there are several AM systems that can be characterized as powder bed, powder feed, and wire feed systems. There are distinct advantages to each type of system dependent upon the intended applications, e.g., repair and refurbishment, small part fabrication, large part fabrication [14]. One of the most important issues is to select (and use) the appropriate technology for the intended task.

1.3.1 Powder Bed Systems

The powder bed systems (process available in following figure) are the most common additive manufacturing equipment for metal based products, where a layer of fine metal powder is uniformly spread in the machine bed and selectively melted by a focused energy source (electron beam or laser beam) to the work area [7,14,15]. The main advantages of this system include the ability to produce high resolution features, internal passages, and maintain dimensional control [14].

![Powder bed system diagram](image_url)
The build station is operated with vacuum, or filled with an inert-gas atmosphere (usually nitrogen or argon), to reduce reactive metal powders (like titanium and aluminum) oxidation, during the build [7,13].

The powder material is stored in the reservoir station; when a new thin layer of powder is required on the build station, build plate goes down at the same time reservoir plate goes up, and powder roller moves horizontally, spreading a new layer of powder in build station, over the previous layer. With a uniform layer of powder, a high power laser beam will fuse the powder according to the CAD data, with high precision and will fuse the defined areas with the layer below. The sinterization and powder spreading processes are repeated layer by layer until part is completely built within the powder bed. The unmelted powder available in the building chamber is removed, and the finished part is revealed on the build plate [7,13,15,16]. The remaining powder that was not used can be recovered and reused in future part productions.

If required, the manufactured part can then be heat treated, alike parts manufactured with traditional processes.

There are many different designations inside powder bed technology, being the most common the Direct Metal Laser Sintering (DMLS), Selective Laser Melting (SLM), Selective Laser Sintering (SLS), and Laser Cusing. Despite all name variation, the melting process in the different designations is basically the same, and also the laser, which can be denominated as Laser Sintering (LS). According to ASTM, LS is a powder bed fusion process used to produce objects from powdered materials using one or more lasers to selectively fuse or melt the particles at the surface, layer by layer, in an enclosed chamber [17-19]. Other powder bed technology available is the Electron Beam Melting (EBM), which uses an electron beam instead of a laser beam.

The most recent equipment versions with this technology can produce accurate and nearly full density parts (> 99.7%), with good mechanical properties. The produced parts more often do not need the post-processing treatments. The surface finish can be improved, with surface gridding and micro-scale features produced [20-22].
1.3.2 Powder Feed Systems

Some authors also use the designations powder deposition and powder injection. Powder feed systems (process available in following figure) are also known as Laser Cladding, Directed Energy Deposition and Laser Metal Deposition [19]. There are two types of powder feed systems in the market. The most common is the one where the part to be “printed” remains stationary and deposition head moves; the other version of system is the one where the deposition head remains stationary and the work piece moves accordingly [13,14].

In powder feed systems technology, a laser is used to melt the powder into the shape required by 3D modelling. However, instead of having the material and the thermal energy source separated, they are directly injected through an inert carrier gas or by gravity feed, and a separate supply of shielding gas is used to protect the molten weld pool from oxidation [7,13,14].

![Figure 7: Powder feed example - direct laser deposition (DLD) [7]](image-url)
The deposition head is a focused laser beam, and can have a single powder-spray nozzle or multiple nozzles, and as particles are deposited, the laser beam provides sufficient thermal energy to melt them, forming a molten pool of material. As the laser materials interaction zone moves along the part’s surface, the molten material rapidly solidifies and forms a continuous track of dense material. Partial overlapping of individual tracks in a suitable pattern produces a continuous layer of material [13,23].

The range of applications to this technology is very wide, due to process preciseness in the deposition, since it is completely automatic. It can be used to add metallic material to existing parts (for repairing, modifications, adjustments, among others) and it is not restricted to a confined volume, like the powder bed systems, enabling the deposition on large parts. In general, this technology is not able to deposit the same volume of material as the powder bed techniques but it is more useful for repair and cladding [13,19]. By overlapping layer after layer, a fully dense 3D object is created, based in CAD files.

1.3.3 Wire Feed Systems

In wire feed systems (process available in following figure), the feedstock material is metal wire and the energy source for these units can include electron beam, laser beam, and plasma arc.
First operation is to place a drop of material and, passage after passage, metal will continue to be placed over, creating the three-dimensional part developed. Usually, these systems are suitable for processing with a high deposition rate and to build large volumes, but the obtained products frequently require more extensive machining than the powder bed or powder feed systems [14].

1.4 **Benefits of Metal-based Additive Manufacturing**

One of the major advantages of using AM, in comparison with SM, is the ability to produce components by effectively joining materials, typically layer upon layer, which could not be produced - until now - using traditional subtractive processes, leading to new innovations, until now unable to be reached [7].

The AM equipment enables the topological optimization, and allows the utilization of equipment to produce parts when and where they are required by production, if changes are required or if they are intended in a certain way.

AM facilitates the prototypes development and decreases the testing period, before new product market launch, as also the reduction of assembly operations, since it is possible to combine parts (including moving complex parts) into a single component, without additional manufacturing processes. This avoids additional costs and time-consuming tooling, by eliminating production steps, reduces material waste, allows an effective managing of the energy used, and helps reducing the carbon footprint [7,8,13,24].

When comparing with subtractive production processes, AM technology brought a wide range of new possibilities and enabled design freedom, by allowing the production of complex parts at a smaller manufacturing cost. The production cost does not vary with the complexity since it will only increase costs marginally, as it is possible to see in the following figure.
The complexity saving is only a small part of the cost saving perspective. Small production series are expensive in traditional processes, due to high costs with molds, manufacturing operations, among others. AM is rapidly becoming a key enabler for accelerated product development, testing processes and design change, completely changing the economic paradigm for production of prototypes and small series, which will now have a smaller cost, enabling the desired conception flexibility [25,26]. AM processes have the potential to transform the cost effective mass customization of complex products that cannot be manufactured easily using traditional (subtractive) technologies [24].

The supply chain paradigm, as we know it, will also change, becoming more agile, and will require strategic redesign. The production will be decentralized and will occur only when and where it is required [26].
There is a rich landscape of available technologies and materials for MbAM. The metals used as feedstocks in the AM are increasing, and at the present time it is possible to use different materials like titanium alloys, aluminium alloys, nickel alloys, high-grade stainless steels, and also tool steel [13]. AM has a huge potential in unique and personalized applications, that could not be produced with standard processes and equipment. Among other examples, can be included medical implants with the exactly required body geometry, flexible electronics, turbine blades with internal cavities, lightweight components, multi-materials components, to name a few [13,24].

To fully meet the potential of MbAM, continued equipment development for full manufacturing readiness and understanding of the materials processes is essential. Due to the rapid market growth and end-user (manufacturing companies mainly) attention, in the upcoming years equipment suppliers will invest in this technology, releasing newer technologies with extensive improvements [13].

The combination between AM technology and finite elements software, which enables the simulation and analysis of design behavior under work conditions, will result in products that are lightweight and more robust when comparing with traditional manufacturing methods.

1.5 **Limitations and Challenges of Metal-based Additive Manufacturing**

The AM process has high production cost, which is a consequence of a slow building rate and metal powder cost. The other major handicaps are related with manufacturing process itself, with anisotropic components, surface roughness finish and dimensional accuracy, which is lower when compared with traditional manufacturing, demanding post-processing operations, like trimming, milling, drilling, grinding, or achieve the same properties has in traditional manufacturing [25].

Some of the major constraints are the slow manufacturing rate, inefficiencies in the process due to technology status (resulting from prototyping), high producing parts costs due to low build rate and feedstock cost, paradigm change in design, equipment parametrization, complex manufacturing process (component anisotropy, surface
finish and dimensional accuracy may be inferior, which requires post-processing), discontinuous production process (nonintegrated systems prevents economies of scale) and limited component size due to be limited to equipment chamber size [13,25,26]. During design, and when CAD file is being imported to the AM equipment, it is required to properly evaluate components geometry, checking if there is any part of component that is overhanging; if this happens, support structures are required, which means that it will be required to introduce a feature that will require a post-processing operation to remove this structure [25,26].

Some of the major difficulties encountered in MbAM are typically associated to the layer manufacturing or layered residual stresses. In the layer manufacturing, it will affect directly the surface roughness and the part accuracy; regarding layered residual stresses, they will be affected by the high thermal gradients (powder melt and solidification in a short time). As result, parts produced with MbAM technology will have inferior surface quality when compared with parts produced with traditional manufacturing technologies, like CNC milling [27].

Since each equipment supplier has its own characteristics for process, and also for feedstock specifications (powder size, for instance), same parts produced in different equipment will have a variation in the quality and mechanical properties of produced parts. Powders require a tight quality control (e.g. composition and particle dimension) to assure that between different lots, properties are maintained, and repeatability is possible. Until now, one of the main materials used in MbAM is Ti-6Al-4V, justified with high cost and utility in high-value applications in aerospace and medical. Industry is expecting new metallic powders, with improved characteristics, for e.g. with smaller particle size [13].

The lasers will also require additional developments, in the power and in accuracy, to enable more efficient sintering processes.

With these improvements, in equipment process, powders, lasers, among others, it will be possible to produce new kind of products with MbAM technology, which until now were only possible to be manufactured through traditional manufacturing processes [13,28].
At this moment, there are several AM technologies and equipment manufacturers available in the market, but it is required further development and improvements on accuracy, mechanical properties and discarding the need of post processing operations. These improvements will happen with the increasing relevance and densification of this technology. However, the required improvements are not only in the AM process and equipment, materials or lasers; they are needed in the methodologies for nondestructive evaluation, to have an extensive knowledge of what is really happening at microstructure level.

1.6 **DIRECT METAL LASER SINTERING**

DMLS was the selected technology to evaluate MbAM at YAZAKI. DMLS is a powder bed fusion technology, which fires an Ytterbium (Yb) fiber laser into the metal powder bed. The laser is aimed to defined points in space demarcated by a 3D model of part to be produced, where it will melt the powder particles, fusing the material together, to create a solid structure, as it is possible to see in the following figure [3,17,18,29].

EOS GmbH - Electro Optical Systems is a German company founded in 1989. Direct Metal Laser Sintering (DMLS) was developed and patented together with Rapid Product Innovations, in 2004 [18].

![Figure 10: Section view of the DMLS 3D printing process [30]](image-url)
DMLS, SLS and SLM process are similar; however, DMLS has a higher detail resolution, when compared with the other technologies. The main reasons for this are the thinner layers used, enabled by a smaller metal powder diameter (20 µm), and high intensity laser beam (Yb-fibre laser with 400 W) [18]. The high intensity laser beam creates solid metal parts by fusing the fine metal powder particles, layer by layer, with the shape defined in the three-dimensional CAD model, as shown in following figure [31].

![Real time DMLS processing of maraging steel powder](image)

**Figure 11**: Real time DMLS processing of maraging steel powder

Parts produced have a high density (almost fully dense), can be geometrically complex, with hollow shapes, and with mechanical properties equivalent to parts produced by traditional manufacturing methods. DMLS is widely used for the direct fabrication of prototypes, tools and functional parts [31].

Material options include maraging steel, stainless steel, aluminium, cobalt-chrome, and copper, nickel and titanium alloys [18,22,31]. It is expected that in the future new materials will be introduced for MbAM, opening the range of applications and products that can be produced with this technology.

Since 2004 DMLS had several technological improvements to improve produced parts quality, including the laser beam delivery system, powder, control of the temperature and atmosphere in the building chamber [3].
As already mentioned, the traditional (or conventional) production processes restrict design and construction freedom when parts complexity increases, making the cost of production also increase.

![Break even analysis](image)

**Figure 12**: Break even analysis for costs in injection moulding illustrates economic benefits of DMLS in comparison to traditional manufacturing [32]

As show in the previous figure, the fixed costs at present time are higher, when compared with traditional process. Nevertheless, as soon as the break-even point is reached, DMLS will enable total cost and cycle time reduction. For instance, AM enables single parts manufacturing in a fast way, and when compared with traditional manufacturing, becomes cost-effectively and flexibly. Small batch sizes, high complex forms, designs with integrated cooling or tempering channels, are not a problem to MbAM and DMLS, but critical in traditional processes [32,33]. With the end of some OEM patent protection, plus the attention that market is starting to show, in the near future technology will become more effective and independent of additional processes to get same finishing as traditional manufacturing processes [11].
METAL-BASED ADDITIVE MANUFACTURING
Evaluation of metallic parts produced with Additive Manufacturing Technology at YAZAKI Europe Limited

1.7 **EOS M 290**

1.7.1 **TECHNICAL DATA**

The equipment selected to produce YAZAKI components was an EOS M 290, as show in the following figure:

![Figure 13: EOS M 290](image)

(1) Indicator; (2) Optics system cover; (3) Emergency STOP button | Service key-operated switch | Inert gas selector switch | Service network connection; (4) Touch-sensitive monitor; (5) Process chamber; (6) Metal powder vacuum cleaner; (7) Recirculating filter system pre-filter stage; (8) Recirculating filter system - fine filter stage.

According to EOS, this model allows a “fast, flexible and cost effective production of metal parts directly from CAD data”. This equipment can produce metal serial components, spare parts and functional prototypes, operating under controlled
atmosphere (nitrogen and argon), enabling a wide range of materials like aluminium, cobalt chrome, nickel alloy, maraging and stainless steel, and titanium [34-36]. With a building volume of 250 x 250 x 325 mm, the equipment was appropriate to produce in one time only, all the parts required and previously defined, to be evaluated [35].

<table>
<thead>
<tr>
<th>Technical Data EOS M 290:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Building volume</strong></td>
</tr>
<tr>
<td><strong>Laser type</strong></td>
</tr>
<tr>
<td><strong>Laser Power</strong></td>
</tr>
<tr>
<td><strong>Laser Wavelength</strong></td>
</tr>
<tr>
<td><strong>Precision optics</strong></td>
</tr>
<tr>
<td><strong>Scan speed</strong></td>
</tr>
<tr>
<td><strong>Focus diameter</strong></td>
</tr>
<tr>
<td><strong>Power supply</strong></td>
</tr>
<tr>
<td><strong>Power consumption</strong></td>
</tr>
<tr>
<td><strong>Nitrogen generator</strong></td>
</tr>
<tr>
<td><strong>Compressed air supply</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Dimensions (W x D x H):</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>System</strong></td>
</tr>
<tr>
<td><strong>Recommended installation space</strong></td>
</tr>
<tr>
<td><strong>Weight</strong></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Data preparation:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>EOS Software Available</strong>: EOS RP Tools</td>
</tr>
<tr>
<td>(<strong>Quality management</strong>)</td>
</tr>
<tr>
<td>(<strong>Quality management</strong>)</td>
</tr>
<tr>
<td>(<strong>Quality management</strong>)</td>
</tr>
<tr>
<td><strong>CAD interface</strong></td>
</tr>
<tr>
<td><strong>Network</strong></td>
</tr>
</tbody>
</table>

As seen in the previous table, one of the most impressive characteristics of this equipment is the Ytterbium-fibre laser, with 400 watts power, which enables a focus diameter of 100 μm, which means that is possible to work with a layer thickness
between 20 and 60 μm, and tolerances between 20 and 50 μm, depending on equipment parameterization and powder material used.

The controlling software is a real advantage in the conversion of CAD, but also in the moment that is intended to foreseen what and how will be the production.

1.7.2 Laser Sintering Process

The basic physical process principle of the laser sintering is the melting of layers of metal powder using an Yb fibre laser.

![Figure 14: Principle of DMLS process with EOS M 290](image)

The laser beam heats the metal powder to a temperature higher than the melting point. The part will be produced by a heating and cooling process to exposed areas, which will solidify and enable the joining of the top layer to the one underneath. The
repetition of this process, layer by layer, will enable the three-dimensional parts, as seen in previous figure [34,38].

Before production starts, it’s required to prepare data. The CAD data needs to be carefully prepared, to avoid errors, and converted to STL format. During data preparation, one of the most critical aspects is the generation of building supports, with specific software (like Magics SG+), which will be constructed directly on the building platform or in the building chamber. They will prevent parts torn out of the powder bed during production, and will absorb internal stresses that may occur during the building process, dissipates excess heat after the melting of the powder and avoid distortions during cooling [39].

![Figure 15: Building supports [39](a) Block support on an area of a part; (b) Angled support; (c) Tooth structure for improved ease of removal in Magics SG+.

With a block support (figure 15a) - default support type recommended by EOS - an area of a part is connected to the building platform with the aid of a grid structure. Sometimes it is required to have supports in areas with difficult access, using - in this case - the angled supports (figure 15b). Usually, the building supports are easy to remove due to the tooth structure (figure 15c).

At this point, with specific software applications to prepare data, provided by EOS, parts will be oriented and positioned, and then “sliced” to enable production. After this, the machine will receive the building task and is ready to start the production [39].

The building process in EOS M290, as presented in the following figure, starts when the building platform moves to the start position and a first layer of metallic powder
material is applied on the building platform. At this point the machine chamber will be flooded with adequate inert gas, until the level of oxygen inside the chamber is below a defined limit. When this is reached, the building process starts, and the laser is beamed to the powder according what was defined in the CAD file [34,35,38].

To ensure the part produced with laser sintering process achieves the desired quality, three main factors need to be controlled: exposure, process related effects (distortion and shrinkage) and ambient conditions.

During the exposure of a layer, the part periphery (or contour) and the enclosed area of the layer, are exposed. The powder is melted and bonded to the powder particles on the same layer and with the underneath layer [38].
During the exposure, the laser beam forms a curing area around the solidified metal powder (previous figure), requiring controlling it to get dimensional accuracy. The dimensional variation is compensated by offsetting the laser beam [35,36,38]. The laser beam offset, affects the enclosed areas of the layer and the contour, requiring proper evaluation to avoid producing parts out of tolerances. The laser sintering process affects the parts geometrical properties. It is possible to get parts with good quality by enabling an effective positioning and orientation of the parts in the building chamber, and by optimizing the part geometry mainly in the critical areas [38].

It is also required to evaluate two additional process-related phenomena: the shrinkage and the distortion. Related with shrinkage, as show in the following figure, the produced part must be bigger enough to compensate the contraction and deformation during the cooling phase, to be according with specified dimensions [38].

![Shrinkage behavior of the part during the cooling phase (Figure 18)](image)

Regarding the distortion, which is dependent on the part geometry and the material used, it occurs when there are large thermal differences during the building process or during cooling after the end of the building process [38]. EOS provides (as optional) software to support equipment end-user, regarding shrinkage effect, which will minimize the influence in final parts.
Consequence of not accomplishing and not following rules related with ambient conditions can result in malfunctions in the building process, machine and accessories. Controlled room temperature, controlled atmosphere humidity and proper supply of inert gas are mandatory to avoid equipment worn-out.

1.8 **The material: Maraging steel**

The internal components (traditional processes) selected to compare with AM technology are produced with two hot work tool steels: if parts are produced in Japan the steel used is AISI S7 and if parts are produced in Europe it is used the AISI Type H13 (1.2344). Components are produced through traditional processes, like CNC milling and trimming, wire electro erosion, among others. Both materials have similar elements, with different compositions, according to the following table:

<table>
<thead>
<tr>
<th>Elements</th>
<th>Chemical composition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td><strong>AISI S7</strong></td>
</tr>
<tr>
<td>Carbon, C</td>
<td>0.55 %</td>
</tr>
<tr>
<td>Chromium, Cr</td>
<td>3.25 %</td>
</tr>
<tr>
<td>Iron, Fe</td>
<td>93.5 %</td>
</tr>
<tr>
<td>Manganese, Mn</td>
<td>0.70 %</td>
</tr>
<tr>
<td>Molybdenum, Mo</td>
<td>1.4 %</td>
</tr>
<tr>
<td>Silicon, Si</td>
<td>0.35 %</td>
</tr>
<tr>
<td>Vanadium, V</td>
<td>0.25 %</td>
</tr>
</tbody>
</table>

These steels present good mechanical behavior and are capable of cold and hot work applications. They have good hardenability, wear resistance, high strength and toughness. With an age hardening treatment it is possible to achieve high hardness (HRC between 58 and 60), which is one of the requirements of YAZAKI [40,41]. The applications to these steels are considerable: tool die for casting, extrusion, stamping and forging, hot shear blades, among others.

As explained, the MbAM technology already uses different metallic alloys, like tool and stainless steel, aluminium, cobalt-chrome, copper, nickel and titanium alloys. Due to
metal-based additive manufacturing

Evaluation of metallic parts produced with Additive Manufacturing Technology at YAZAKI Europe Limited

Material specificity used at YAZAKI, and looking to the material offer from EOS, the only viable option was the maraging steel.

Maraging steels are iron-nickel alloys with molybdenum, cobalt, titanium and aluminium, with very low carbon. With properties like high strength, superior toughness and weldability, they are usually used in aerospace applications, machinery and tooling [22,31]. Maraging steels are a good alternative, since they reduce the risk for quench cracking, while the high nickel content and absence of carbides provides a good corrosion resistance [27].

EOS maraging steel is coded as MS1, and its nominal composition is described in following table:

<table>
<thead>
<tr>
<th>Alloying Element</th>
<th>Fe</th>
<th>Ni</th>
<th>Co</th>
<th>Mo</th>
<th>Ti</th>
<th>Al</th>
<th>Cr</th>
<th>Cu</th>
<th>Mn</th>
<th>Si</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>wt% Balance</td>
<td>17-19</td>
<td>8.5-9.5</td>
<td>4.5-5.2</td>
<td>0.6-0.8</td>
<td>0.05-0.15</td>
<td>≤ 0.5</td>
<td>≤ 0.03</td>
<td>≤ 0.1</td>
<td>≤ 0.01</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4: Technical properties of maraging steel processed with EOS M 290 [27,42,43,45]

<table>
<thead>
<tr>
<th>Specification:</th>
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</tr>
</thead>
<tbody>
<tr>
<td>Material</td>
<td>EOS MS1</td>
<td></td>
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<tr>
<td>DIN No.</td>
<td>1.2709</td>
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<tr>
<td>Material Name</td>
<td>X3NiCoMoTi 18-9-5</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Size Ranges (µm)</td>
<td>25-63</td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Density (g/cm³)</td>
<td>8.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Relative Density</td>
<td>approx. 100 %</td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

| Technical data:     |        |        |        |        |        |        |        |        |        |        |        |
| Achievable part accuracy | small parts (< 80 x 80 mm) | approx. ± 20 µm |        |        |        |        |        |        |        |        |        |
|                      | large parts |        |        |        |        |        |        |        |        |        |        |
| Age hardening shrinkage | (6 hours at 490°C) | approx. 0.08 % | (in all directions) |        |        |        |        |        |        |        |        |        |
| Min. wall thickness  | 0.3 - 0.4 mm |        |        |        |        |        |        |        |        |        |        |

EOS MS1 is a steel powder, specially optimized to be used in EOS equipment, has good mechanical properties and age-hardenst to achieve superior strength and hardness.
It has good material properties like high strength, high toughness, good weldability and dimensional stability, is easily machined and presents a good thermal conductivity. It is possible to improve material hardness up to 54 HRC (approximately) with a 6 hours at 490°C age-hardening treatment. In as-built and age-hardened states the parts can be machined, spark-eroded, welded, micro shot-peened, polished and coated if required [36,42]. Some technical properties are presented in table 4.

Due to the layer wise building method, the parts have a certain anisotropy, which can be reduced or removed with appropriate heat treatment [42,46]. Usually, the heat treatment applied is an age hardening, and there is a significant improvement in the mechanical properties of the produced parts, as shown in the following table.

<table>
<thead>
<tr>
<th>Table 5: Maraging steel key mechanical properties [45]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Mechanical Properties</strong></td>
</tr>
<tr>
<td>Ultimate Tensile Stress</td>
</tr>
<tr>
<td>Yield Strength</td>
</tr>
<tr>
<td>Hardness</td>
</tr>
</tbody>
</table>

The EOS MS1 is built from gas atomized powder and their typical morphology before processing shows a majority of powder particles bear spherical and near-spherical morphology, without sharp edges and corners, which allows a free flow of the powder during layer deposition, which will increase the process efficiency [27,47]. In following Scanning Electron Microscopy (SEM) micrographs it is possible to see powder particles size and shape.

![Figure 19: Maraging Steel SEM micrographs [47]](image-url)
The combination between morphology previously described and the small powder particle diameter will enable a better control of the thermal gradient when the laser makes the sinterization of the powder, which will ensure a better surface finish to the produced part, limited mechanical stress during production, better details and reduced size of production supports.
EXPRESSMENTAL PROCEDURE

2 EXPERIMENTAL PROCEDURE

The AM equipment used to build specimens was an EOS M 290, and the powder used was the maraging steel provided by EOS, the MS1, as shown in the following figure.

![EOS M 290 and EOS Maraging Steel MS1](image)

*Figure 20: EOS M 290 (left picture) and EOS Maraging Steel MS1 (right picture)*

The metallic parts that were selected to be produced through MbAM on this trial are used in YAZAKI production. These specific parts have a very high consumption (worldwide), and are used in one of the core production processes. Due to their specificity and required accuracy, their importance to production and manufacturing of wire harness is very high.
In the start of this project, a partnership was created with a Portuguese company (Unite Global Tooling Solutions), which has the EOS equipment and a good knowledge in the production of AM metallic parts for some years now. Unite received required CAD data, *.STL files format, with selected parts. All information was imported and prepared (disposition in building table, components geometry to define required building supports) with EOS and Materialise NV© software; after this, required information was transferred to equipment, enabling the start of the YAZAKI parts production. Layout of production available in the next figure:

![Figure 21: Materialise build preparation, with parts selected for evaluation, disposed in the production table](image)

UNITE made several adjustments to maximize the achieved quality of parts, and improve the finishing details. According to the supplier information, the parameterization applied in this production is the one pre-defined by EOS, and the parts were produced in a nitrogen atmosphere.

After parts production it was decided to apply to them different heat treatments, in order to evaluate how parts would behave. The heat treatments selected where based
in recommendations of EOS for MS1 material [42], and also one based in the work of Yasa et al. [31], available in table 6.

Before the heat treatments, it was required the removal of all building supporting structures (following figure), required to produce parts, otherwise, after heat treatment, it would be more difficult due to expected hardness increase. It was selected a supplier to make these trims, experienced with these parts used at YAZAKI.

![Figure 22: YAZAKI parts before (left picture) and after (right) trimming the building supports](image)

The heat treatments were conducted in the furnaces (figure 23) available in the Department of Metallurgical and Materials Engineering (DEMM), at Faculdade de Engenharia da Universidade do Porto (FEUP).

![Figure 23: Heat treatment furnaces available at DEMM (FEUP), used for the heat treatments](image)
Two age hardening heat treatments were applied, 8 hours at 480 °C [31] and 6 hours at 540 °C [42], with the parts inside of the furnace during the heating and cooling processes, as presented in table 6.

It was also intended to evaluate if an annealing would have a significant impact in the MbAM produced parts, since annealing is required to the maraging steels. The selected treatment was held at a temperature of 850 °C over one hour; the specimens were not inside the furnace during heating and cooling. After annealing, the same age hardening treatments were applied.

The heat treatments applied to the produced parts are resumed in the following table:

<table>
<thead>
<tr>
<th>Designation</th>
<th>Solution Annealing</th>
<th>Age hardening</th>
</tr>
</thead>
<tbody>
<tr>
<td>T4</td>
<td>Not applied</td>
<td>- Stage 1: Environment temperature to 480 °C in 4h30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Stage 2: 8 hours at 480 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Stage 3: 480 °C to environment temperature in 6 hours</td>
</tr>
<tr>
<td>T5</td>
<td></td>
<td>- Stage 1: Environment temperature to 540 °C in 5h30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Stage 2: 6 hours at 540 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Stage 3: 540 °C to environment temperature in 6 hours</td>
</tr>
<tr>
<td>ST4</td>
<td>- Furnace pre-heat to 850 °C</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- 850 °C during 1 hour</td>
<td></td>
</tr>
<tr>
<td></td>
<td>- Air cooling</td>
<td>- Stage 1: Environment temperature to 480 °C in 4h30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Stage 2: 8 hours at 480 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Stage 3: 480 °C to environment temperature in 6 hours</td>
</tr>
<tr>
<td>ST5</td>
<td></td>
<td>- Stage 1: Environment temperature to 540 °C in 5h30</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Stage 2: 6 hours at 540 °C</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Stage 3: 540 °C to environment temperature in 6 hours</td>
</tr>
</tbody>
</table>

All heat treatments applied to MbAM parts were made without a controlled atmosphere inside the furnace.

To evaluate MbAM produced parts, it was decided to evaluate parts - before and after heat treatment - for hardness, dimensional analysis, microstructure and tensile...
strength. It was also decided to make a powder characterization to the EOS Maraging Steel MS1, through SEM, to evaluate the particle size and shape.

All the dimensional analysis measurement and reports were prepared at YAZAKI European Laboratory, based in Portugal, which is accredited by IPAC (Instituto Português de Acreditação). The dimensional analysis was performed with optical 2D Microscope (X and Y axis: range of X = 0 to 200 mm, Y= 0 to 99 mm), with a global uncertainty of measurement equal to ± 0.0055 mm. The evaluation was executed following a YAZAKI internal procedure LNS-Z97-2003 (Level 2.00), based in ASME Y14.5-2009, in a temperature and relative humidity controlled room.

The hardness test was performed in the Department of Metallurgical and Materials Engineering (DEMM), at Faculdade de Engenharia da Universidade do Porto (FEUP), with the DuraVision 20 (EMCO-TEST), and the HV20 Vickers Hardness was measured. One specimen was prepared for each, with one cubic centimeter, for the following conditions:

- Sample no. 1: As-received part, without heat treatment (MbAM);
- Sample no. 2: Annealing treatment only (An.);
- Sample no. 3: With age hardening at 480 °C (T4);
- Sample no. 4: With age hardening at 540 °C (T5);
- Sample no. 5: With annealing and age hardening at 480 °C (ST4);
- Sample no. 6: With annealing and age hardening at 540 °C (ST5).

To convert the HV20 to HRC, and enable the comparison with traditional data available inside YAZAKI, it was used the following formula [48]:

\[
HRC = \frac{100 \times HV - 14500}{HV + 223}
\]

In each specimen, seven indentations were made to determine the hardness of the material to deformation.

The powder and the microstructural characterization were performed at Materials Centre of the University of Porto (CEMUP) with a high resolution scanning electron microscope (SEM) FEI Quanta 400 FEG ESEM, while the composition was analyzed by an
energy dispersive X-ray spectrometer EDAX Genesis X4M coupled to the SEM. The EDS measurements were executed at an accelerating voltage of 10 and 15 keV by the standardless quantification method. For the microstructural characterization specimens with one cubic centimeter were used (similar to the ones used in hardness test), and the metallographic analysis of the samples followed the standard metallographic preparation: cutting, grinding and polishing.

For the tensile testing, nine (9) specimens were built according to the following standard drawing:

![Figure 24: Tensile testing specimen](image)

The tensile testing was carried at CINFU (Centro de Formação Profissional da Indústria da Fundição) according to ISO 6892-1:2012B, with Shimadzu UH equipment, which has a maximum strength of 1000 KN. The specimens were divided in three groups, as follows:

1. Three (3) as-received specimens;
2. Three (3) as-received specimens with polished gauge area;
3. Three (3) age hardened T4 specimens.

The characterization of tensile specimens failure was made at Materials Centre of the University of Porto (CEMUP) using SEM and EDS with same parametrization has described for powder and the microstructural characterization.
EXPERIMENTAL RESULTS AND DISCUSSION

3 EXPERIMENTAL RESULTS AND DISCUSSION

3.1 POWDER CHARACTERIZATION

The as-received powder particles of the gas atomized maraging steel mainly present a spherical or near-spherical morphology, as presented in the following figure.

Figure 25: Dimensional analysis of the as-received maraging steel powder observed by SEM
The observed morphology has no sharp edges and corners. The powder particles have sizes ranging from 6 μm until 60 μm, and with an average size around 30 μm (information based in supplier certificate).

During analysis with SEM, two exceptions were found: bean shaped particles and clusters.

Occasionally, some long non-spherical particles appeared, and seemed to be fused between themselves, with some resemblances to beans, phenomenon that happens due to particles cooling. In the example shown in the previous figure, the total particles length is approximately 60 μm, and in the top extremity it is possible to see smaller ones (less than 10 μm) also fused. The bean particle presents an irregular surface (red box detail in previous figure), and a similar phenomenon was also present in other particles. When observing this phenomenon in detail, a dark gray inclusion was found (next figure), which was analyzed through EDS (figure 28).

In the particles noted with the orange arrows (previous figure), it is possible to see small sized particles attached to bigger ones. This shows an adhesion phenomenon between particles, and the most reasonable explanation is that this process occurs during the metallic powder production, through gas atomization.
Figure 27: Powder particles with irregular surface, and dark gray inclusion observed by SEM

Figure 28: Result of EDS analysis in dark gray inclusion (Z4) presented in figure 27
The EDS spectrum of Z4 area (figure 28) revealed that the dark gray inclusion contains a big proportion of aluminium, titanium, and oxygen. Iron, nickel, molybdenum and cobalt could be the result of the volume of interaction of the EDS analysis. Based on this, it is possible to define that this kind of inclusions are mainly aluminium and titanium oxides, and are resultant from the powder gas atomization process.

As previously stated, it was observed a second uncommon structure (following figure). This structure is a big sized cluster, in some cases with 60 μm long, which looks like an agglomerate of small melted powder particles (with size smaller than 10 μm). These clusters present an irregular cylindrical shape, but it was possible to observe others with spherical, oval and elliptical irregular shapes. The common characteristics between them are the several smooth edges presented, which possibly happen due to melting phenomenon that occurs during atomization.
The clusters physical aspect is different from the usual shape of particle. Due to this, it was performed an EDS analysis to the cluster (figure 29), to determine if the chemical elements are different from known chemical composition of EOS maraging steel MS1 (available in table 3, page 26). The EDS spectrum (figure 30) of Z3 area revealed that cluster contains iron, nickel, molybdenum, cobalt, titanium and carbon. Comparing this analysis with the known composition of the maraging steel, all these components are part of the chemical composition and are the major alloying chemical elements.

<table>
<thead>
<tr>
<th>Element</th>
<th>At %</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>7,97</td>
</tr>
<tr>
<td>Mo</td>
<td>2,77</td>
</tr>
<tr>
<td>Ti</td>
<td>1,43</td>
</tr>
<tr>
<td>Fe</td>
<td>62,60</td>
</tr>
<tr>
<td>Co</td>
<td>8,76</td>
</tr>
<tr>
<td>Ni</td>
<td>16,48</td>
</tr>
</tbody>
</table>

Figure 30: Result of EDS analysis in cluster, in the area marked with Z3 (presented in figure 29)

During the powder observation it was found one particle (figure 31) with some kind of film plate inlaid, as it is possible to see in the following figure. During SEM observation it was tried to find additional particles with the same feature, without success.

To identify the composition of the two areas, both were analyzed with EDS: Z1 for the inlaid film plate, and Z2 for the powder particles.
The EDS spectrum of Z1 area (figure 32) revealed that the film plate contains a big proportion of titanium and nitrogen, which indicates that this area is a particle of titanium nitride film. One possible explanation for the visible plate observed, is that it has been formed through a chemical reaction between the titanium available in the material composition and nitrogen, which can be available during gas atomization (no information available about the gas used) or in the equipment building chamber. Other possible scenario is that this plate is a titanium residue in the powder, due to a poor atomization process, and during the atomization process fused together.

About the EDS spectrum of Z2 (figure 33), this area revealed that the powder particle contains a big proportion of iron, nickel, molybdenum, cobalt, and carbon. Comparing this morphology with the known maraging steel composition, and following the EDS spectrum of Z3 area, already mentioned, the components are part of the known chemical composition and are the major alloying chemical elements of the maraging steel.
Figure 32: Result of EDS analysis in the particle with the inlaid film plate; area marked with Z1 (figure 31)

<table>
<thead>
<tr>
<th>Element</th>
<th>At %</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>1.87</td>
</tr>
<tr>
<td>N</td>
<td>28.69</td>
</tr>
<tr>
<td>Ti</td>
<td>69.43</td>
</tr>
</tbody>
</table>

Figure 33: Result of EDS analysis in the particle with the inlaid film plate; area marked with Z2 (figure 31)

<table>
<thead>
<tr>
<th>Element</th>
<th>At %</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>15.01</td>
</tr>
<tr>
<td>Si</td>
<td>0.61</td>
</tr>
<tr>
<td>Mo</td>
<td>3.03</td>
</tr>
<tr>
<td>Ti</td>
<td>1.05</td>
</tr>
<tr>
<td>Fe</td>
<td>57.03</td>
</tr>
<tr>
<td>Co</td>
<td>7.91</td>
</tr>
<tr>
<td>Ni</td>
<td>15.35</td>
</tr>
</tbody>
</table>
The metallic powder is one of the most critical aspects within MbAM, having a direct impact in the achieved quality, mechanical properties, and surface characteristic. The production of these powders is a hard and costly process, making powders expensive. The gas atomization is a process to manufacture high quality metal powders, with a perfectly spherical shape, without sharp edges and corners, what will guarantee the free flow of the powder during layer deposition, thus increasing process efficiency.

The detected bean shape and clusters, plus the dimensions bigger than 50 μm, can represent a problem during layering in the machine bed, since this is the height of layer (50 μm) that EOS equipment uniformly spread in the machine bed.

### 3.2 Dimensional Analysis

As previously mentioned, it was required to remove all building supports, operations made with CNC milling and wire EDM machining. The CAD drawings were shared with supplier to facilitate removal operations.

Before making the dimensional analysis they were adjusted to the usual requirements, as required by YAZAKI. Since the supplier knows very well these parts, during the removal operations, the supplier detected that the majority of parts were distorted (example shown in the following figure).

![Part distortion before trimming (left side picture) and same part after trimming (right side picture)](image-url)
The trimming operations to remove distortion and to remove building supports conditioned the dimensional analysis evaluation, creating a bottleneck since most of the measurements evaluated are out of specified dimensions and tolerances. By analyzing all reports with dimensional analysis\(^2\), in the trimmed dimensions, it is possible to confirm that after trimming most dimensions are not in accordance with what is required by the part’s drawings. The majority of discrepancies are in the areas of distortion, and also where it was required to remove the supports. For untrimmed dimensions, most of them in critical work areas, which represents tight tolerances values to accomplish, it was not possible to identify a clear trend regarding the evaluated dimensions, mainly because values dispersion was found between similar dimensions in the different parts. It was possible to confirm that if the outside dimensions were not trimmed, they would comply with the defined dimensions and tolerances, when compared with other areas, for instance, the work area of parts.

It is known that the laser sintering process affects the geometrical properties of parts, and promotes distortion. Part geometry, in this particular case, does not explain the reason why distortion appeared, since all compared parts were built in the same position/direction, the bottom part is always based in building supports and provides good support with lower part of the component. One possible explanation is the thermal gradient (powder melts and solidifies in a short time) during the building process. The laser passage building speed could also be an explanation, but - in this specific case - the supplier used EOS specifications. Shrinkage could also be a possibility, but it was not possible to make a proper evaluation if it happened. Supplier parts usually control shrinkage parameter by analyzing the different productions made with this equipment, adjusting software equipment with the resultant parameter.

Dimensional analysis results do not enable a clear understanding. Major objectives were to evaluate the distortion and shrinkage, and if it would be possible to produce parts achieving tolerances required by YAZAKI drawings (10 to 20 µm). It is clear that

\(^2\) Due to confidentiality agreement and privileged information it is not possible to share the drawings and the dimensional analysis reports.
the reached results are not satisfactory and future evaluations should be carried out, with a different approach.

In future evaluations, additionally to produce YAZAKI parts that should be used to evaluate processability, it must be considered the development of specific specimens that can enable proper dimensional analysis to evaluate if it is possible to achieve required dimensions and tolerances (starting at 5 µm) for parts produced through MBAM, and also evaluate the shrinkage and distortion of parts. It would be also interesting to evaluate these conditions - dimensioning, shrinkage and distortion - based on parts positioning and alignment inside the building chamber.

### 3.3 Hardness

As mentioned, for each specimen, seven (7) measurements were made. The next two following tables present average hardness for each specimen:

**Table 7: Average Vickers hardness measurement to the different specimens**

<table>
<thead>
<tr>
<th></th>
<th>HV20</th>
<th>YAZAKI</th>
<th>MbAM</th>
<th>An.</th>
<th>T4</th>
<th>T5</th>
<th>ST4</th>
<th>ST5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Hardness</td>
<td>623</td>
<td>407</td>
<td>312</td>
<td>605</td>
<td>510</td>
<td>597</td>
<td>535</td>
<td></td>
</tr>
<tr>
<td>Traditional Vs MbAM Samples</td>
<td>-216</td>
<td>-311</td>
<td>-18</td>
<td>-113</td>
<td>-27</td>
<td>-88</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Deviation (σ)</td>
<td>6</td>
<td>7</td>
<td>6</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>7</td>
<td></td>
</tr>
</tbody>
</table>

**Table 8: Average Rockwell C hardness measurement to the different specimens**

<table>
<thead>
<tr>
<th></th>
<th>HRC</th>
<th>YAZAKI</th>
<th>MbAM</th>
<th>An.</th>
<th>T4</th>
<th>T5</th>
<th>ST4</th>
<th>ST5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Hardness</td>
<td>57</td>
<td>42</td>
<td>31</td>
<td>56</td>
<td>50</td>
<td>55</td>
<td>51</td>
<td></td>
</tr>
<tr>
<td>Traditional Vs MbAM Samples</td>
<td>-15</td>
<td>-25</td>
<td>-1</td>
<td>-7</td>
<td>-1</td>
<td>-5</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Standard Deviation (σ)</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

In previous tables it was presented the achieved hardness results, both in HV and HRC. In the column YAZAKI it is presented the value of parts produced with traditional manufacturing process. Regarding other columns, MbAM is related to the sample without heat treatment, An. with annealing treatment only, T4 with age hardening at 480 °C, T5 with age hardening at 540 °C, ST4 with annealing and age hardening at
480 °C, and ST5 with annealing and age hardening at 540 °C (the heat treatments conditions are described in table 6, page 31).

The MbAM samples hardness, as built, are higher than expected, which should be between 33 and 37 HRC [42]. Samples produced had an average hardness of 42 HRC, which represents a very good value, but the phenomenon associated to this increase is not known, such as the implications of this in the heat treatment.

Comparing T4 with ST4, the results are similar, with advantage to T4; the annealing will not bring any advantage to the age hardening. The comparison between T5 with ST5 gives slight advantage to the part with annealing. Comparing ST5 with T4, T4 has advantage, with a higher hardness which can be achieved without annealing, which represents cost and time saving.

YAZAKI requires that the parts evaluated have hardness between 56 and 58 HRC. The traditional process samples measured had an average hardness of 57 HRC and the samples produced with MbAM with T4 age hardening had an average hardness of 56 HRC. Comparing the hardness value between the parts manufactured with traditional processes and parts produced with MbAM, there isn’t a significant difference between them, and both are within YAZAKI requirements.

3.4 MICROSTRUCTURAL INVESTIGATION

Samples were produced with MbAM technology with a layer thickness of 50 µm, and before age hardening they were analyzed with SEM. From previous experiences, where parts were produced with MbAM technology, it was considered to apply a hot isostatic pressing (HIP) or hipping process, to remove internal porosity and voids. HIP is a process where it is simultaneously applied a high temperature and pressure to improve mechanical properties and create fully dense materials, consolidating powders, and interfacial bonding [49].

The immediate impression is that the parts produced present porosity, as seen in the following figure. Usually pores are dark colored and present an irregular shape, which
are not similar to structures presented since they are dark gray colored and have a round or long shape.

By observing the surface of specimens it was only possible to observe one pore (blackspots), available in figure 36, revealing that parts relative density is higher than 99%.

![Figure 35: SEM analysis to material surface, without age hardening, through SEM observation](image1)

![Figure 36: Pore found in specimen surface, with SEM](image2)

With this observation, it was decided to skip the hipping process, and go directly to selected heat treatments, as previously discussed.
Coming back to dark gray spots in the specimens' microstructure, when the SEM magnification was augmented (figure 37 is the magnification of the red square in figure 35), it was discarded the pore theory, due to resemblance with inclusion described in bibliography [31,47].

According to some bibliography, inclusions of titanium and aluminum combined oxides (TiO$_2$:Al$_2$O$_3$), and oxides of titanium, aluminium, molybdenum, and silicon can be present in maraging steels microstructure [31,47]. Inclusions can deteriorate the mechanical properties of components, especially on maraging steels that were age hardened, becoming more brittle [31].

To confirm this scenario, EDS was carried out to confirm the compositions of inclusions. The EDS spectrum of Z1 area (figure 38) revealed titanium, aluminium, and oxygen, enabling the titanium and aluminum combined oxides (TiO$_2$:Al$_2$O$_3$), as described in bibliography [31,47]. The EDS spectrum of Z2 area (figure 39) is similar to the ones presented in figure 30 and 33, and composed by iron, nickel, molybdenum, cobalt, and titanium, allowing a stable composition of the maraging steel produced through MbAM.
METAL-BASED ADDITIVE MANUFACTURING
Evaluation of metallic parts produced with Additive Manufacturing Technology at YAZAKI Europe Limited

Figure 38: Result of EDS analysis in area Z1 (left side graphic), shown in figure 37

<table>
<thead>
<tr>
<th>Element</th>
<th>At %</th>
</tr>
</thead>
<tbody>
<tr>
<td>O</td>
<td>61,54</td>
</tr>
<tr>
<td>Al</td>
<td>5,29</td>
</tr>
<tr>
<td>Ti</td>
<td>31,89</td>
</tr>
<tr>
<td>Fe</td>
<td>1,28</td>
</tr>
</tbody>
</table>

Figure 39: Result of EDS analysis in area Z2 (right side graphic), shown in figure 37

<table>
<thead>
<tr>
<th>Element</th>
<th>At %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>3,62</td>
</tr>
<tr>
<td>Ti</td>
<td>1,08</td>
</tr>
<tr>
<td>Fe</td>
<td>68,27</td>
</tr>
<tr>
<td>Co</td>
<td>9,17</td>
</tr>
<tr>
<td>Ni</td>
<td>17,86</td>
</tr>
</tbody>
</table>
The maraging steels present a good strength and toughness, which are achieved by the age hardening, or aging, of a ductile, low-carbon body-centered cubic (BCC) martensitic structure with relatively good strength [31].

![Image of maraging steel SEM pictures revealing microstructure without age hardening]

**Figure 40:** Maraging steel SEM pictures revealing microstructure without age hardening

It was very difficult to etch specimens, hindering the microstructure evaluation. Analyzing the microstructure, available in the previous figure, it is not very easy, but some areas have a fine microstructure, resembling a martensitic phase. Similar results in bibliography refer that it is possible to identify the martensitic phase, and since parts are not fully martensitic there is presence of austenitic phase. It is also mentioned the presence of a cellular/dendritic morphology of the microstructure, with a very fine solidification columnar grains with an intercellular spacing that are smaller than one (1) µm [22,31,47].

DMLS is, likewise all powder bed systems, a rapid directional solidification process. According with Casalino et al. *the orientation of the columnar growth depends on the actual thermal gradient into the liquid and the solute enrichment of the liquid in front of the solid-liquid interface, which determines the constitutional undercooling. As gradient decreases, crystallization mode changes from planar to cellular, cellular-dendritic and, finally, dendritic solidification mode. Moreover, the higher cooling rate, the finer microstructure features is (cell spacing, interdendritic space, size of dendrites, etc.)* [22].
It is possible to see the titanium and aluminum combined oxides (TiO$_2$:Al$_2$O$_3$) inclusions in some examples marked in the following figure with the red circles, which were confirm through the EDS analysis carried out, and as previously described.

Bibliography mentions that the age hardening is the standard treatment for maraging steels, used with the purpose of creating a uniform distribution of fine nickel-rich intermetallic precipitates during the aging of the martensite; the precipitates will strength the martensitic matrix. It is also aimed to minimize or eliminate the reversion of metastable martensite into austenite and ferrite [31,47].

After heat treatment, the material has a similar material surface to sample without heat treatment (figure 35 and 37), appearing inclusions in the material, as presented in the following figure.
As already described, inclusions of titanium and aluminum combined oxides (TiO$_2$:Al$_2$O$_3$), and oxides of titanium, aluminium, molybdenum, and silicon can be present in maraging steels microstructure [31,47].
To confirm if heat treatment did not change material properties, it was analyzed through EDS, to confirm the compositions of inclusions seen in figure 42. The EDS spectrum of Z1 area (figure 43) is similar to the ones presented in figure 30, 33 and 39, and it is also composed by iron, nickel, molybdenum, cobalt, and titanium, allowing a stable composition of the maraging steel produced through MbAM. The EDS spectrum of Z3 area (figure 44) revealed titanium, aluminium, and oxygen, enabling the titanium and aluminium combined oxides (TiO2:Al2O3), as described in bibliography.

Despite of all the analysis made before, it was found a film plate inside one inclusion (figure 41, Z2 area), like the one previously presented in figure 31.

The EDS spectrum for Z2 area revealed (figure 45), likewise in the figure 32, revealed that the film plate contains a big proportion of titanium and nitrogen, which indicates that this area is a particle of titanium nitride film.
It was performed one additional evaluation to the specimens, by observing the surface after sintering (next figure). It is possible to see surface roughness, which indicates that trimming operations in some areas and polishing will be required, to achieve part drawings requirements.
YAZAKI drawings require a high level of finishing (buffing of 0,2) in some areas of the parts, with no damage of the surface and low roughness; this is required to reduce the force of friction. After buffing operation, final dimensions are required to be inside tolerances.

Buffing is a mechanical finishing operation made with a work wheel that has an abrasive, and the objective is to smooth the workpiece surface.

Usually, buffing is a low harsh process and it is possible to achieve a smooth finishing in the applied areas.

Due to this, in one of the parts a buffing operation was applied to evaluate, before heat treatment, how MbAM parts would behave with this kind of operation. The results achieved were actually very good, as shown in the following figure, where it is possible to see a mirror surface after buffing. The black markings visible on the top of the surface were made during the applied polishing process, since trial was executed with adapted equipment, and can be removed with some additional operations.

![Buffed MbAM part, in the work area](image)

**Figure 47: Buffed MbAM part, in the work area**

### 3.5 Material tensile testing

For the tensile testing, 9 specimens were produced, as previously mentioned.

During the MbAM parts production, the equipment showed an error, and it was forced to be stopped. Supplier did not scrap parts that were being built, refurbished them
and made a parameter re-setting. The specimens present a crack in material surface, as shown in following figure.

![Figure 48: MbAM production failure in tensile test specimens](image)

This was informed and accepted, and was faced as an opportunity to evaluate through tensile testing, what happens to the parts and what will be their mechanical behavior after this kind of situation during parts production.

This defect also happened in some of the other parts produced, which in some was more evident than in others, as shown in following figure.

![Figure 49: Examples of defects which have happened during parts production](image)

One of the main interests about studying this was to evaluate if parts will have a different mechanical behavior, when this kind of problem happens. It was thought that the failure could only be superficial, and parts would have a good performance.
In the following pages it will be presented the results achieved with tensile testing, and due to the poor results achieved, it was decided to evaluate fracture with SEM, enabling a more accurate evaluation of the defect.

It is clear that the parts hardness requirements were achieved, with all measurements performed, as confirmed in the previous point.

Next table provides the mechanical properties derived by tensile testing performed.

**Table 9: Tensile tests results, performed at CINFU according ISO 6892-1:2012B**

<table>
<thead>
<tr>
<th></th>
<th>Gauge Initial Length (mm)</th>
<th>Gauge area diameter (mm)</th>
<th>Fm (N)</th>
<th>Elongation, E (%)</th>
<th>Ultimate Tensile Strength, Rm (MPa)</th>
<th>Gauge Final Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>As-received specimens</td>
<td>15,000</td>
<td>6,46</td>
<td>17902,5</td>
<td>2,50</td>
<td>546</td>
<td>15,375</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6,47</td>
<td>38956,3</td>
<td>0,00</td>
<td>1185</td>
<td>15,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6,47</td>
<td>39131,3</td>
<td>6,30</td>
<td>1190</td>
<td>15,945</td>
</tr>
<tr>
<td>Specimens with polished gauge area</td>
<td>15,000</td>
<td>6,42</td>
<td>3056,9</td>
<td>1,40</td>
<td>94</td>
<td>15,210</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6,46</td>
<td>17902,5</td>
<td>2,60</td>
<td>546</td>
<td>15,375</td>
</tr>
<tr>
<td>Age hardening specimens</td>
<td>15,000</td>
<td>6,47</td>
<td>60206,3</td>
<td>0,00</td>
<td>1831</td>
<td>15,000</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6,47</td>
<td>24328,1</td>
<td>-</td>
<td>740</td>
<td>15,000</td>
</tr>
</tbody>
</table>

The mechanical behavior of maraging steel (Yield Strength, Elongation and Ultimate Tensile Strength) depended on the relative density [22]. According to the information provided by EOS, Maraging Steel MS1 relative density is 8,1 g/cm$^3$. In this case, as already seen, the parts porosity is very reduced, meaning parts should have a very good Tensile Strength (Rm) and Elongation (E).

Due to the production stoppage during parts production, as seen in the previous figures (48 and 49), it was created a failure in the specimens' surface, and the repercussions were catastrophic.

**Table 10: Comparison between EOS theoretical values and tensile testing specimens achieved value**

<table>
<thead>
<tr>
<th>Mechanical Properties</th>
<th>EOS value to part after age hardening</th>
<th>Age hardening specimens</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield Strength</td>
<td>&gt; 1900 MPa</td>
<td>-</td>
</tr>
<tr>
<td>Ultimate Tensile Strength</td>
<td>&gt; 1950 MPa</td>
<td>1831 MPa</td>
</tr>
<tr>
<td>Hardness</td>
<td>50 - 54 HRC</td>
<td>56 HRC</td>
</tr>
</tbody>
</table>
R0.2 could not be determined since the material almost does not present ductility. This defect causes the rapid cracking propagation. However, even with this defect, one of the heat-treated samples, with T4, shows an ultimate tensile strength close to the indicated value (Rm = 1831 MPa).

The failure created during production stoppage, available in all specimens (such as in some of the produced parts), created an accumulation of tensions in this point, and when the tensile force was applied, parts began to fracture in those points.

The failure was observed with SEM (next figure). It can be observed that the failure is not continuous and, observing in detail, it is possible to see powder particles not completely sintered and maintaining the round shape. This means that when this kind of phenomenon happens, the sinterization is not complete, explaining why it was not possible to determine R0.2 and the poor results of the ultimate tensile strength.

After observing the failure available in the tensile strength specimens, it is possible to view, with SEM, a fracture for each one of them.
In the following figure it is observed, through SEM, the fracture surface of the as-received specimen, where it was possible to observe two distinct areas. This heterogeneity shows one broader area («A» detail in the following figure), contrasting with a smaller area («B» detail in the following figure).

![Figure 52: Surfaces fractures for the as-received specimen, observed through SEM](image)

In the «A» area, available in the previous figure, it is possible to see parallel lines, following two directions (similar to a cross), which suggest that these were created during the layer-by-layer sintering when the laser is passing. It is possible to also see the powder topography, suggesting a poor sintering between layers. In the «B» area is possible to see a dimple structure, typical from ductile fracture. In this region is possible to see some bigger structures, surrounded by the dimple structure; augmenting this area («C» and «D»), it is possible to see with deeper detail the dimple structure, as also the presence of unmelted particle powder, suggesting a poor sinterization, as previously referred.

According to Manfredi et al. [22] the ductile fracture is the result of the growth and coalescence of micro-voids and the fragile fracture is due to the macro-voids formed...
during the sintering process with low energy density, which will facilitate the brittle rupture [22,50].

The previously described heterogeneity also appeared in a specimen with polished gauge area (figure 53), also happening in the age hardening specimen (figure 54).

Figure 53: Specimen with polished gauge fracture surface, observed through SEM

Figure 54: Crossed structure in age hardening specimen, observed through SEM
Looking to the fracture surface of the specimen with polished gauge area and the age hardened, and comparing them with the as-received specimens, the same crossed structure is available. Using higher amplification, it is possible to see powder particle not sintered in the fracture surface (next figure).

When equipment fails, the powder layer will be poorly sintered, creating problems in the morphology of the produced part, with poor connection between layers. The crossed structure, with parallel lines, presented in the following figure, was analyzed through EDS, in area Z1 and in area Z2, to analyze the difference between the two available structures represented with gray and black color, respectively.

Figure 55: Crossed structure in polished gauge area specimen, observed through SEM

EDS was carried out to confirm the compositions of the crossed structure seen in the fractures. The EDS spectrum of Z1 area (figure 56) revealed iron, nickel, molybdenum, cobalt, titanium, and carbon. Comparing this morphology to the known maraging steel composition, the components are part of the known chemical composition and are the major alloying chemical elements of the maraging steel.
Evaluation of metallic parts produced with Additive Manufacturing Technology at YAZAKI Europe Limited

**Figure 56**: Result of EDS analysis in area Z1, shown in figure 55

<table>
<thead>
<tr>
<th>Element</th>
<th>At %</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>8,26</td>
</tr>
<tr>
<td>Mo</td>
<td>3,26</td>
</tr>
<tr>
<td>Ti</td>
<td>1,05</td>
</tr>
<tr>
<td>Fe</td>
<td>61,74</td>
</tr>
<tr>
<td>Co</td>
<td>8,95</td>
</tr>
<tr>
<td>Ni</td>
<td>15,74</td>
</tr>
</tbody>
</table>

**Figure 57**: Result of EDS analysis in area Z2, shown in figure 55

<table>
<thead>
<tr>
<th>Element</th>
<th>At %</th>
</tr>
</thead>
<tbody>
<tr>
<td>C</td>
<td>15,00</td>
</tr>
<tr>
<td>O</td>
<td>24,19</td>
</tr>
<tr>
<td>Al</td>
<td>1,99</td>
</tr>
<tr>
<td>Mo</td>
<td>1,55</td>
</tr>
<tr>
<td>Ti</td>
<td>13,33</td>
</tr>
<tr>
<td>Fe</td>
<td>31,20</td>
</tr>
<tr>
<td>Co</td>
<td>4,66</td>
</tr>
<tr>
<td>Ni</td>
<td>8,08</td>
</tr>
</tbody>
</table>
The EDS spectrum of Z2 area (previous figure) revealed iron, nickel, molybdenum, cobalt, titanium, and carbon. Comparing with Z1 area, there is presence of oxygen and an uncommon percentage of titanium, which will enable titanium oxides. To explain why this percentage of titanium oxide is available in the fracture of surface is not easy; one possible explanation is that this oxide has a boiling point higher than the maraging steel, and - due to this - it will float from layer-to-layer, always moving to the top of the last sintered layer. Additional to this, almost all parts produced through MbAM present a blue color in the surface (as seen in figure 57), which is a phenomenon attributed to titanium [51].

![Figure 58: Blue part surface in finished MbAM parts](image)

It was only possible to find this due to the fracture analysis and corresponding EDS analysis.

### 3.6 MbAM Parts Processability

Before starting this project, one of the assumptions made was the trial - and respective run and rate evaluation - of MbAM parts, to check processability and compare with traditional processes. This was not done due to trimming effects in produced parts, and lack of mechanical polishing in work areas.
CONCLUSIONS

4 CONCLUSIONS

In this study, metal-based additive manufacturing (MbAM) was evaluated, by manufacturing metallic parts used in YAZAKI production. Parts were fabricated with maraging steel, processed through direct metal laser sintering (DMLS).

MbAM still is in a lower level when compared with the traditional manufacturing processes, and for sure the upcoming future will bring many technological upgrades, to diminish the difference. Before starting this study, it was conceptualized a road plan, to evaluate in several stages the MbAM technology, with a clear objective: introduce it in YAZAKI in the nearest future possible. This study is the kick-off of the project, and due to this it was decided to start by evaluating the technology and analyze the produced parts.

After parts fabrication, they were trimmed to remove building support required by technology, and afterwards they were age-hardened with recommended treatment from EOS and one from bibliography with better results. After this, tensile test and hardening was evaluated, and also microstructure and dimensional analysis. Additionally, some analysis was made to the maraging steel powder.

The powder characterization showed that particles have a near-spherical morphology, but during the analysis it was also found particles with bean and cluster shape. The particle size has a wide range, from 6 μm until 60 μm, which means that some particle are bigger than the layer defined for the EOS equipment (50 μm), which can represent a problem during the powder layering in the machine bed. The powder composition is defined according to the supplier’s information. It was found aluminium and titanium oxides inclusions and titanium nitride film, revealing a poor atomization process to obtain the metallic powder.
Regarding dimensional analysis, the results were out of the specified measurements. The selected supplier to trim supports was forced to trim areas to provide required finishing and reduce distortion. After trimming operations were out of the drawings’ specified dimensions. Future analysis will require a different approach to properly evaluate this field.

About heat treatments, two different age-hardening were applied, with and without solution annealing, as shown in table 6 (page 31). The best hardness result was achieved in the heat treatment described in the study of Yasa et al. [31]. In this age hardening, the achieved hardness is 56 HRC, which is within the YAZAKI requirements for this kind of parts. The annealing has not brought visible advantages to parts, as confirmed with hardness tests; not applying annealing will decrease costs and will reduce parts lead time. In future studies, to improve the heat treatments applied, to achieve better results in the surface of material and in the parts mechanical properties, age hardening heat treatments should be done in a vacuum or inert gas controlled atmosphere furnace chamber.

The produced samples are almost pore-free, revealing that parts relative density is very high (over 99%). During SEM analysis inclusions were found, and when analyzed through EDS revealed titanium and aluminum combined oxides (TiO2:Al2O3), and oxides of titanium, aluminium, molybdenum, and silicon, which are expected in the maraging steels. Inclusions are present before and after age hardening, showing that these oxides - as expected - do not dissolve with age-hardening treatment. The specimens’ composition was analyzed through EDS, before and after age hardening, in different areas of different specimens. These analyses revealed the presence of iron, nickel, molybdenum, cobalt, titanium and carbon in the composition; these alloying elements are the most significant in powder steel composition. It was not possible to deeply analyze the specimens’ microstructure, since it was very difficult to etch, creating several difficulties in the microstructure analysis. It is possible to identify a fine microstructure resembling to martensitic phase, in the specimens without age hardening.
Regarding tensile testing, results achieved were catastrophic, and do not allow any conclusions. During specimens’ production, MbAM equipment had a forced stoppage due to a problem, creating a defect in the parts. It was considered to continue with these parts, since it was a good opportunity to evaluate what would be the consequence of this kind of stoppage during production. With the obtained results it is possible to clearly state that the defect is not superficial, and will decrease considerably the mechanical properties of MbAM parts. During the evaluation of the crack there were no fused particles, and a parallel structure, which enables to identify the last laser passage in the top layer sinterized, crossed with the underneath layer, also parallel. Evaluating these structures with EDS it was possible to identify areas with a high percentage of titanium oxides, interleaved in the maraging steel composition, much higher than the amount referred by powder supplier (and superior the percentage found in EDS analysis). The hypothesis raised is that this happens due to the high boiling point of titanium oxides, when the powder is being fused by the laser, the oxides will overfloat to the top of the last sintered layer. This is generally confirmed by the blue surface color in the as-received parts; in future studies, additional analysis should be carried out, to confirm this and to understand this behavior.
FUTURE CHALLENGES

5 NEXT STEPS AND FUTURE CHALLENGES

MbAM is not exactly a new technology, and the world awakened to this reality. The possibility of replacing traditional manufacturing processes by MbAM is still far away and it is expected that in the forthcoming years, companies from different areas, producing different products, with a high level of personalization, will increase the use of this technology as an alternative, for the different development phases and as production alternative. If market interest (companies, consumers) continues to increase, suppliers of MbAM technology will continue to investigate to improve current equipment available in the market, by developing effective and more reliable production processes, with superior finishing quality, new metallic materials powders (with smaller particle grain size and less expensive), and equipment price reduction.

The immediate step after this study (second phase), to continue MbAM project at YAZAKI, will be the production of new specimens, to repeat the tests were it was not possible to achieve results (dimensional analysis and the tensile testing) and to investigate deeper the technology and the parts produced by it, like specimens orientation/placement inside the building chamber during production influence in the mechanical properties, heat treatments vs. mechanical properties, titanium oxides blue surface in as-received parts, among others. Specific specimens should be developed to enable an appropriate evaluation, and avoid - for instance - building supports removal, which is - as seen - always critical to remove. At the same time, it should also be considered the production of new YAZAKI parts, to evaluate performance in production environment, comparing results with traditional processes.

The parts that were selected to make this study are the most difficult and demanding available in YAZAKI, and were selected exactly due to that; nevertheless, should be considered open to other parts used in YAZAKI.
During the second phase, it should also be considered to make a business case (cost-benefit analysis, return of investment, benefits vs. risks, operational costs, project planning), to support YAZAKI decision. The business cases, together with engineering information, will enable a well-grounded decision.

In a third phase, subsequent step to what was previously described, it will be required to increase of running tests in YAZAKI production, to assess if MbAM technology performance and feasibility. It should also be taken into consideration the development of specific tools and parts to be fabricated thru MbAM, and also dedicate products to this technology.

MbAM will be important in the future of YAZAKI, and should be faced as an opportunity to introduce the holistic approaches Industry 4.0 and Industrial Internet of Things (IIoT). Companies are entering in a new manufacturing chapter, where advanced manufacturing and new technologies are starting to “meddle” in the manufacturing processes, connecting the production technologies systems with the production processes. Issues like MbAM will for sure influence and support this paradigm change.

With this study it was not only possible to see the potential of technology and how adequate it is for YAZAKI, but also allowed the correction of some steps that were being considered. This is the ideal time to take the leadership and to be - again - in the pole position of new and advanced manufacturing technologies. The opportunity is now, and these and other developments will create new competition, new opportunities, and new challenges. The future looks exciting!
Metal-based additive manufacturing: Evaluation of metallic parts produced with Additive Manufacturing Technology at YAZAKI Europe Limited

REFERENCES

1. T. Kandler, T. Ebenhöch, This is Yazaki, ed., YAZAKI 2016


42. E.G.E.O. Systems, EOS Maraging Steel MS1, ed., 2014