Mechanical and Corrosion Behaviour of Maraging Steel Processed by Powder Bed Fusion using Laser Beam

Thesis submitted in partial fulfilment for the

award of degree

Doctor of Philosophy

By

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Dedicated

To

My Beloved Parents

and

My Elder and Younger Brother

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JAYDEEP VISHWAKARMA

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LIST OF SYMBOLS

Symbols and Abbreviations	Description
P	Laser Power
V	Scan Speed
T	Layer Thickness
D	Hatch spacing
P	Relative Density
R_a	Average surface roughness
R_q	Root mean square roughness
R_z	Average max. hight roughness
$P_{ct}.El$	Percentage Elongation
σ_{ys}	Yield Strength
σ_{UTS}	Ultimate tensile strength
e_f	Elongation upto fracture
e_u	Uniform elongation
A_{IP}	Strength anisotropy index
Δ	Elongation anisotropic index
σ_c	Cyclic compressive strength
σ_t	Cyclic Tensile strength
R	Stress Ratio
$\dot{\varepsilon}$	Strain rate
$\Delta\varepsilon/2$	Strain amplitude

$\Delta\varepsilon_e/2$	Elastic strain
$\Delta\varepsilon_p/2$	Plastic strain
$\Delta\sigma/2$	Stress amplitude
N_i	No. of cycle for crack initiation
N_f	No. of cycle to fatigue fracture
μ	Micro meter
Γ	Impendence constant
W	Angular frequency
Z	Impendence
F	Frequency

PREFACE

Additive manufacturing (AM), commonly known as 3D printing, is an industrial computer-controlled process that produces three-dimensional objects by depositing materials in layers on the base material. Additive manufacturing uses various materials depending on the printing process. These materials range from metal and alloys, thermoset polymers, thermoplastics, and ceramics to composites. In AM, production from prototypes to end-use parts can be done and processing is faster, cheaper, easier to use and more accessible compared to subtractive manufacturing methods, which are more complicated and expensive. Now-a-days, industries are adopting AM technology because it can greatly improve efficiency and agility while minimizing supply chain risk, while automated processes in AM can reduce the need for specialized labour. The latest industrial revolution, Industry 4.0, is encouraging the integration of intelligent production systems and advanced information technologies. Additive manufacturing (AM) is considered to be an essential process in this industrial revolution. There are two important techniques in metal additive manufacturing i.e., Powder Bed Fusion (PBF) and Direct Energy Deposition (DED). In powder bed fusion, required thickness of powder is spread on the base plate and the powder is fused selectively by laser or electron beam by computer-controlled software. In directed energy deposition, both metal powder and laser beam are guided through nozzle and the nozzle can move in X, Y and Z directions to achieve the given dimensions of parts layer by layer. Products manufactured by powder bed fusion are comparatively better in density and properties and hence powder bed fusion is preferred and the most adopted technique out of the industrially accepted technologies available. Practically, AM processed parts consist of stacking of series of laser scanned layers to get desired cross section and height. Due to complex heating and

cooling cycles and layer wise processing characteristics, microstructural inhomogeneities and non-uniform distribution of defects can occur which affect the properties of the as-built parts. The products may also have variation in properties in different build directions depending on the angle between layer orientation and application of load as well as exposure to different media. Hence it is necessary to investigate the effect of build orientation on behaviour of materials subjected to different kinds of loading and exposed to various environments.

The growth of any new technology is only possible if the product formed by the technology is reliable and efficient. The performance of AM parts with respect to build orientation need to be understood before placing them in a given application and the parts should function reliably and efficiently in different orientations. Also, the effectiveness of post-processing techniques such as heat treatment to reduce layered anisotropy and get enhancement in the performance of parts is required to be explored.

Maraging steel is an advanced high strength steel, specially used in many industries due to its unique properties. It is a high-strength, high-toughness and corrosion-resistant steel that is ideal for applications that require high-performance parts and can be strengthened through heat treatment, particularly ageing. Maraging steel is often used in applications that require high strength and toughness, such as aerospace and defence industries. It exhibits good weldability, machinability and corrosion resistance also which makes it an attractive option for use in many other industries such as oil and gas, medical and automotive sectors. Important reason for the adoption of maraging steel in additive manufacturing is its unique combination of properties such as high strength, high toughness, good weldability, corrosion resistance and age-hardening ability, which make it well-suited for producing high-performance parts with complex geometries. These excellent properties, combined with the growing popularity of additive manufacturing,

make maraging steel an attractive material for processing by AM which can find applications in various strategic sectors.

In view of this, maraging steel powder of 15-45 μm size was selected to build the samples in 0^o, 45^o and 90^o build orientations. Further, the test coupons for tensile, fatigue, wear, erosion and corrosion behaviour were prepared and tested to investigate the effect of build orientation on various properties. The results obtained can be utilized for the improvement in design, quality and reliability of parts as per the applicability and usage of the product in intended functions.

OUTLINE OF THE THESIS

The thesis is organised into seven chapters as mentioned below.

Chapter 1 provides a comprehensive background on additive manufacturing and its classification, focusing specifically on powder bed fusion (PBF) / selective laser melting (SLM). The possibility of defects in SLM parts, such as lack of fusion, porosity and inconsistent material properties, are also discussed. The need for processing steels using additive manufacturing and the reasons for favouring maraging steel in AM, are mentioned. A literature review of the microstructure, tensile, low cycle fatigue, wear, erosion and corrosion behaviour of additively manufactured maraging steel is presented and it is found that there are very few studies that have investigated all of these properties comprehensively. Therefore, this work aims to fill this research gap and investigate the microstructure, tensile, low cycle fatigue, wear, erosion and corrosion behaviour of additively manufactured maraging steel in more detail. The chapter also discusses the effect of heat treatment on functionality of parts. With the help of literature, the process parameters were optimized by Ansys Additive software and also optimum heat treatment

was chosen which can enhance both strength and ductility. The motivation for the present research work is explained at the end of this chapter.

Chapter 2 presents a detailed description of the raw materials, processing techniques and experimental procedures employed in the course of the investigation. Divided into three sections, the first section focuses on the materials selection and processing techniques, including the parameters used for processing and the heat treatment given to the samples. The second section deals with the characterization of processed parts and different experimental and testing procedures for the samples. This includes the microstructural characterization of additively manufactured and conventional samples, along with the details of the geometry of tensile, wear, erosion and corrosion samples, testing procedures and parameters. The third section gives procedures adopted for the fractography of tensile and fatigue tested samples by SEM, as well as the analysis of worn, eroded and corroded samples by SEM, EDS and XPS.

Chapter 3 focuses on the investigation of the effect of build orientation on the microstructure and physical properties of maraging steel processed by Additive Manufacturing (AM) and conventionally manufactured (CM). The samples were processed in orientations of 0^o, 45^o, and 90^o using Powder Bed Fusion using Laser Beam (PBF-LB) and were given solution treatment and aging. The density, surface roughness and microstructural characterization of all the samples were investigated and compared with those of CM samples. The presence of Ni_3Ti and Fe_2Mo precipitates after both AM processing and heat treatment was confirmed using Transmission Electron Microscopy (TEM). This study provides valuable insights into the influence of build orientation on the microstructure and physical properties of maraging steel, which can aid in the development of optimized processing parameters for AM.

Chapter 4 investigates the effect of build orientation on the mechanical behaviour of additive manufactured maraging steel compared to the behaviour of conventionally manufactured maraging steel. Tensile testing shows that the 45° orientation specimen exhibits the best combination of strength and ductility and heat treatment improves the tensile properties, reduces anisotropy and residual stresses. The sample built in 0^o orientation exhibits longest fatigue life before heat treatment. Post-heat treatment is found to be necessary to improve fatigue behaviour further and unmelted regions resulting from processing are found to be the most detrimental and cause reduction in fatigue life. SEM analysis shows that cracks initiated from surface and inner defects. Overall, this chapter provides valuable inputs of the effects of build orientation on the mechanical behavior of additive manufactured maraging steel samples and the effect of post heat treatment.

Chapter 5 explores the wear and erosion behaviour of additively manufactured (AM) maraging steel in comparison with conventional materials. The study compares the wear and erosion characteristics of maraging steel with three different build orientations (0^o, 45^o, and 90^o) with those of cast and hot-rolled samples. The wear and erosion behaviour of the as-built and heat-treated maraging steel samples were examined under various loads and the samples were analyzed using scanning electron microscopy (SEM) and atomic force microscopy (AFM). The results show that the wear rate increases with an increase in load and is influenced by build orientation, with 90^o oriented samples exhibiting higher wear resistance in both as-built and heat-treated conditions. The erosion resistance of the conventional samples is inferior to that of the additive samples prior to heat treatment. However, after heat treatment, erosion resistance increases, and the erosion resistance of the 0^o samples is found to be higher than those of the other build

orientations. The study provides insights into the potential of AM technology to produce wear-resistant components, with the 90^{o} orientation found to be more wear-resistant, and heat treatment can further improve the wear and erosion resistance of the samples. The results of this study can assist in the selection of appropriate build orientation and heat treatment parameters for producing wear-resistant components using AM technology.

Chapter 6 describes the corrosion behaviour of additively manufactured (AM) maraging steel compared to the behaviour of conventionally produced maraging steel in a 3.5% NaCl solution. The study explores the impact of build orientation and solution and aging treatment on the corrosion resistance of the samples. The results show that as-built samples have increased resistance to corrosion with a decrease in the angle of inclination, as a result of structural heterogeneity and higher grain boundary density. However, heat treatment causes a decrease in corrosion resistance due to the precipitation of intermetallic phases and reverted austenite formation and the corrosion-resistant oxide layer is not observed on the heat-treated samples. The findings reveal a notable difference in pitting corrosion between the as-built and heat-treated samples, emphasizing the importance of optimizing build orientation and heat treatment parameters to enhance the corrosion resistance of AM maraging steel. These findings provide valuable information about the corrosion behaviour of AM maraging steel and suggest the need for further research to fully understand the relationship between microstructure, build orientation, and corrosion behaviour.

Chapter 7 summarizes the major conclusions of the thesis and suggests future research directions in the field of AM metals and alloys.