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Understanding the Effect of Retained Austenite on Mechanical Properties of Additive Manufactured 1.2709 Grade Maraging Steel

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Abstract:

Maraging steels are notable for their low carbon content and exceptional combination of ultra-high strength, ductility, machinability, dimensional stability, and fracture toughness. They hold promise for use as spring steel in sectors like automotive and food. Additive manufacturing (AM) offers a more cost-efficient method for creating complex geometries with precise control over microstructure, mechanical properties, and corrosion resistance, all within shorter production times. Mechanical properties are significantly affected by the presence of retained austenite (RA) and reversed austenite. Although considerable research has focused on the relationships between input parameters and output parameters, the specific effects of RA and reversed austenite on mechanical properties remain underexplored. This study presents initial findings on the additive manufacturing of maraging steels of 1.2709 grade for lightweight applications. The mechanical properties of the samples are analyzed, and the impact of RA content on mechanical property is also discussed and correlated.

Introduction:

Maraging steels are a class of ultra-high-strength alloys characterized by high nickel content (typically 15–25%) and additions of elements such as molybdenum, cobalt, and titanium. Unlike conventional steels that rely on carbon-based hardening, maraging steels derive their strength through aging, which precipitates intermetallic compounds in a low-carbon martensitic matrix. This unique mechanism imparts exceptional tensile strength (up to ~2,000 MPa) [1] while maintaining excellent fracture toughness and dimensional stability.

The alloy chosen in this study is 1.2709 grade (X3NiCoMoTi18-9-5) maraging steel which is a commercially available grade for additive manufacturing. Additive manufacturing (AM), particularly techniques such as Powder Bed Fusion of metals using a laser beam (PBF-LB/M), has emerged as an effective method for processing maraging steels. AM enables layer-by-layer fabrication of geometrically complex parts with high precision, reduced material waste, and faster development cycles. Maraging steels are especially compatible with AM due to their good printability and responsiveness to post-process heat treatments [2].

In 1.2709 steel, austenite (gamma phase, γ) forms at high temperatures above 820 °C [2]. During cooling, especially rapid cooling (quenching), austenite typically transforms into Ni-martensite (α_2). This happens in those steels with less carbon content. Ni-martensite is unlike the conventional carbon containing martensite which can be characterized by increased ductility and lower hardness. It is typically formed during diffusionless transformation from austenite due to fast cooling to form a soft and ductile carbon free martensite [3]. However, while cooling from solutionised condition, some austenite, may remain untransformed, which is denoted as retained austenite (RA). RA is characterized by its face-centered cubic (FCC) structure, compared to the body-centered tetragonal (BCT) structure of Ni-martensite. RA along with Ni-martensite after aging improves ductility and impact toughness, reducing the material's brittleness. It can absorb more energy during deformation, enhancing the toughness of the steel [4]. While RA can decrease yield strength and tensile strength, it also allows for greater uniform elongation before failure [5]. Repeated heating and cooling cycles can increase the amount of RA [6]. This study discusses the preliminary results of successful additive manufacturing of 1.2709 grade maraging steels, estimating the as-built RA content and understanding its impact on tensile properties out of the mechanisms reported in literature.

Experimental Procedure:

The precursor powder was chosen to be 1.2709 grade maraging steel (X3NiCoMoTi18-9-5). This was based on the consistent microstructural and mechanical property behaviour exhibited by this alloy available in literature. The precursor powder was procured from m4p material solutions GmbH (Magdeburg, Germany). The powder was characterized using different methods to analyse its as-received properties and chemical composition.

Test specimens of size 5 × 5 × 8 mm^3 were designed to do the initial characterization to estimate the as-built properties. Additive manufacturing of the test specimens was done on a TruPrint 1000 (Trumpf GmbH + Co. KG, Ditzingen, Germany) at Ruhr University Bochum. The machine uses a fiber laser (1070 nm) as the energy source, has a maximum power of 200 W and a focal diameter of 30 µm. The maximum scan speed is 3 $m \cdot s^{-1}$ and the cylindrical built platform measures Ø 100 mm. The processing parameters of the test specimens were selected based on the literature available for similar powder [7] and a parameter studies with this powder. A laser power of 160 W was chosen, and the scan speed was set to 400 $mm \cdot s^{-1}$. Layer thickness was 20 µm and hatch distance was 125 µm.

The as-built specimens were subjected to microstructural and mechanical property studies. Optical microscopy was carried out on a VHX 6000 microscope (Keyence Corporation, Osaka, Japan), to identify the pores and inclusions in the specimen. Vickers microhardness was estimated using FV-300 (Future-Tech Corp, Kawasaki, Japan) microhardness tester. Microhardness of the as-built specimen was studied at different orientations to analyse the hardness behavior with regard to different loading directions. The samples were mounted at different orientations to the build direction. Load was applied in the cross section of these mounted directions. The peak load applied was 300 kgF and a dwell time of 10 s was given. An average of 10 indents were made to take the standard deviation. Uniaxial tensile testing was done on an Instron 5982 UTM (Instron GmbH, Darmstadt, Germany) machine available at University of Hyderabad, India to determine the tensile properties of the as-built specimen. Tensile samples were machined according to DIN 50125-B 5 × 25 from additive manufactured cylinders.

RA contents of the as-built samples were determined using an Empyrean Panalytical (Malvern Panalytical Ltd, United Kingdom) X-ray diffractometer (XRD) operated at 40 kV and 30 mA with Cr-Kα monochromatic source with a step size of 0:02° and step time of 10 s according to the DIN EN ISO 21714 standards. Detailed studies on microscopy have been conducted and will be discussed in an upcoming publication.

Results:

The chemical composition of the powder matched well with the manufacturer specifications with negligible deviations from the data sheet.

The optical microstructure of the sample imaged at different depths from the as-built sample surface showed a uniform microstructure. However, pores of different size and shape have been observed at different depths from the sample surface.

When the microhardness of the as-built specimen was analysed, it has been observed that the samples exhibited hardness values same as the ones reported in literature by Kempen et. al., with a negligible standard deviation [8].

XRD analysis was performed, and the austenite peaks were analysed to quantitatively estimate the austenite content of the as-built specimens. The specimens showed a higher austenite content than the value reported by Osman et.al., which reported an RA content of 4.9 % in the as-built condition [9].

The tensile test conducted on the as-built specimens yielded an elongation higher than the reported tensile elongation by Osman et.al., which is 12.8% [9]. A yield strength of 1,006 MPa and tensile strength of 1,158 MPa were also reported in this study, both lower than the values obtained in the present work. The higher austenite content has contributed to the increased elongation. But the higher strength with higher austenite content is contradictory and needs to be investigated further. The stress-strain plot showed a broad region of elongation after the yield point showing a prolonged region of uniform deformation.

Discussions:

The adopted 1.2709 grade maraging steel is a commonly used precursor powder for additive manufacturing of maraging steels with high strength and toughness. Nickel is a strong austenite stabilizer, but in maraging steels, it enables the formation of martensite upon aging without the need for high carbon content.

The optical microscopic images show a quite uniform microstructure with relatively less inclusions or gas porosities. However certain pores can be observed at higher depths from the surface of the specimen. As there is no significant evidence of large pores or lack-of-fusion defects in this field of view implying favourable process parameters.

The slight increase in the hardness from 0° to 90° orientation suggests a directional dependence of the mechanical response, which is expected in PBF-LB/M-fabricated specimens. This variation can occur due to the thermal gradients, melt pool geometry, and solidification texture, which differ based on orientation relative to the build direction [10]. The lower hardness in the build direction (0°) can be attributed to grain growth and orientation aligned with the direction of load application during indentation. Higher density of cellular boundaries and substructure refinement in directions perpendicular to the build (45° and 90°), which may resist dislocation movement more effectively can contribute to increased hardness in these orientations. It has been reported that, variations in residual stresses due to layer-by-layer deposition, can influence indentation response differently along various orientations [11,12]. Detailed hardness-microstructural co-relation will be discussed in the upcoming publication.

The reason that a higher austenite content is observed in the as-built condition compared to the literature being the application of lesser laser power in this study [9,13]. Hence it can be understood that the laser power has an influence on the austenite content. RA is known for its high ductility and strain induced transformation under loading (TRIP effect) which enhances ductility. Ni-martensite is soft and ductile but its impact on strain hardening is comparatively less. To understand their individual contribution to tensile behavior it is important to perform additional investigations using EBSD and to compare the tensile behaviour after the aging treatments [14–16]. The stress-strain curve exhibits a broader region with uniform deformation. This can be attributed to the enhanced ductility through TRIP effect. Under uni-axial tensile loading, metastable austenite can transform into martensite through the Transformation-Induced Plasticity (TRIP) effect. TRIP effect can delay necking and enhance uniform elongation, contributing to a combination of strength and ductility [13].

It should be noted that the strength of 18Ni maraging steel under the traditional casting process is only ~950 MPa , which is much lower than 1,158 MPa observed in AM condition [9,17]. This can be attributed to the higher RA content which is inherent in traditional casting process, and it can be observed from the EBSD micrographs reported in H. Li et. al [17–19]. The strength of 1.2709 grade maraging steel manufactured through additive manufacturing process reported in literature typically ranges from 1,000-1,300 MPa with an elongation of 12-13 %, RA content of 4.9-9 % and hardness of 384-400 HV [9,13].

The presence of RA reduces the overall hardness of the as-built specimen because RA is a softer phase compared to martensite and does not contribute to precipitation hardening, which is the main hardening mechanism in this alloy. Aging heat treatment is necessary to improve mechanical properties. The as-built microstructure mainly consists of martensite with significant RA. However, the rapid cooling in LPBF prevents precipitation of intermetallic phases like $Ni_3(Mo,Ti)$, Ni_3Ti, and Fe_2Mo responsible for maraging steel's strength. Aging treatments reduce RA by transforming austenite into martensite and promote Ni diffusion-driven precipitation. Mechanical properties strongly depend on the austenite-to-martensite transformation and precipitation of $Ni_3(Ti, Mo)$ phases. Ongoing research on controlling RA content through heat treatment aims to clarify its effect on mechanical behavior.

Conclusion:

Additive manufacturing of 1.2709 maraging steel via Powder Bed Fusion of metals with a laser beam (PBF-LB/M) produced specimens with mild anisotropy and good mechanical properties. The observed anisotropy across build orientations is due to melt pool morphology and columnar grain growth along the build direction, creating directional mechanical dependencies. The as-built microstructure contains martensite with a significant amount of retained austenite

(RA), higher than reported in literature at lower laser power (160 W). RA plays a dual role by enhancing ductility through transformation-induced plasticity (TRIP) during deformation while reducing hardness and yield strength because it is softer than martensite. These findings highlight the critical influence of RA and crystallographic texture on the mechanical behavior of PBF-LB/M processed maraging steels. Detailed fractography and EBSD texture analysis are needed to fully understand tensile and hardness behavior. Post-processing heat treatment can vary RA content, improving mechanical properties and expanding lab-scale applications of this alloy.

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