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Tension-compression asymmetry of additively manufactured Maraging steel

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ABSTRACT

Additive Manufacturing (AM) or "3D printing" refers to processes used to synthesize an engineering part, where successive layers of material are formed under computer control to create a three-dimensional object. AM methods allow for production of parts with complex geometries and exceptional properties, which is of particular interest of automotive, aerospace, marine, and defence industries. Most of the parts produced for these applications are non-critical, however applications involving large deformations, such as impact, are of serious interest to industry. Unlike most conventional materials, AM metals do not have the same compressive and tensile behavior. This paper presents a preliminary study of experimental results of the tensile and compressive behaviour of additively manufactured Maraging Steel (MS1) using Digital Image Correlation (DIC) technique. Compression and tension samples in the form of cubes and rods were prepared using Direct Metal Laser Sintering (DMLS) technique through an EOS M290 machine. Compression data was collected using a DIC system to investigate the anisotropy of the strain field in the material. Results showed some material anisotropy due to build direction and dramatic improvement in elongation to failure in compression. Finally, a tension-compression asymmetry analysis of the additively manufactured MS1 revealed that the extreme softening in tension is not a result of void nucleation/growth in the material, but rather geometric softening due to necking.

1. Introduction

Additive manufacturing (AM) is defined as the process of joining materials as small as 20 microns layer by layer to make objects from 3D CAD models [1]. Of particular interest is a powder bed fusion technique, namely Direct Metal Laser Sintering (DMLS) method developed by EOS GmbH [2], which is also called Selective Laser melting (SLM). Additive manufacturing techniques allow an increased freedom of design while maintaining a light and stable final product when it comes to complex geometries. They also offer a reasonable cost, especially for small batch sizes that would otherwise be extremely expensive [3]. Many industrial sectors such as aerospace have recently started adopting additive technology in their products. In addition, new industries such as marine and offshore are keen to implement these advanced manufacturing techniques in the next generation of their products [4]. However, numerous key challenges still exist due to unexplored mechanical behaviour of these materials under complex loading conditions [5].

Several experimental methods have been used recently to accurately measure different parameters in additively manufactured parts. Strantza et al. [6] used acoustic emission methods to investigate crack propagation in additively manufactured and conventional titanium alloys. Brenne et al. [7] used Digital Image Correlation (DIC) along with Electron Backscatter Diffraction (EBSD) technique to study the microstructure and mechanical behaviour of Ti-6Al-4 V microlattice structures made using Selective Laser Melting (SLM). Using Split Hopkinson Bar, DIC, and EBSD techniques, Tancogne-Dejean et al. [8] studied the mechanical behaviour of SLM-stainless steel 316 L microlattice structures under static and dynamic loading conditions. Harris et al. [9] investigated the impact response of multiple SLM-stainless steel hybrid lattice structures under different strain rates. Spagnuolo et al. [10] investigated the damage behaviour of 3D printed AlSi10Mg pantographic sheets. They presented a method to accurately simulate the onset of fractures during uniaxial tensile test of these SLM-sheets.

Maraging steels are a grade of low carbon martensitic steels with superior strength and fracture toughness with particular applications in defense, marine, aerospace, and tool and die [11]. EOS has developed specific Maraging steel powder called MS1 for the DMLS machines, which possesses comparable properties as conventional tool steel in as-printed and subsequent heat-treated conditions [12]. Both in as-built and age-hardened states, MS1 has shown excellent machining, welding, and micro-shot peening properties [13]. In addition, due to the high strength of MS1, it can be used to 3D print light yet strong microlattice structures or tools with conformal cooling channels [14]. Additively

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manufactured steels, mainly MS1, are quickly gaining traction in engineering applications [15]. The design versatility of MS1 is promising due to its mechanical properties; however, characterization and understanding, and especially modeling of material behavior, is still very developmental [16], where experimental data is in high demand for furthering this understanding.

A study conducted by Spitzig et al. [17] compared the mechanical response in tension and compression for wrought maraging steel and showed nearly identical hardening behaviour for both loading cases, with only a decrease in yield strength in tension. However, this is not the case when maraging steel is produced by AM. This is not a steel-specific phenomenon, where hardening in tension is significantly reduced compared to compression. Longhitano et al. [18] presented experimental results for tension and compression tests for AM Ti-6Al-4 V and found significantly higher hardening rates in compression. This held true even when heat treatments were applied to samples. Many studies have attributed this behaviour (and others such as nanoprecipitation in maraging steels [19]) to porosity and microvoids inherent in AM materials due to extreme thermal gradients during manufacture [20] and inclusions due to unmelted powder [21]. Supposed evidence for this is due to the observation of heavily dimpled fracture surfaces [22]and the strong relationship between porosity and macro-strain at failure [23]. However, there is no available analysis on hardening between tension-compression available in the literature to support this claim, that decreased hardening in tension samples is solely due to porosity and voids.

Most of the parts additively manufactured using MS1 have applications that experience complex loading conditions including bending, impact, compression, tension, and shear during their operations. Having similar compressive and tensile behaviors is very normal in conventionally produced metals, which is not the case for DMLS-MS1. This paper presents experimental results and analysis on the tensile and compressive behaviour of additively manufactured MS1. In order to precisely capture the deformation field in the compression mode, DIC apparatus was set up and used for measurements. Compression and tension samples in the form of cubes and rods were prepared using DMLS technique through an EOS M290 machine. Results showed that MS1 has a high tension-compression asymmetry, which has to be considered for further analyses and modeling exercises.

2. Material and DMLS procedure

Rod shaped samples (12 mm in diameter and 120 mm long) along with cubes of 25 × 25 × 25 mm were built using an EOS M290 machine located at Additive Metal Manufacturing (AMM) Company in Concord, ON, Canada. The machine was equipped with a building plate of 250 × 250 × 325 mm, a 400 W Yb-fiber laser and a laser beam spot size of 100 μm. Samples were printed using MaragingSteel MS1 powder, where the chemical composition of the MS1 powder is presented in Table 1. The MS1 powder, provided by EOS of North America (produced by gas atomization method with particle size 15–45 μm), was subsequently printed into test samples with a layer thickness of 40 μm. Tensile samples and compressions samples were produced with 285 W laser power at 960 mm/s scan speed with 0.11 mm hatch distance using stripes hatch strategy. Strip scanning strategy was used to fabricate the samples. To investigate the influence of building direction on the dynamic mechanical properties of the samples, the samples were built both in vertical and horizontal directions. Build direction was perpendicular to tension/compression directions.

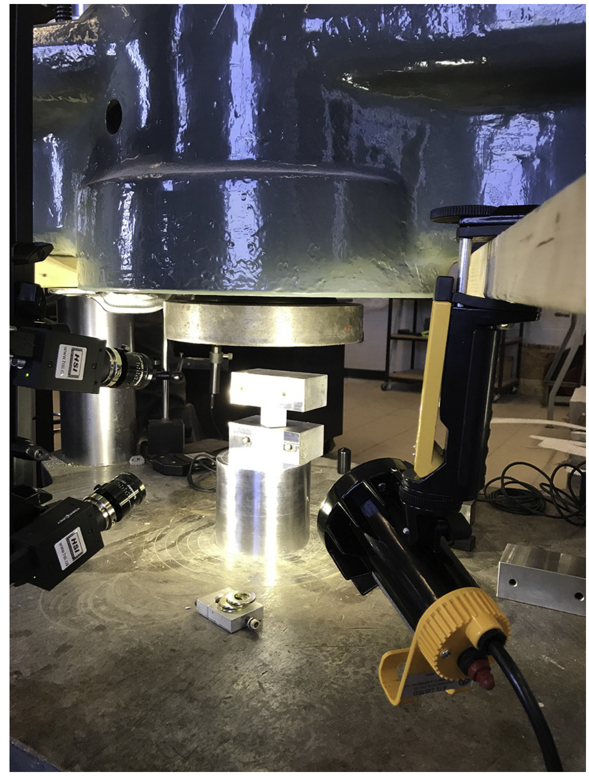

Fig. 1. The compression test setup along with the DIC system.

3. Experimental setup

In order to perform the compression tests, first hardness measurements were carried out on the as-built cube samples using a Rockwell hardness testing machine (CLARK-Model CRM12) with a 1/16″ diameter diamond ball under 100 kg load. The values of hardness for 10 indentations on the surfaces of the samples were averaged and reported based on HRC scale.

To prepare tensile test samples, the as-built cylindrical samples were machined according to ASTM E8-15a standard [24]. Tensile tests were performed using an Instron machine (Model 1332 with 25 mm extensometer) at a ramp speed of 1.3 mm/min. Tensile tests were repeated three times for both vertical and horizontal samples and the typical engineering and true stress-strain curves were reported.

The compression samples were tested using a Baldwin universal testing machine retrofitted with Instron controls and had hydraulic 200kip capacity. The DIC system used to capture the stain field during the compression test was dual Point Grey global shutter CMOS sensor cameras offset by 28° and aligned vertically at 120 mm away from the specimen, which was attached to the frame for in-situ images recording of the sample surfaces. Polarizers were used to reduce reflection from lighting. The image capturing system recorded 2700 frames at 500 ms intervals. Displacement was calculated using the average of two Linear Variable Differential Transformers (LVDTs) placed equidistant from the sample on opposite sides. The compression samples were placed between two hardened H13 steel with 58 ± 2 HRC to solely measure the deformation of MS1 block during compression. The compression sample along with the two rigid H13 blocks were almost 50% covered with black powder particle to create appropriate contrast for the DIC

Table 1
Chemical composition of MaragingSteel MS1 (wt-%).

Ni	Co	Mo	Ti	Al	Cr, Cu	C	Mn, Si	P, S	FE
17–19	8.5–9.5	4.5–5.2	0.6–0.8	0.05–0.15	≤ 0.5	≤ 0.03	≤ 0.1	≤ 0.01	Balance