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Nondestructive Evaluation of Additively Manufactured Metallic Components

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Abstract. Nondestructive evaluation (NDE) methods are successfully used for detection of surface and internal flaws, and also for characterization of materials. Additive manufacturing (AM) of metallic components is rather complicated due to many process variables affecting the performance and quality of the final product. Qualification, verification, and industry adoption of AM parts is dependent upon the capability of NDE. This paper presents the initial results of the on-going studies about NDE of additively manufactured metallic parts, performed at METU.

Keywords: Additive manufacturing, Metallic materials, Nondestructive material characterization, Ultrasonics
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Introduction

Nondestructive evaluation (NDE) methods are successfully used for detection of surface and internal flaws; for material characterization by determining microstructure (grain size, phases, etc.), mechanical properties (hardness, strength, toughness, etc.), and residual stress; and also, for long-term monitoring by detecting alterations in structures to prevent failures.

Additive manufacturing (AM), which was started as a rapid prototyping tool, provides almost unrestricted freedom to design and to produce complex-shaped and high-value engineering components. It is a revolutionary technique for fabrication of critical and novel components that could not be produced via conventional manufacturing routes. It can also improve the service life of the components by providing innovative repair methods.

AM of metallic components is rather complicated due to existence of many process variables affecting the performance and quality of the final product. Qualification, verification, and industry adoption of AM parts is directly dependent upon the capability of NDE [1-3].

The on-going research studies about NDE of additively manufactured metallic parts at METU mainly focus on Ni-based super alloys and maraging steels. Inconel 718 is an age hardenable Ni-based superalloy with Cr and Fe as major alloying elements. Due to low machinability of this alloy, selective laser melting (SLM) is a preferred technique to produce complex-shaped products. However, the abrupt temperature gradient and high solidification rate during SLM, a supersaturated solution matrix is formed with brittle Laves phase precipitating at the subgrain boundaries, and the precipitation of γ' and γ'' phases is restrained. A solution treatment is necessary to eliminate micro-segregation and to dissolve the Laves phase in the γ matrix. Furthermore, an age hardening treatment is essential to improve the mechanical properties [4]. Chen-Ming et.al. [5] adopted a double-step aging procedure for wrought Inconel 718 to precipitate γ' and γ'' at 720°C, and γ' at 620°C, and investigated the creep behaviour. The microstructure of the SLMed Inconel 718 is considerably different from that of the cast or wrought one. The SLMed Inconel 718 requires higher homogenization temperatures [6]. Any difference in the initial microstructure will lead to different phase transformation kinetics during heat treatment.

Therefore, heat treatment procedure of the SLMed parts should be optimized to obtain the desired microstructure and mechanical properties. In the study of Huang et al. [7], the as-built specimens were solution treated at the temperatures between 980 and 1280°C for different times, and cooled with various rates. They concluded that the dissolution of Laves phase improves the ductility and the precipitation of strengthening phases in the aging treatment.

Maraging steels are carbon-free iron-nickel alloys that contain high amount of alloying elements. They are usually preferred for specific applications where high specific strength is required, such as rocket motor cases and landing gears. They consist of martensitic structure, and their superior mechanical properties are achieved via aging treatment. First, a soft lath-type bcc martensitic structure with supersaturated Mo and Co is obtained by air cooling. Then, aging treatment at a suitable temperature hardens the martensite due to precipitation of Ni–Mo, Fe–Mo, and Fe–Ni intermetallic phases. Thus, optimization of aging temperature and time is critical to achieve design requirements. Mutua et. al. [8] has investigated the anisotropic tensile behavior of the SLMed maraging steel in both as-built and heat-treated conditions, and reported that anisotropic behaviour of the as-built specimens disappears after heat treatment. As-built MS300 cannot reach its maximum strength and toughness. Bai et al. [9] achieved the highest mechanical properties by optimizing the age hardening parameters. For MS250 and MS300 steels, it has been reported that as aging temperature increases, sound velocity decreases severely due to the formation of reverted austenite [10, 11].

In general, parameter optimization of AM processes (selective laser melting, direct laser sintering, electron beam melting) and subsequent processes (HIP, heat treatment) needs feedback from NDE in terms of detecting flaws such as porosities, cracks, etc., and determining microstructure and mechanical properties. Thus, extensive research efforts on NDE of AM components are necessary.

This paper presents the initial results of the non-destructive material characterization studies on additively manufactured and heat treated metallic parts, performed at METU.

Experimental

Inconel 718 and MS300 maraging steel specimens having various geometries (cubic specimen, tensile test specimen) were produced via selective laser melting (SLM) by the EOS-Germany. During SLM, the building direction was kept constant to minimize its effect on mechanical properties of the specimens. $N_2(g)$ was used to prohibit the oxidation of alloying elements. Effects of various heat treatments on microstructure and mechanical properties were investigated. In addition to metallographic investigations, hardness and tensile tests, the longitudinal wave velocities were measured using 2.25 MHz straight-beam probe, as the ND characterization via ultrasonics. The Time of Flight (ToF) principle was used to measure the distance between the transducer and the back-wall of the specimen. The sound velocities were calculated by dividing the distance travelled to the average ToF value. The average value was calculated by considering four echoes.

The Inconel 718 specimens were heat treated via three different procedures: DA (direct aging at 720°C for 1.5 h), STA (solutionizing at 955°C for 1 h + DA), homogenization at 1095°C for 1 h + STA. The MS300 specimens were aged at 450°C for 1 to 8 h.

Results and Discussion

a) Inconel 718

Micrographs of the as-built cubic specimen given in Figure 1 show that the surface-2 has irregular and elongated grain morphology along the building direction while the surface-1 has arc-shaped-lines which represent the melt pool boundary and the scanning path of the laser beam.

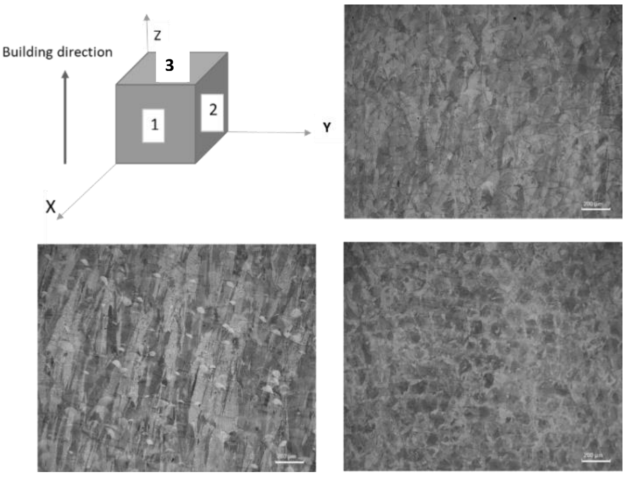

Figure 1. *Representative micrographs of the surfaces of the SLMed Inconel 718 cubic specimen*

After DA treatment, the Laves phase remains, and elongated grains in the building direction and arc-shaped lines are still observed. The microstructure after the STA treatment does not contain columnar grains and arc-shaped lines. Partial recrystallization occurs and needle shaped δ phase forms in the grains and near the grain boundaries. γ′ and γ″ phases precipitate, and some Laves phase exists. When homogenization + STA treatment is applied, complete recrystallization occurs, the grains coarsen and become equiaxed, and the Laves phase dissolves in the matrix, i.e., a microstructure similar to the wrought one is obtained.

Figure 2 shows the hardness values measured on the perpendicular surfaces of the cubic specimen. DA treatment has a slight effect on hardness due to precipitation of only γ′. However, in the STA treatment, precipitation of γ′, γ″ and δ phases improves hardness remarkably. Homogenization + STA treatment causes complete dissolution of the Laves phase, full precipitation of the γ′ and γ″ phases, and thus, hardness reduces in comparison to the STA treatment.

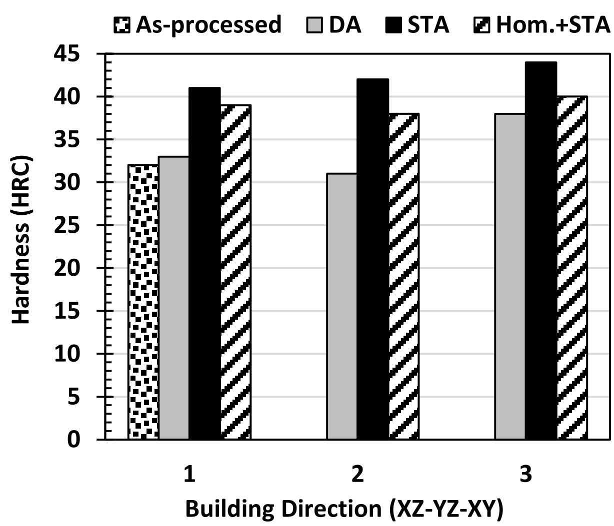

Figure 2. *Effect of heat treatments on hardness of the SLMed Inconel 718 specimens*

Ultrasonic waves are elastic-mechanic waves propagating by atomic vibrations. The sound velocity is mainly dependent on elastic modulus, Poisson's ratio and density of the material. It is sensitive to the changes in the grain structure, phases, and residual stresses [12].

Figure 3 shows that there is an almost perfect positive linear relationship between hardness and the longitudinal wave velocity of the SLMed and heat treated Inconel 718 specimens.

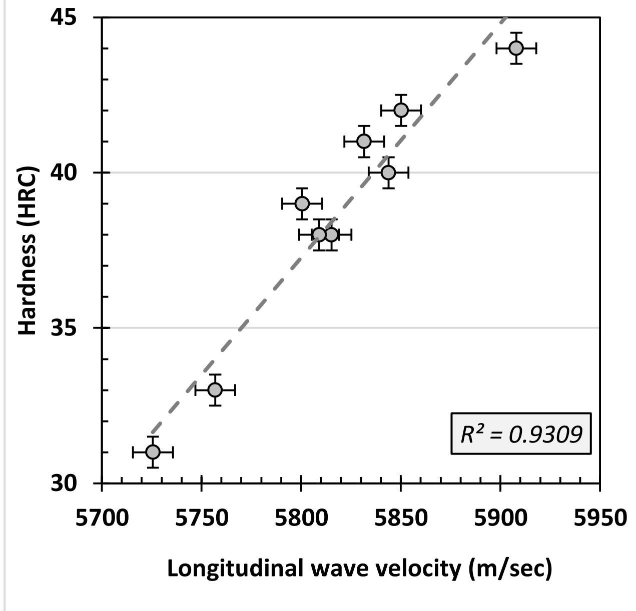

Figure 3. *Correlation between hardness and longitudinal wave velocity (Inconel 718, SLMed and heat treated)*

b) MS300 maraging steel

For MS300 specimens, the variations of hardness and longitudinal wave velocity values with the aging time at 490°C are given in Figure 4.

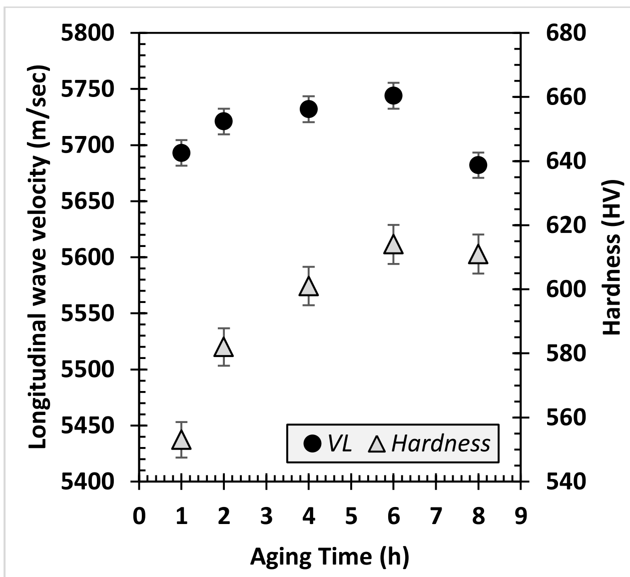

Figure 4. *Variation of longitudinal wave velocity (V_L) and hardness with aging time at 490°C (MS300, SLMed and aged)*

Initially, the magnitudes of both parameters increase with aging time, however they tend to decrease after reaching their maxima at 6h. The initial increase in hardness and sound velocity values is caused by precipitation of Ni_3Ti. Further increase in these values with aging time can be attributed to the precipitation of fine Fe_2Mo.

The reversal of the rising trend in hardness upon aging for longer times is due to the formation of reverted austenite. As the softest phase of steels, austenite has the lowest elastic modulus, and dependingly, the minimum sound velocity. Although the precipitation of Fe_2Mo continues with its hardening effect, the softening due to the reversion to austenite is more dominant.

Conclusions

Additive manufacturing of metallic components via the selective laser melting (SLM) technique and subsequent heat treatments have many parameters affecting performance and quality of the final product.

In addition to non-destructive (ND) inspection for flaw detection, development of ND methods for characterization of microstructure and mechanical properties has critical importance for verification and qualification of the SLMed components having predictable and controlled properties.

The initial results of the research studies at METU show that measurement of ultrasonic wave velocity is a promising method to determine the microstructure and mechanical properties of the SLMed and heat treated Inconel 718 and MS300 steel specimens, nondestructively.

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