The effect of heat treatment on mechanical properties and microstructure of additively manufactured components

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Abstract. Components from maraging steel MS1 (1.2709) and aluminium alloy AlSi10Mg were fabricated by additive manufacturing (AM). As-built and heat-treated components were analysed in terms of mechanical properties and microstructure. The heat treatment of the material MS1 was performed by a solution annealing at 850°C for 1 hour, ageing temperature at 480°C for 3 hours and air cooling. The heat treatment of the AlSi10Mg was performed by stress relieve at 300°C for 2 hours. Ostbayerische Technische Hochschule Amberg-Weiden carried out tensile tests of as-built and heat-treated samples. Samples were afterwards analysed in COMTES FHT a.s. for further tests of porosity and microstructure using optical and scanning electron microscopy. The aim of the present work is to show the change of mechanical properties and the microstructure with a heat treatment after AM.

1 Introduction

Additive manufacturing (AM) is technology, which builds up 3D objects for example of plastic, metal or concrete. Using AM technology, three dimensional parts are fabricated directly from CAD models and built in a layer-by-layer manner. AM technology allows freeform fabrication of geometrically complex parts without special fixtures as required in material removal processes. The term AM includes many technologies which cover: 3D Printing, Rapid Prototyping (RP), Direct Digital Manufacturing (DDM), layered manufacturing and additive fabrication. AM is being used to fabricate end-use products in aircraft, dental restorations, medical implants, automobiles, and even fashion products [1]. Currently, the most used alloys for additive manufacturing are stainless steels (e.g. GP1, 316L, 17-4PH), cobalt chrome (e.g. MP1, SP2), Inconel 625 and 718, titanium Ti6Al4V, maraging steel MS1 and aluminium AlSi10Mg [2].

This work presents the effect of heat treatment on mechanical properties and microstructure of maraging steel MS1 and aluminium AlSi10Mg parts additively manufactured from powders produced by EOS. The change of yield strength (YS), ultimate tensile strength (UTS), elongation (El) and hardness will be shown in this work. Light microscope and the scanning electron microscopy will be used for documenting fractography, microstructure and porosity change after heat treatment.

Maraging steel MS1 (1.2709) studied in this work is martensitic hardened steel, with excellent strength combined with high toughness, very good mechanical properties, and easily heat treatability by means of simple age hardening process to obtain excellent hardness and strength. The nominal composition is given in **Table 1** [2].

Table 1. Chemical composition of maraging steel MS1

Element (wt.%)	Ni	Co	Mo	Ti	Al	Cr, Cu	C	Mn, Si	P, S
Maraging steel MS1	17-19	8.5-9.5	4.5-5.2	0.6-0.8	0.05-0.15	≤0.05	≤0.03	≤0.1	≤0.01

Aluminium alloy AlSi10Mg is a typical casting alloy with good casting properties and is typically used for cast parts with thin walls and complex geometry. In the frame of aluminium alloys family, AlSi10Mg offers good strength, hardness and dynamic properties and is therefore also used for parts subjected to high loads. The nominal composition is shown in **Table 2** [2].

Table 2. The chemical composition of aluminium alloy AlSi10Mg

Element (wt.%)	Si	Fe	Cu	Mn	Mg	Ni	Zn	Pb, Sn	Ti
AlSi10Mg	9-11	≤ 0.55	≤ 0.05	≤0.45	0.2-0.45	≤0.05	≤0.10	≤0.05	≤0.15

2 Experimental Procedure

The maraging steel MS1 and AlSi10Mg had different processing history. Samples of tested materials were annealed (HT) or they stayed untreated (As-built). **Table 3** summarized the heat treatment conditions. As-built and heat-treated components were analysed in terms of mechanical properties and microstructure.

Table 3. Heat treatment condition of the analyzed samples

Sample	Heat treatment condition
MS1-AB (as-built)	No heat treatment
MS1-HT	Solution annealing 850°C for 1 hour, ageing temperature 480°C for 3 hours, air cooling
AlSi10Mg-AB (as-built)	No heat treatment
AlSi10Mg –HT	Stress relieve 300°C for 2 hours

2.1 Mechanical properties

Ostbayerische Technische Hochschule Amberg-Weiden carried out tensile tests of as-built (AB) and heat-treated (HT) samples. They tested 3 AB samples and 3 HT samples of each material extracted in a horizontal direction. Average mechanical properties such as yield stress (YS), ultimate tensile strength (UTS), elongation (El) and hardness with HV5 load are summarized in **Table 4** and shown in **Figure 1**. The results of maraging steel MS1 shows, that the heat treated samples have higher hardness, yield stress and ultimate tensile strength, which increased about 61%. Elongation was reduced by about 4.1%. Heat treated samples of the aluminium alloy AlSi10Mg have lower values of hardness, ultimate tensile strength and yield stress. Elongation increased by about 0.9% and ultimate tensile strength was reduced about 18% after heat treatment.

Table 4. Mechanical properties of analyzed samples

Sample	YS (MPA)	UTS (MPa)	El (%)	Hardness HV5
MS1 AB	1061,3 ± 6,9	1178,8 ± 5,4	9,3 ± 0,1	361
MS1 HT	1826,0 ± 17,3	1896,6 ± 4,9	5,2 ± 0,1	542
AlSi10Mg AB	202,8 ± 8,1	282,6 ± 41,6	2,5 ± 1,5	95
AlSi10Mg (HT)	148,5 ± 1,6	231,0 ± 16,0	3,4 ± 1,6	75

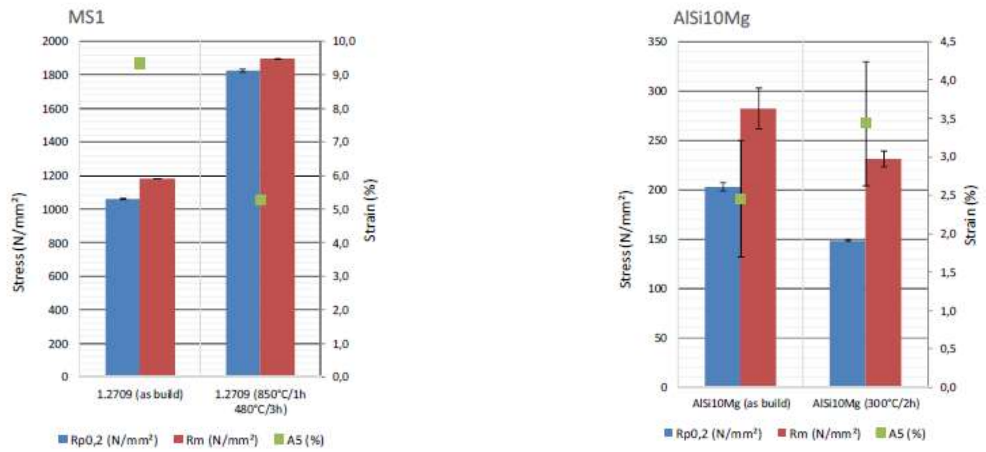

Figure 1. Mechanical properties of the AB samples and HT samples materials MS1 and AlSi10Mg

2.2 *Fractography*

After the tensile test, a fractographic analysis was performed on AB and HT samples using the scanning electron microscopy (SEM). Although yield stress and ultimate tensile strength of the maraging steel MS1 increased after heat treatment, ductile fracture with dimple morphology was proved in both conditions. Also, AlSi10Mg as-built and heat treated samples have a similar ductile fracture in both conditions with high porosity content (see red arrows in **Figure 2**)

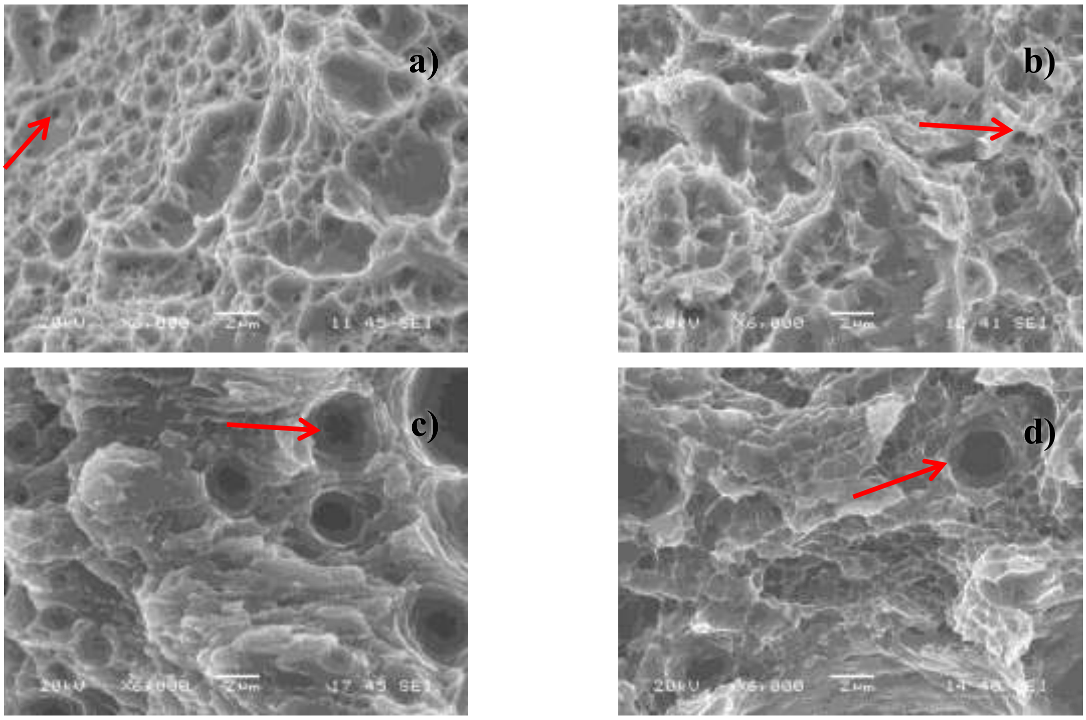

Figure 2. Fractured samples with a dimpled ductile fracture (arrows indicate pores) a) MS1-AB, b) MS1-HT, c) AlSi10Mg-AB, d)AlSi10Mg-HT

.2.3 *Porosity and microstructure*

An important parameter for a material fabricated by additive manufacturing is porosity. The porosity greatly affects the mechanical properties. The pores could be the crack initiators. Samples from maraging steel MS1 exhibit very low porosity. Samples from AlSi10Mg exhibit porosity close to 5% for untreated samples and about 3.5% for samples after the heat treatment. **Table 5** shows the values of porosity of all tested samples.

Table 5 Comparison of the porosity

	MS1 AB	**MS1 HT**	**AlSi10Mg AB**	**AlSi10Mg HT**
Porosity (%)	0,26	0,23	4,94	3,54

For the microstructure analysis, the samples were cut by the scheme shown in Figure 3 in three directions. Planes XZ and YZ were taken along the building axis (axis Z) whereas XY has a normal parallel to the building axis. Samples from each plane underwent standard metallographic preparation consisted of grinding followed by polishing. The microstructure of the maraging steel was revealed by etching in the Vilella-Bain etchant and Picral 4%. Aluminium alloy AlSi10Mg was etched with Keller´s reagent. The metallographic observation was performed by means of a light microscope and scanning electron microscope.

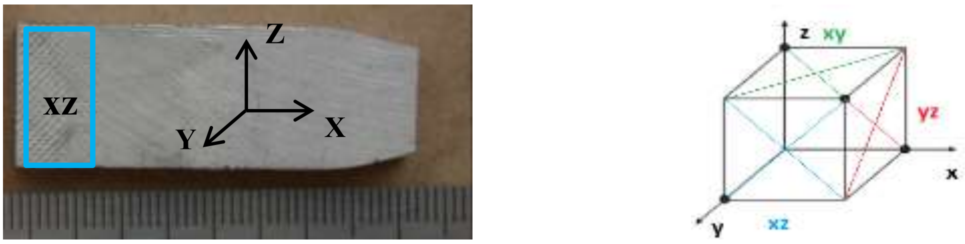

Figure 3. Scheme of sampling

3D microscopic images in **Figure 4** and **Figure 5** document the microstructure of the maraging steel MS1 and aluminium alloy AlSi10Mg. Images show the structures of untreated materials with semicircularly shaped melt pools along the Z axis. XY-plane shows the tracks of the laser scan. After the heat treatment, the maraging steel MS1 melt pool borders disappeared, the melt pool borders of the AlSi10Mg are less visible. Higher magnification images in the XZ plane are shown in **Figure 6**, **Figure 7** and **Figure 8**. **Figure 6** a) demonstrates the maraging steel MS1 in as-built state with melt pools visible after etching in Picral 4%. Microstructure revealed by etching in Vilella-Bain reagent is martensitic with no visible retained austenite (**Figure 6** b). **Figure 6** c) shows the maraging steel MS1 cellular dendritic structure with different grain shapes, which is due to the solidification rate of a local melted region. **Figure 7** demonstrates the change of microstructure after the heat treatment when the melt pools boundaries disappeared and the carbides are precipitated along the grain boundaries as was proved by the electron microscopy [3, 4, 5].

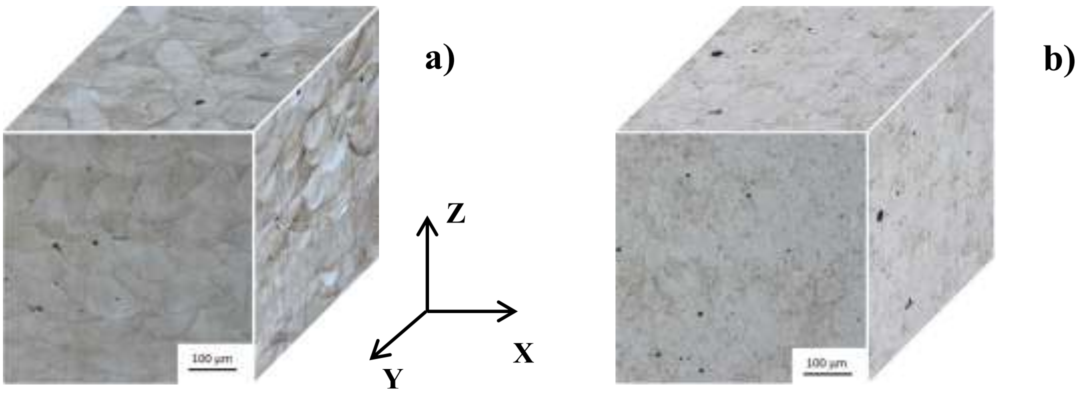

Figure 4. 3D images a) untreated maraging steel MS1 (AB) b) heat treated maraging steel MS1

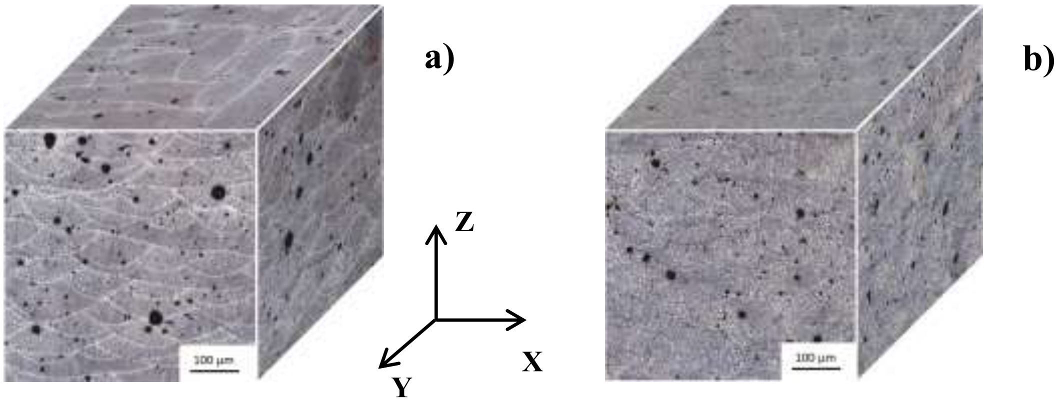

Figure 5. 3D imagines a) untreated AlSi10Mg (AB) b) AlSi10Mg after heat treatment (HT)

Figure 6. The maraging steel MS1 microstructure in as-built state (XZ plane) a) etched in Picral 4%, b) etched in a Vilella-Bain reagent, c) SEM image of the cellular structure with visible melt pools boundaries etched in Picral 4%

Figure 7. The maraging steel MS1 microstructure in heat treated state (XZ plane) a) etched in Picral 4%, b) etched in a Vilella-Bain reagent, c) SEM image of the structure with carbides precipitated along the grain boundaries

Aluminium alloy AlSi10Mg microstructure is composed of fine cellular dendritic structure inside the melt pools with a larger dendritic cell on the melt pools boundaries due to the thermal gradient. The cells are mainly composed of aluminium with fine silicon network (**Figure 8** a). **Figure 8** b) shows similar structure with less visible melt pools boundaries and with small Si based particles [6, 7].

3 Conclusion

The effects of heat treatment on the hardness, tensile properties and microstructure of maraging steel MS1 and aluminium alloy AlSi10M have been investigated in this research. Tensile test and hardness

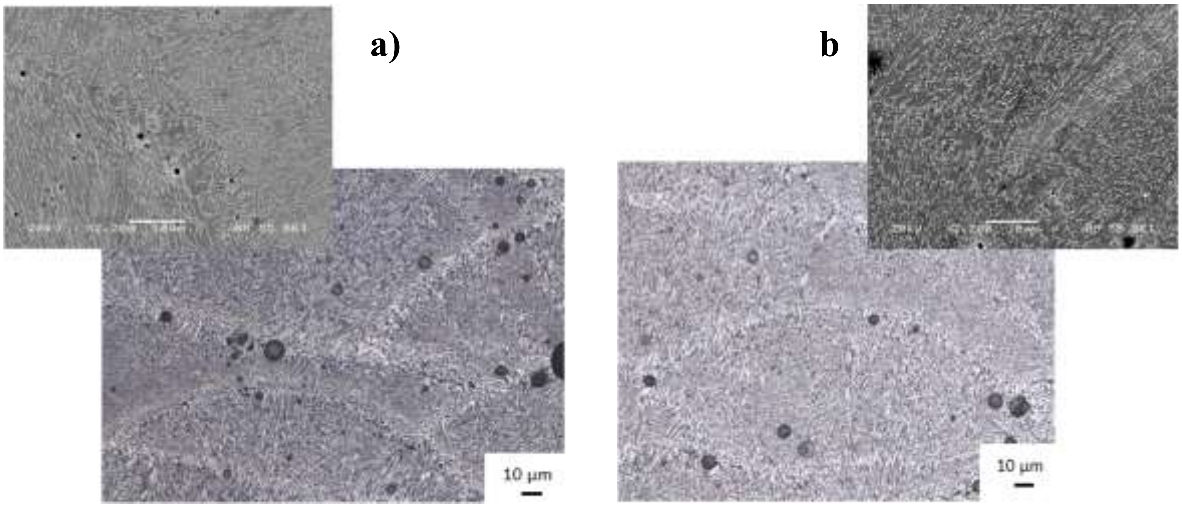

Figure 8. AlSi10Mg microstructure of XZ plane a) light and electron microscopy of the aluminium alloy in as-built state b) light and electron microscopy of the aluminium alloy in annealed state

results revealed that heat treated samples of maraging steel have higher yield stress about 58%, ultimate tensile strength increased about 61% and elongation reduced about 4,1%. Hardness increased by 181 HV5. Stress relived aluminium alloy AlSi10Mg has lower values of yield stress of about 13.8%, ultimate tensile strength decreased 18%, elongation increased about 0,9% and hardness decreased from 95 HV to 75 HV. This result of aluminium alloy might be mainly due to the relief of internal stress. Fractography shows that all analysed fractures have a ductile fracture with dimple morphology. The porosity of the maraging steel is similar in both conditions. The porosity of aluminium alloy AlSi10Mg is close to 5% for untreated samples and about 3.5% for heat treated samples. Martensitic maraging steel MS1 changed typical microstructure of melt pools composed of cellular dendritic structure to the microstructure with carbides precipitated along the grain boundaries after heat treatment. Aluminium alloy AlSi10Mg has similar microstructure in both conditions.

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