Effect of heat treatment on mechanical properties of duplex steel SAF 2507 manufactured by DED

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Abstract: This work is focused on the influence of heat treatment on the mechanical properties of duplex steel SAF 2507 produced by direct laser deposition (DLD). Duplex steels combine the advantages of ferritic and austenitic steels and reach excellent combination of mechanical and corrosion properties. The best properties are achieved by approximately equal phase ration of ferrite and austenite. Therefore, the proportion of austenite and ferrite before and after heat treatment was investigated within the study. Direct laser deposition technology was used for sample production. The DLD works on the principle of laser melting of the feedstock material (powder), which is carried by a protective gas into the nozzle. The material is successively deposited on the build platform. This technology can be used as an additive manufacturing process for surface repairs and component modifications. In this experimental study, the samples were deposited and subsequently subjected to the heat treatment. Solution annealing was chosen as the heat treatment method. The microstructure was characterized by LM, SEM and EBSD analyses. The mechanical tests were performed by a tensile testing on miniaturized specimens extracted from the experimental material in three orientations. The heat treatment had a fundamental effect on the proportion of austenite and ferrite, but also on the resulting mechanical properties. From the mechanical properties the maximum values of YS/UTS ~ 680/830 MPa were reached and after heat treatment ~ 540/760 MPa were reached.

1 Introduction
Duplex steels contain a balanced proportion of ferrite and austenite. For the best mechanical properties and corrosion resistance, the optimal proportion is 1:1. These steels are most often used in the marine, petrochemical, oil, gas and shipbuilding industries. They have one of the highest chromium contents of the entire group of cast stainless steels [1], [2]. The chromium levels range from 21 to 27%. Corrosion resistance is increased by alloying with molybdenum (up to 6%) and nitrogen. With such compositions, the two-phase structure is achieved by nickel additions at 5.5 to 8.5%. Nickel and nitrogen are the austenite-forming elements that compensate for the high content of ferrite-forming elements (chromium, molybdenum). If a certain proportion of ferrite and austenite contents is intended to be achieved, the levels of ferrite-forming and austenite-forming elements must be balanced as well. A small change in the composition can cause a significant change in the resulting microstructure and thus in the properties of the steel. However, the proportion of both constituents depends not only on the chemical composition but also on applied heat treatment. Before use, duplex steels have to be heat treated. Duplex steels are usually subjected to solution annealing at about 1100 °C to convert unwanted carbides and intermediate phases into a solid solution [3]-[4][5] [6]. Localized heating sources used in additive manufacturing lead to residual stresses, structural instability and crack formation. Residual stresses in the built structure are important to consider in order to ensure that they remain within the safe limits for the structure [7].
Preheating is one of promising methods to reduce residual stress [8]. DED technology can even handle extraordinary material combinations, such as Ni with Ti [9], Ti6Al4V with TiC, Invar with TiC, many others as per the application requirement [10].

2 Material and methods

The Insstek MX-600 machine was used for the deposition process. Its energy source is a 2 kW fibre-guided Ytterbium laser. The whole process took place under a protective atmosphere of argon 4.8. A powder designated as SAF 2507 with a particle size of 45-150 μm from Sandvik Osprey LTD was the feedstock material. The chemical composition of the powder is shown in Table 1 that is stated chemical composition from the material data sheet supplied by the manufacturer. The additive manufacturing parameters are listed in Table 2 [5]. A heat treatment was applied for solution annealing of the material. The heat treatment regime was a sequence of heating up to 1100 °C, then the material keeping at the temperature for 60 minutes followed by cooling in water. Figure 1 shows a cut design of the samples.

Table 1 Chemical composition of SAF 2507 [wt. %]

|    | Fe | C  | Cr | Ni  | Mo | Mn | Si | N   | O    | Cu | Al | P  | S   |
|----|----|----|----|-----|----|----|----|-----|------|----|----|----|-----|
| Bal.| 0.02| 25.2| 7.0| 4.02| 0.9| 0.5| 0.3| 0.05| 0.02| 0.01| 0.008| 0.006|

Table 2. Deposition parameters

| Module | Layer height | Beam diameter | Feed rate | Hatch distance | Deposition strategy |
|--------|--------------|---------------|-----------|----------------|-------------------|
| SDM 800| 250 μm       | 800 μm        | 849 mm/min| 0.5 mm         | ZigZag            |

The samples were then cut away from the platform and prepared for metallographic analysis. Metallographic sections were prepared by grinding and polishing. The microstructure was revealed by etching in Beraha II with K₂S₂O₅. It was observed under a light microscope (Nikon ECLIPSE MA200) and in a scanning electron microscope (JEOL IT 500 HR). The EBSD camera (EDAX Hikari Super) provided information on the proportion of ferrite and austenite on area 800x900 µm with step by 1 µm.

The tensile properties of the experimental material were investigated based on the results of miniaturized tensile test (MTT). The reliability of the method was documented in other studies [11]. The specimens were manufactured by wire electric discharge machine (WEDM) and subsequently polished. The tests were conducted under quasi-static conditions at room temperature in accordance to the standard ISO 6892-1 using a universal testing machine TiraTest with a linear drive and load capacity of 10 kN. At least four specimens per condition were tested. The deformation was tracked...
by contactless extensometer Mercury RT based on Digital Image Correlation technique. Before starting the testing procedure, the specific dimensions of each specimen (width and thickness) were measured by a micrometer and noted. Then, the specimens were cleaned using alcohol-based agent and a stochastic pattern was created on the surface for DIC measurement. After testing, the specific dimensions were measured again by stereomicroscope and the tensile characteristics calculated (yield strength – YS, ultimate tensile strength – UTS, uniform elongation – Ag, total plastic deformation – A and Reduction of Area – RA).

3 Results

3.1 Microstructure

The microstructure was observed on LM and SEM after etching in Beraha II reagent. Ferrite and austenite phases in different ratios were observed in the microstructure before and after heat treatment, see in Figure 2. In the as built state, the elongated grains of ferrite grow through several layers and there are fine-grained areas along the boundaries of the meltpool. The austenitic phases in three variants forms during deposition and following cooling. Grain boundary austenite (GBA) was formed as first along ferrite grain boundaries at the highest temperatures between 1350 °C and 850 °C, widmanstätten austenite (WA) creates thin needles, whereas the intergranular austenite (IGA) precipitates as fine particles within ferrite grains at the lowest temperature. All types of austenite are visible in Fig1b as-deposited state. Ferrite grains in the etched samples grew across several layers of the build. The meltpool boundaries are lined with heat affected zones (HAZ). GBA predominates inside meltpools and IGA predominates in HAZ. Meltpool is marked in Figure 2 (1a) in orange and in Figure 3 by black arrows. HAZ is marked in red in Figure 2 (1a) and in purple arrows in Figure 3. The austenitic grains (mostly IGA) were roughened after heat treatment and the IGA was evenly distributed. Furthermore, the fine-grained area of ferritic grains disappeared.

**Figure 2** Microstructure of SAF 2507 - 1) as built, 2) heat treated, a) LM - 100x, b) SEM - 1000x

3.2 EBSD analysis

In the as built state (Figure 3a)), there was austenite along the boundaries of ferritic grains (GBA) and meltpools (IGA). GBA was uniformly distributed, whereas IGA was mainly found along the meltpool boundaries and in the heat affected zone (HAZ) [5]. Furthermore, the ratio of austenite and ferrite before and after heat treatment was measured by EBSD. After the heat treatment, the austenitic grains grew evenly throughout the volume of the material (Figure 3 b)). The proportion of ferrite and austenite was determined by EBSD and the results are shown in Table 3.
Table 3 Austenite and ferrite content [%]

|          | Austenite | Ferrite |
|----------|-----------|---------|
| As built | 21.1      | 78.9    |
| Heat treated | 52.4      | 47.6    |

Figure 3 EBSD analysis results, a) as built, b) heat treated

3.3 Mechanical properties

The specimens were tested in as built and heat-treated states in three different orientations designated as XZY, YZX and ZXY according to the document ASTM WK49229 [14]. The obtained strength values, elongation and reduction of cross-sectional area are summarized and compared in Figures 4 and 5. Table 4 shows typical mechanical properties of as built 2507-AM powder L-PBF (Laser beam-Powder Bed Fusion) in heat treated condition (solution annealing 1040-1110 °C followed by air or water cooling) evaluated at room temperature. [15]

Table 4 Mechanical properties of SAF 2507 (manufactured by L-PBF) [15]

| Condition   | Direction | $R_{p0.2}$ [MPa] | $R_m$ [MPa] | $A$ [%] | $Z$ [%] |
|-------------|-----------|------------------|-------------|---------|---------|
| Heat treated| Horizontal| 627              | 956         | 207     | 39      | 74      |
|             | Vertical  | 626              | 923         | 202     | 43      | 74      |

The applied solution annealing significantly affected the tensile characteristics of AM-ed material. The specimens subjected to the heat treatment yielded lower strength values (~540/760 MPa of YS/UTS) and almost twice higher elongation (~30%) in comparison to the as built material. The as built specimens tested in ZXY orientation were distinguished by the highest yield and uniform tensile strength (~680/830 MPa) over all tested specimen batches. In contrast, the heat-treated ZXY-specimens exhibited the lowest ultimate tensile strength (~750 MPa). The elongation values (uniform elongation at UTS point and total plastic elongation at the end of the test) were rather uniform within each batch, nevertheless, the results for as built material were characterized by increased uncertainty due to a relatively high data scatter observed. In the case of the annealed specimens, the orientation effect appeared to be negligible [6]. In comparison with the measured results and values from Table 4, it is assumed that lower values were achieved. The differences in the "as build" state may be due to the smaller powder particles for L-PBF and after the heat treatment the differences depend on the heat treatment parameters. The mechanical properties in the "as build" state will depend on the ratio of austenite and ferrite, when a smaller amount of austenite achieves higher strength. [16]
Figure 4 MTT results of AM-ed duplex steel SAF 2507 in as built and solution annealed states, tested in three orientations – yield and ultimate tensile strength values.

Figure 5 MTT results of AM-ed duplex steel SAF 2507 in as built and solution annealed states, tested in three orientations – uniform and total elongation, reduction of cross-sectional area.

4 Conclusion
This paper deals with the influence of heat treatment on the resulting microstructure and mechanical properties of duplex steel SAF 2507. After the heat treatment, the amount of austenite and the uniform ratio of austenite to ferrite in the steel increased. The mechanical properties changed after the heat treatment and the reduction of YS/UTS from ~ 680/830 MPa to ~ 540/760 MPa was recorded. On the contrary, the ductility of the material increased almost twice. Due to an increase in the austenite content of the duplex steel after heat treatment was observed, it is likely to affect the mechanical properties because austenite is characterized by lower strength and higher elongation than ferrite.

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