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Laser metal deposition with wire of Inconel 718 on pre-heated substrates

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Abstract

Laser metal deposition with wire (LMD-w) is an additive manufacturing technology with high deposition rates for large parts. During the LMD-w process, a metallic wire is fed into a laser-induced melt pool. A weld bead is created since the melt pool and the substrate move relative to each other. Several beads next and/or on top of each other create layers, coatings, or 3D elements. The process, however, generates high temperatures in a very short time resulting in high temperature gradients, leading to distortion, or cracking. This study investigates how lowering the temperature gradients with pre-heated substrates affects deposition results and how it influences microstructure, hardness and surface roughness using Inconel 718 material. By focusing on beads' appearance and temperature of the melt pool, the resulting microstructure, porosity, and cracks were analyzed.

Keywords: Additive Manufacturing; Laser Metal Deposition with Wire; Inconel 718; Pre-heating

1. Introduction

Highly stressed components in aircraft engines and other areas are commonly made from the nickel-based superalloy Inconel 718 (IN718) because it has excellent mechanical properties at elevated temperatures. The conventional production chain for such components, which often have geometrically complex elements, includes primary forming, forging, rough turning and several milling steps. The forging operation has a major influence on the outstanding mechanical properties of IN718 components. The economic efficiency of the

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production chain is limited by a high material and time requirement, especially in the case of machining since large amounts of metal need to be removed.

Additive manufacturing processes such as wire-based laser metal deposition (LMD-w) offer economical and technological alternatives and are characterized by a high degree of design freedom and the possibility of near-net-shape production. Disadvantages are the limited mechanical properties and surface finish resulting from the characteristic weld structure. It is important to identify interactions between the manufacturing chain of IN718, the resulting microstructural and mechanical workpiece properties as well as the application behaviour of the components, especially in engine development (Reichmut and Berster, 2017). In the present work, we investigate how pre-heating the substrate during the LMD-w process influences the microstructure, hardness and surface roughness.

2. State of the art

A common additive manufacturing process, laser metal deposition (LMD), can be divided into powder-based (LMD-p) and wire-based (LMD-w) processes. In LMD-p, there is no connection between the workpiece and the tool. As a result, larger kinematic errors are tolerated, and the welding process becomes more stable. When several layers are built, this error between the actual and target geometry plays a role in the process stability. However, IN718 powders are a health hazard: They can contaminate the equipment, leading to increased wear and requiring workpiece cleaning steps. Overspray can also occur with LMD-p. This refers to the powder that does not adhere to the substrate as part of the weld bead, but contaminates the installation space and the workpiece. Other disadvantages of the powder are potential hydrogen embrittlement and the high energetic effort required for powder production (Benson, 2012).

In LMD-w, a focused laser beam is used to create a melt pool on a substrate into which a metallic wire is continuously fed. The melt pool is protected from oxidation by a shielding gas. In most cases, the laser optics, wire feed system and shielding gas guide are combined in one processing head. A relative movement between the processing head and the substrate creates individual weld beads. Several weld beads next to each other result in a layer; weld beads or layers on top of each other result in a component. Handling systems can be, for example, industrial robots or Cartesian axis systems (Klocke, 2015). In LMD-w, 100% of the material is utilized and there is little chemical activity due to the smaller specific surface area.

During the LMD process, the high-power density of the laser induces very high cooling rates – 5,000 to 10,000 K/s – of the weld beads. Due to the process, heat treatment of the adjacent weld beads occurs (secondary temperature cycle). The high cooling rate produces a directional dendritic microstructure (Arrizubieta et al., 2017). In IN718, especially the elements niobium and molybdenum accumulate interdendritically (Bürgel et al., 2011). These segregations are not dissolved during secondary temperature cycling or heat treatment (Arrizubieta et al., 2017). The grain structure forms along the temperature gradients. While in the primary temperature cycle an alignment of the grains from the centre to the edge of the weld bead occurs, the secondary temperature cycle causes the grains to grow beyond the former bead contours (Brandl et al., 2012). Thus, large grains are formed, their exact shape depending on the temperature cycle, and may lead to cracks along the twin boundaries. The interdendritic segregations play an important role in the phase segregation in IN718. Due to the higher concentration of some elements, the undesirable topologically close pack (TCP) phases and δ-phase are formed more frequently. In addition to stresses of phase transformation, tensile residual stresses are induced due to thermal stress and solidification shrinkage. These can lead to large distortion. In addition, the individual beads lead to macroscopic waviness (Oliari et al., 2017).

Many materials are available for the LMD-w process, including steels and tool steels, nickel-, titanium- and cobalt-based alloys. In this work, we investigate the superalloy NiCr19Nb5Mo3, commonly known as Inconel 718 (IN718), which is a precipitation hardenable nickel-chromium alloy with significant content of iron (Fe), niobium (Nb) and molybdenum (Mo) as well as low aluminium and titanium content. IN718 components, which are manufactured after various heat treatments in accordance with AMS standard 5662 or 5664, are characterized by high strengths Rm = 1300...1500 MPa and a high elongation at break A = 12...23% even at high temperatures T > 600 °C (high creep strength) (Appa Rao et al., 2004).

A lot of investigations on LMD-w processing of IN718 have been made; however, they have not investigated the extent to which pre-heating the substrates during the LMD-w process influences the microstructure, hardness and surface roughness.

3. Experimental set-up

The experimental set-up for the LMD-w with pre-heated substrates (S355J2) is shown in Fig. 1. An industrial robot (ABB IRB 6660, ABB Asea Brown Boveri Ltd., Zurich), mounted on a linear axis, guides the laser cladding head. This head is a self-made unit from Fraunhofer IPT called LMD-w-20-L. The LMD-w-20-L has a lateral wire feed angle of 20°. The wire feed system used is an Abicor Binzel MFS-V3 (Alexander Binzel Schweisstechnik GmbH & Co. KG, Buseck). The wire used was Inconel 718 massive wire with a diameter of 1.2 mm. The shielding gas nozzle is mounted on the opposite side of the wire nozzle. The shielding gas used was Argon (99.996 vol.-%) with a flow rate of 18 l/min. The laser beam is placed in the center of the cladding head between wire nozzle and shield gas nozzle with a spot diameter of 2.1 mm. The laser system used was a Laserline LDF 4500-30 high-power diode laser with an OTS-5 optic (both Laserline GmbH, Mühlheim-Kärlich) installed inside the cladding head. The substrate plate was located over an induction coil. The induction system “BIG 50/100” is a 50 kW system (Hüttinger Elektronik GmbH + Co. KG, Freiburg). A high-speed camera Lightning RDT Plus (DRS Data & Imaging Systems Inc., Oakland) was used to investigate the process zone, and an IR camera VarioCAM HD (InfraTec GmbH, Dresden) to measure the surface temperature of the substrate. The core temperature of the substrates was monitored with thermo-couples (TC Mess- und Regeltechnik GmbH, Mönchengladbach).

The process parameters are shown in Table 1. The laser power was set at a constant 1700 W. The ratio between the machine feed rate and wire feed rate was also constant at 1:1.1 for a machine feed rate of 1200 mm/min and 1600 mm/min. The pre-heating temperature was between room temperature and 500 °C.

For the experiments, the substrates were heated by the induction system to the defined temperature. The laser cladding process was conducted as one-directional linear beads with a length of 65 mm on top of the pre-heated substrates. Ten beads were cladded next to each other with an offset of 1.8 mm. Ten layers were cladded on each other to create a block. The offset height of each layer was measured after each layer and was between 0.6 mm and 0.7 mm. After each bead, the core temperature was checked to be in a range of +/- 10% of the target value before the next bead was started. Three blocks of each parameter set were created and analyzed.

Table 1. Process parameters

Pre-heating temperature [°C]	Laser power [W]	Wire feed rate [mm/min]	Machine feed rate [mm/min]
RT	1700	1760	1600
100	1700	1760	1600
300	1700	1760	1600
500	1700	1760	1600
100	1700	1320	1200
300	1700	1320	1200
500	1700	1320	1200

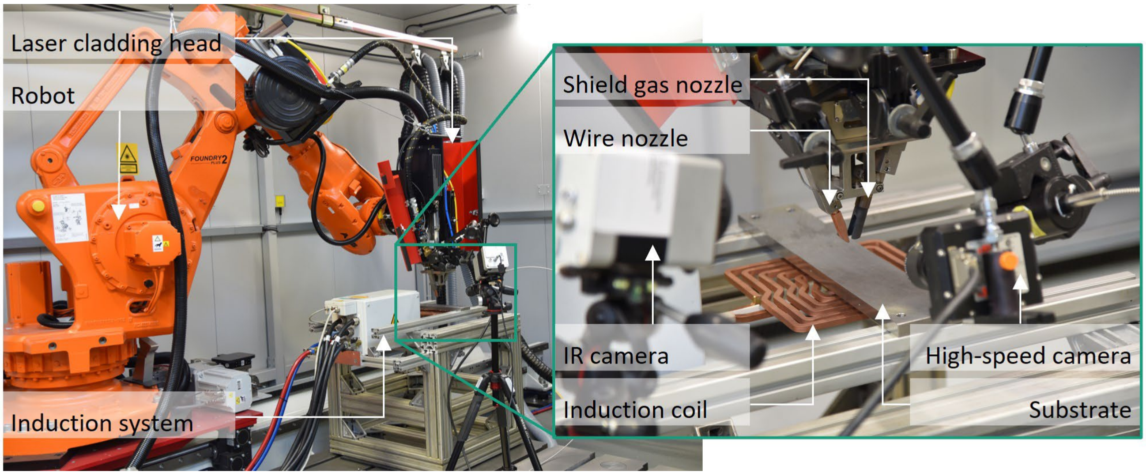
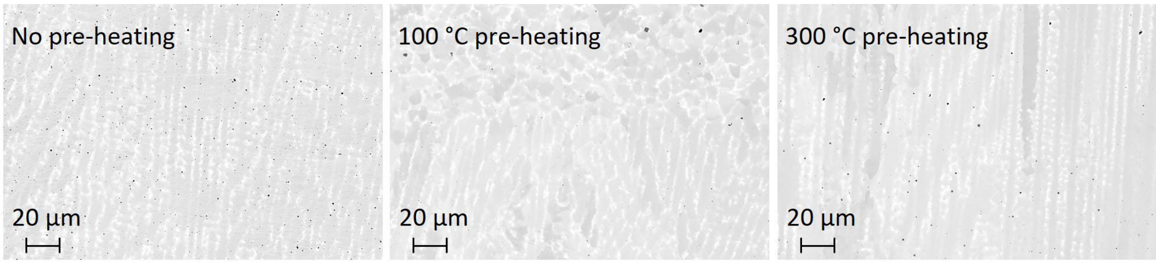


Fig. 1. Experimental set-up

4. Results and discussion

For the microstructure analysis, sections of the 9th and 10th layer were selected. In this area, there is no mixture with the substrate material anymore. Fig. 2 shows the microstructure between room temperature (left), 100 °C (middle) and 300 °C (right) pre-heating temperatures. In all cases, there is a dendritic microstructure. At the edges of the dendrites, Nb accumulates to the δ-phase (Ni3Nb) as shown as the white areas in the picture. The black dots in the pictures are small pores. The small grey dots are TiN. No large pores or cracks were detected. Compared to the samples processed at room temperature (left picture) the dendritic microstructure is larger. This is caused by the increased amount of energy in the process caused by the pre-heating. Nevertheless, there is no significant change in the size of the dendritic microstructure between 100 °C and 300 °C.



Process Parameter:

Laser power = 1700 W; Machine feed rate = 1600 mm/min; Wire feed rate = 1760 mm/min

Fig. 2. Microstructure of IN718 in dependence on the pre-heating temperatures

In Fig.3 no significant change in the microstructure between the different pre-heating temperatures can be seen. There are only slight changes between the different feed rates. As the feed rate increases, the size of the dendrites decreases due to the reduced amount of energy input. Furthermore, the cooling rate decreases as pre-heating temperature increases and feed rates decrease.

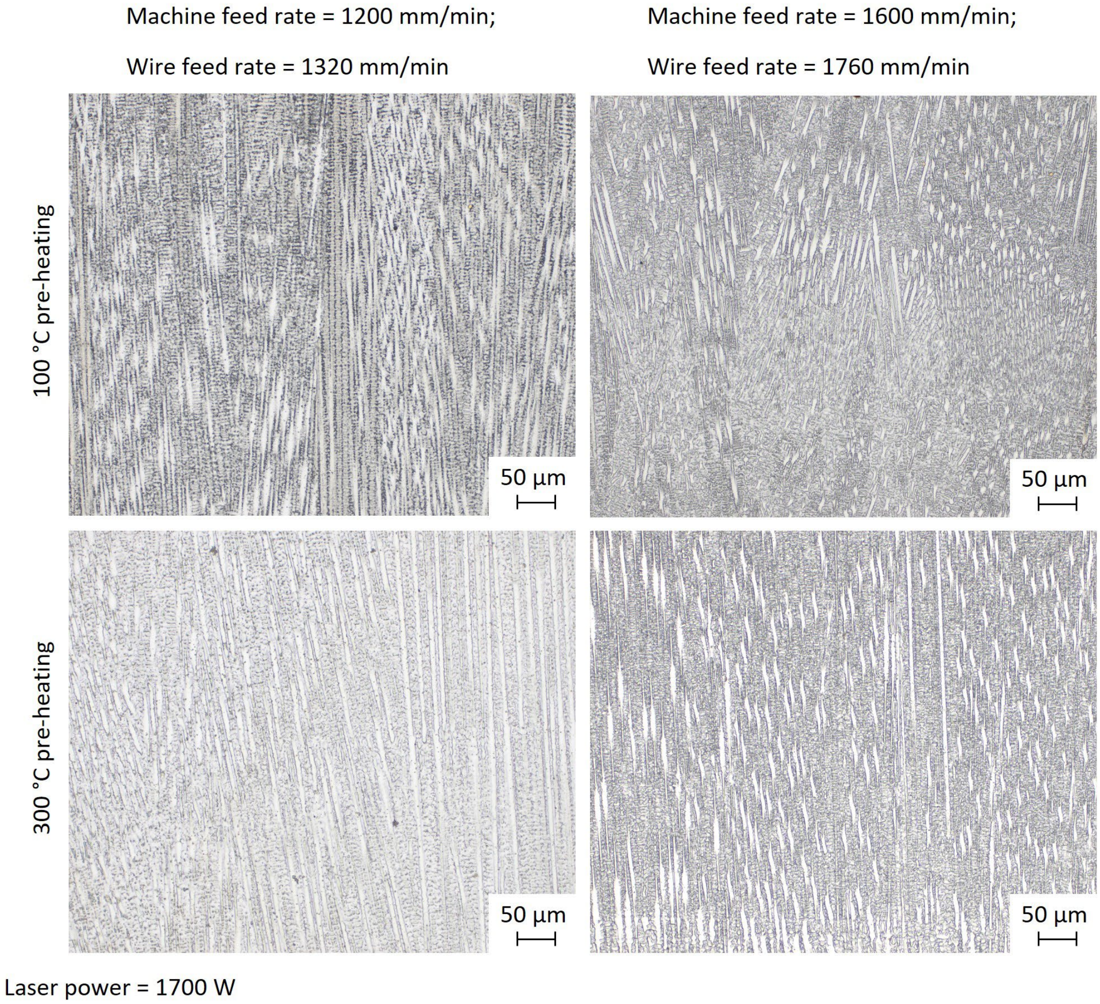


Fig. 3. Microstructure of IN718 in dependence on the pre-heating temperatures and machine feed rates

That the cooling rate decreases as pre-heating temperature increases and feed rates decrease can be deduced from Fig. 4, which shows how long the temperature remains above 500 °C of a small surface element for different machine feed rates in dependence on the pre-heating temperature. The duration over 500 °C (including the rise and fall of the temperature) increases with increasing pre-heating temperature from 0.41 s at 100 °C pre-heating to 1.05 s at 500 °C for a machine feed rate of 1200 mm/min. The duration approximately doubles between 300 °C and 500 °C for both machine feed rates. For a machine feed rate of 1600 mm/min, the duration increases from 0.31 s at 300 °C to 0.62 s at 500 °C. For lower feed rate, the duration of temperatures above 500 °C also increases due to the higher energy input caused by the longer process duration.

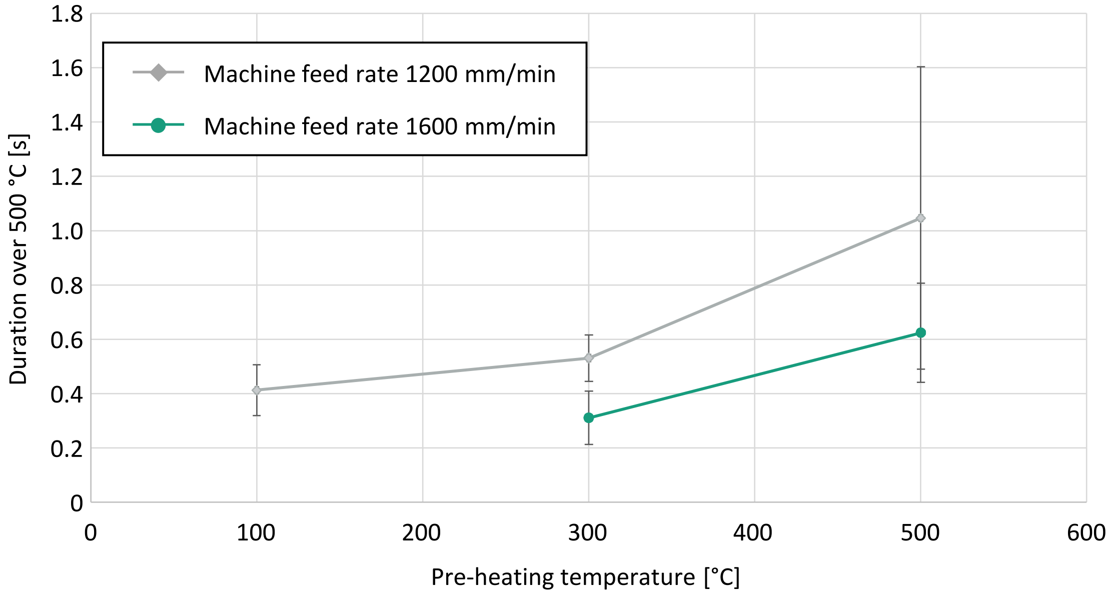


Fig.4. Duration of segment temperature over 500°C in dependence on pre-heating temperature and machine feed rate

The melt pool size was analyzed with high-speed camera images. Fig. 5 shows the results in dependence on the pre-heating temperatures for different machine feed rates. With increasing pre-heating temperature, the size of the melt pool increases from 1.3 mm² at 100 °C pre-heating temperature to 1.8 mm² at 500 °C pre-heating temperature for a 1200 mm/min machine feed rate. Also, for a higher machine feed rate of 1600 mm/min, the melt pool size increases from 1.5 mm² at 300 °C pre-heating temperature to 1.9 mm² at 500 °C. More material is molten by constant laser power and cools down slower. Therefore, the flow of the material is better; unevenness or gaps in a single bead and between the beads are filled up. This results in a better surface roughness. Fig. 6. shows the surface roughness Sa and Sz in dependence on the pre-heating temperature for the different machine feed rates. The diagram shows that the roughness decreases as pre-heating temperatures increase. Sa decreases from 8.8 µm at 100 °C pre-heating temperature to 8.2 µm at 500 °C pre-heating temperature at a machine feed rate of 1200 mm/min. The corresponding Sz decreases from 505 µm at 100 °C pre-heating temperature to 290 µm at 500 °C pre-heating temperature. At a machine feed rate of 1600 mm/min, the Sa value increases from 7.1 µm at 100 °C pre-heating temperature to 8.0 µm at 500 °C pre-heating temperature. The standard deviation for the Sa value at 100 °C pre-heating temperature is very high: +/- 1.7 µm. The same occurs for the corresponding Sz., which decreases from 200 µm at 100 °C pre-heating temperature to 121 µm at 500 °C pre-heating temperature. The Sz value of 300 °C pre-heating temperature, however, is higher: 272 µm. The standard deviation is +/- 218 µm for 100 °C pre-heating temperature and, therefore, this Sz value is subject to a high degree of uncertainty.

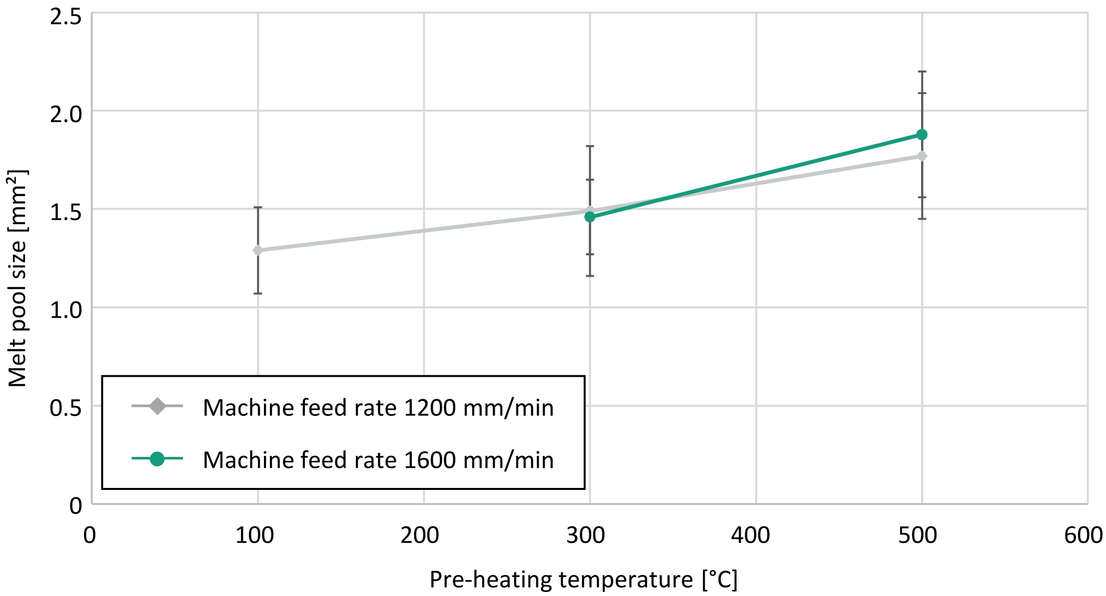


Fig. 5. Melt pool size in dependence on the pre-heating temperature and the machine feed rate

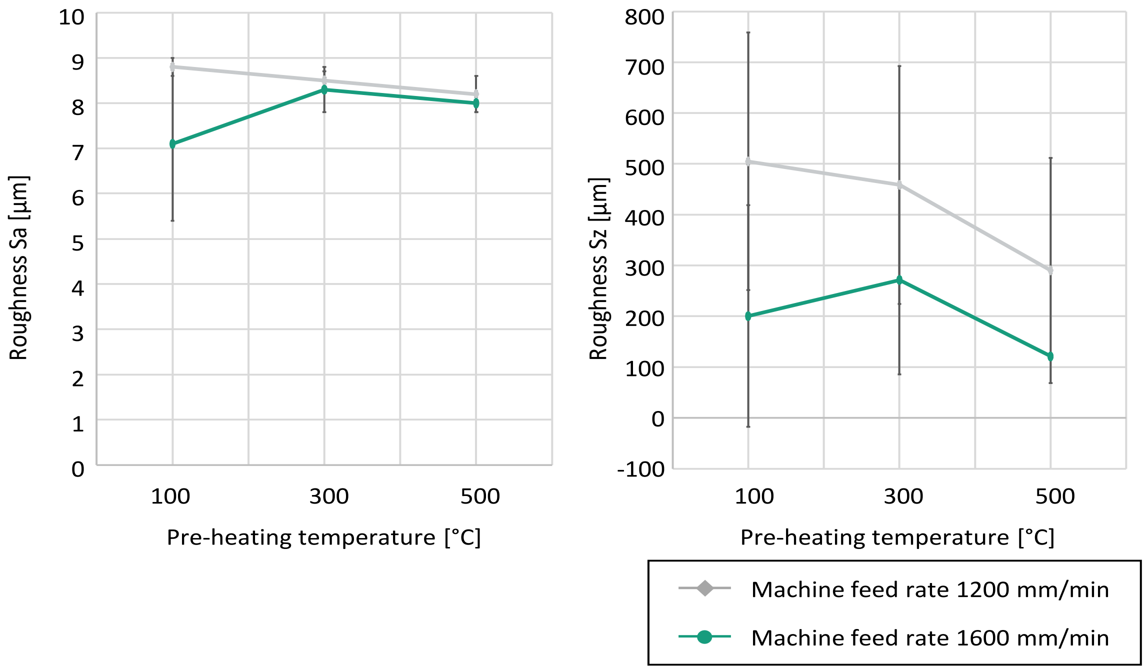


Fig.6: Roughness Sa and Sz in dependence on pre-heating temperature and machine feed rate

Fig. 7 shows the micro hardness in dependence on the pre-heating temperature for the different machine feed rats. The hardness is in a constant range between 235 HV30 (lowest value) and 254 HV30 (highest value) both at 300 °C for the different machine feed rate. The pre-heating temperature has no significant influence on the hardness in the area under consideration.

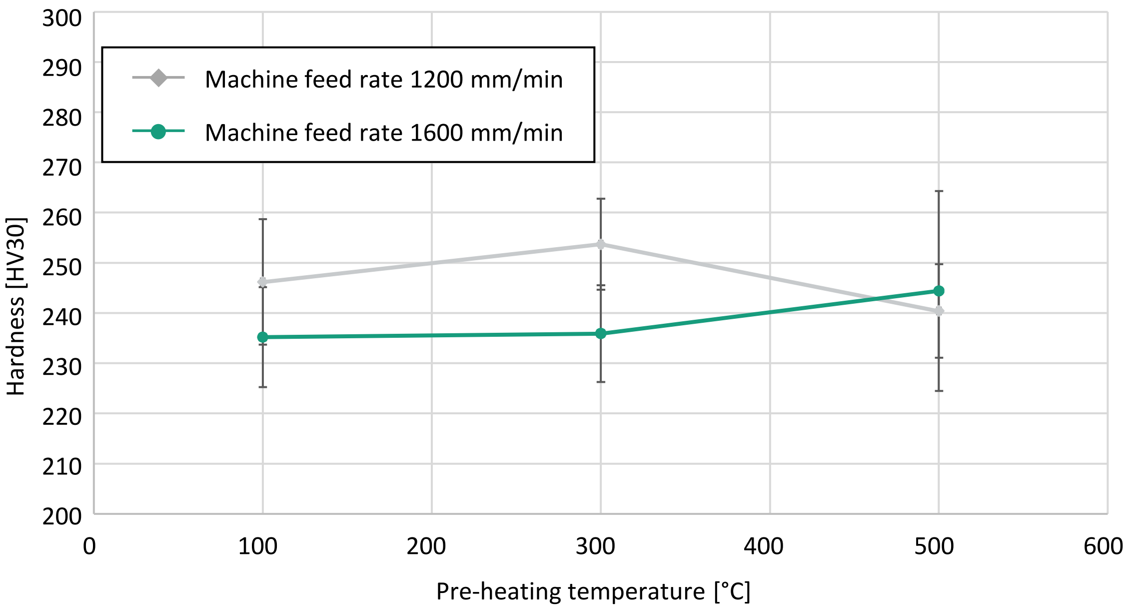


Fig. 7. Hardness in dependence on pre-heating temperature and machine feed rate

5. Conclusion

This study shows how substrate pre-heating for the wire-based laser metal deposition (LMD-w) process for Inconel 718 influences the microstructure, hardness, and surface roughness. The pre-heating was done with an induction system to a achieve pre-heating temperatures of 100 °C, 300 °C and 500 °C. Due to the higher energy input, there is a slight growth of the dendrites as pre-heating temperature increases. The duration of temperatures over 500 °C increases as pre-heating temperature increases. Furthermore, the melt pool size increases as pre-heating temperature increases, leading to decreased surface roughness. In the parameter range investigated here, no influence of the pre-heating temperature on the hardness could be determined.

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