

# Comparison of mechanical properties of heat-treated components made by the WAAM from Inconel 718 alloy

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**Abstract.** The mechanical properties of the Inconel 718 alloy are not only determined by the chemical composition, but also by the processing of the alloy itself. Segregation of refractory elements such as niobium and molybdenum often occurs with Inconel 718 nickel alloy resulting in formation of hard and brittle phases. Homogenization annealing after deposition is currently the most viable way of controlling the microstructure of a component made by the WAAM. The paper compares three regimes of heat treatment (annealing temperature of 980 °C and annealing time of 30, 90 and 120 minutes) in terms of 0.2 yield strength, tensile strength, ductility and impact energy. The results revealed the reduction of 0.2 yield strength and tensile strength of heat-treated samples by 30% and 15% respectively. Annealing time did not have a statistically significant effect on 0.2 yield strength and tensile strength. The Charpy impact test exhibited increased impact energy after heat treatment. With an annealing time of 30 minutes, the impact energy rose by 56%, and with an annealing time of 120 minutes, it increased by 96%.

## 1 Introduction

Additive manufacturing (AM) is nowadays one of the hot topics in the manufacturing and engineering worlds. Among the different additive manufacturing techniques, wire and arc additive manufacturing (WAAM) is suitable to produce large metallic parts owing to the high deposition rates achieved, which are significantly larger than powder bed techniques, for example. The interest in WAAM is steadily increasing, and consequently, significant research efforts are underway [1].

The materials to be processed also play a critical role, and due to the vast possibilities of materials that can be used in WAAM, the same process variant may have different effects on the microstructure and/or mechanical properties of the parts. During parts fabrication, the deposited material undergoes various heating and cooling cycles that may result in different grain structures along their height. Grain structure control is of major importance since it determines the material mechanical properties. Typically, WAAM parts comprise large columnar grains, formed by epitaxial growth from the substrate aligned along the build-up direction normal to the solid/liquid interface, which has the maximum temperature gradient, thus eliminating the need for nucleation sites [2]. This type of growth results in anisotropic properties, which can be detrimental for multi-axial loading conditions. Equiaxed grains are desirable since they can reduce crack susceptibility while improving ductility, resulting in components with (near) isotropic properties.

Nickel-based alloys are a class of materials mostly used in the aerospace and nuclear industries, for instance in transition ducts and gas turbines. These alloys are characterized by high strength at elevated temperatures, low thermal expansion, and excellent corrosion resistance. Their common austenitic matrix makes them suitable to operate within a wide range of temperatures. High costs, ability to adhere to cutting edges, and the

presence of abrasive carbide particles makes Ni-based alloys difficult to machine, so WAAM becomes a viable technique to eliminate the material waste and consequently the overall costs associated with processing of this alloy. Upon solidification, Ni-based alloys may exhibit the solidification cracking [3], liquation cracking [4], ductility-dip cracking [5], and strain-age cracking [6]. Hence, special care must be taken during WAAM of these materials. Typically, Ni-based alloys, such as Inconel 625 and Inconel 718, have high concentrations of alloying elements that can segregate during solidification in the interdendritic spaces. Moreover, their mechanical properties are highly governed by the Laves phase, and its morphology is dependent on thermal history which consequently affects the parts final properties. Inconel is a solid solution-strengthened nickel-based superalloy, that with the addition of substitutional alloying elements, such as Cr and Mo, provides nucleation sites and the preservation of austenite once cooled. Other phases commonly found in Inconel that are used for strengthening effects, include  $\gamma'$  phase [Ni<sub>3</sub>(Al, Ti, Nb)],  $\gamma''$  (Ni<sub>3</sub>Nb, ordered bct D022 structure), and blocky MC carbides. Nevertheless, the mechanical properties of Inconel alloys can decrease with the formation of undesirable phases, such as the  $\delta$ -phase (Ni<sub>3</sub>Nb, orthorhombic) [7]. Inconel 625 parts manufactured by WAAM consist of vertically columnar dendrites in an austenitic phase ( $\gamma$ ) matrix [8].

Research is currently being done to find ways to prevent this. There are two possible ways to prevent the formation of the Laves phase in the interdendritic regions. The first way is to prevent its formation already during WAAM. Several researchers aimed at this problem. Their results showed that the morphology and composition of the Laves phase strongly depended on the heat input and cooling rate. The formation of the Laves phase due to the segregation of refractory elements into interdendritic regions is controlled by the

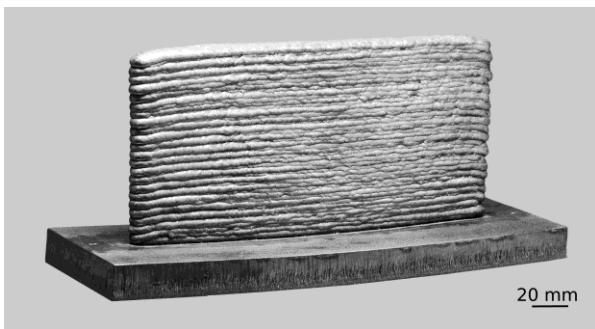
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thermal conditions during WAAM. Currently, it is difficult to monitor and control the formation of the Laves phase because the component undergoes multiple thermal cycles during the WAAM process. The second method consists in dissolving the Laves phase into the matrix using heat treatment. At present, homogenization annealing after welding represents the most feasible way of controlling the appearance of the Laves phase in the microstructure of a component made by the WAAM method. However, standard homogenization annealing procedures that are designed for cast or wrought Inconel 718 may not be suitable for Inconel 718 after WAAM due to their different resulting microstructure. Homogenization annealing can be a suitable way to improve the microstructure of materials after WAAM. However, little is known about the effects of homogenization annealing on the grain size and resulting mechanical properties of Inconel 718 after WAAM [9], [10].

The aim of the work is to compare the mechanical properties of components made of Inconel 718 alloy after different heat treatment regimes and to evaluate them statistically.

## 2 Materials and methods

A steel plate made of material S235 with dimensions of 300 × 100 × 20 mm was used as a substrate. The corrosion-resistant nickel alloy Inconel 718 in the form of NiCro 718 MIG wire with a diameter of 1.2 mm was used as a filler material. Four components made by consecutive overlaying of individual deposits had the shape of a linear wall with a height of 100 mm and a length of 225 mm (Fig. 1).



**Fig. 1.** Wall shaped component made by WAAM.

The Fronius TPS 600i power source in CMT regime and 99.996 % pure argon as shielding atmosphere were used to deposit the walls. The HKS WeldAnalyst system was used to determine the RMS (root mean square) values of deposition current and voltage. The measured WAAM parameters and calculated heat input are summarized in Table 1.

**Table 1.** Used parameters of WAAM process.

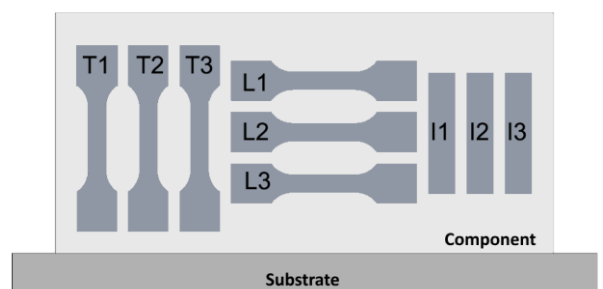
RMS current value [A]	209.61
RMS voltage value [V]	13.66
Deposition speed [mm/s]	5
Wire feed rate [m/min]	8
Shield gas flow rate [l/min]	15
Heat input [J/mm]	527.65

The substrate was removed by EDM and three components were heat-treated by annealing. The temperature and annealing time are documented in Table 2.

**Table 2.** Parameters of heat treatment.

Annealing temperature [°C]	Annealing time [min]
980	30
980	60
980	120

After heat treatment, the components were milled to a thickness of 7.5 mm. Subsequently performed radiographic testing did not reveal any internal defects. The samples for the static tensile test and the Charpy impact test were made by abrasive water jet cutting and milling in accordance to EN ISO 6892-1 and EN ISO 148-1. In order to evaluate the anisotropy of components, two groups of samples orientation were prepared for static tensile test, the transverse (T1-T3) and longitudinal (L1-L3). The samples for Charpy impact test were situated in transverse direction only (I1-I3). The cross section of impact test samples was 7.5×10 mm. The depth of V shaped notch was 2 mm. The placement of samples on each component is shown in Fig. 2.



**Fig. 2.** Placement of samples on component

The tensile test was carried out on the LabTest 5.250 SP1 - VM universal testing device according to the EN ISO 6892-1 standard. The Charpy impact test was carried out according to the STN EN ISO 148-1 standard on a LabTest CHK300 with a pendulum impact energy of 300 J.

### 3 Results and discussion

The average values of the 0.2 yield strength, tensile strength and ductility of the transverse and longitudinal samples are summarised in Table 3 and Table 4.

**Table 3.** Mechanical properties of transverse samples

Sample	Rp0.2[MPa]	Rm [MPa]	A [%]
Without heat treatment	510.4	829.8	19
980°C/30 min	354.3	708.7	34.6
980°C/60 min	348.7	694.0	44.4
980°C/120 min	346.5	700.5	40.3

**Table 4.** Mechanical properties of longitudinal samples

Sample	Rp0.2[MPa]	Rm [MPa]	A [%]
Without heat treatment	502.7	830.3	31.5
980°C/30 min	335.3	719.7	36.5
980°C/60 min	365.7	727.7	39.0
980°C/120 min	334.7	708.7	41.6

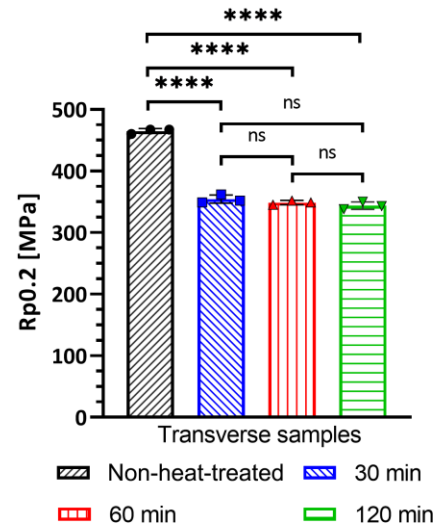
The average impact energy of the samples without and with heat treatment evaluated by Charpy impact test is presented in Table 5.

**Table 5.** Average impact energy of samples after Charpy impact test

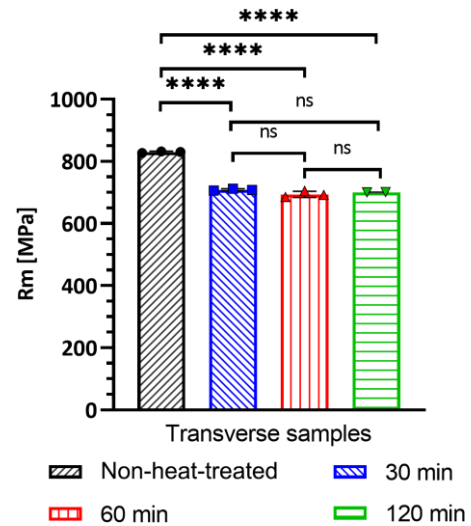
Sample	Impact energy [J]
Without heat treatment	38.4
980°C/30 min	60.0
980°C/60 min	42.0
980°C/120 min	75.3

ANOVA analysis of 0.2 yield strength and tensile strength of transverse samples are presented in Fig. 3

and Fig. 4 respectively. The differences among heat-treated samples are not statistically significant. On the other hand, statistical significance was confirmed between non-heat-treated and heat-treated samples. As the statistical significance was not confirmed between the samples with different annealing time, it can be assumed that the dissolution of the strengthening phases already occurred at the shortest annealing time, i.e. 30 minutes. The reduction of mechanical properties due to phase dissolution was also observed by the others [11, 12].

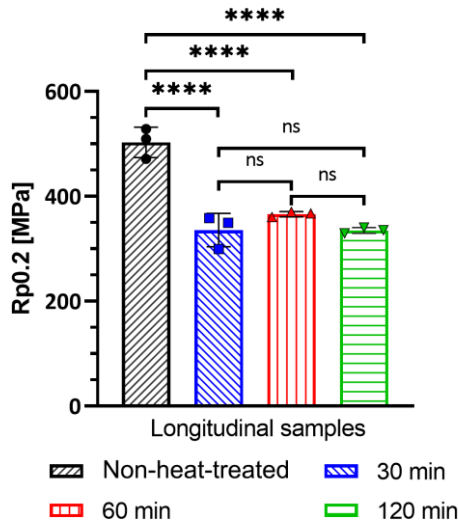


**Fig. 3.** ANOVA analysis of transverse samples 0.2 yield strength

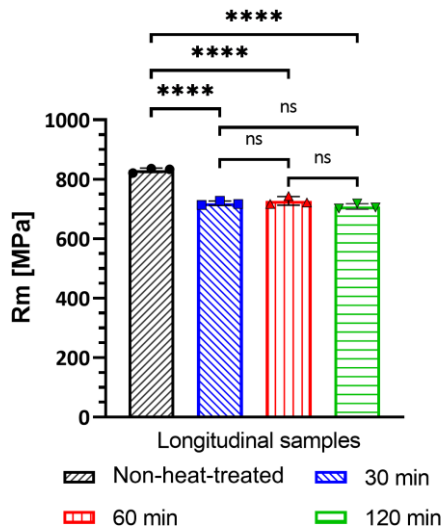


**Fig. 4.** ANOVA analysis of transverse samples tensile strength

Similar results of mechanical properties were also observed in the case of longitudinal samples (Fig. 5 and Fig. 6). However, the difference between 0.2 yield strength and tensile strength of the heat-treated samples was not statistically significant.



**Fig. 5.** ANOVA analysis of longitudinal samples 0.2 yield strength



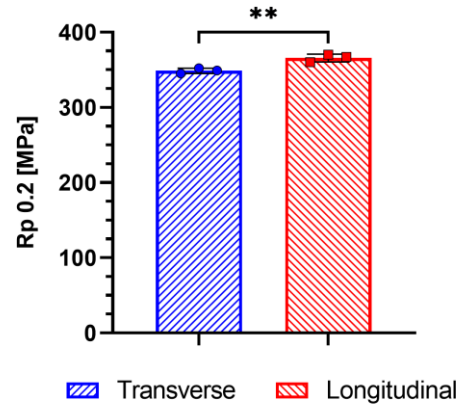
**Fig. 6.** ANOVA analysis of longitudinal samples tensile strength

Regarding the comparison of the 0.2 yield strength and tensile strength of the transverse and longitudinal samples, the statistical analysis confirmed the significance between the two groups of specimen orientation only in the case of an annealing time of 60 minutes (Fig. 7 and Fig. 8).

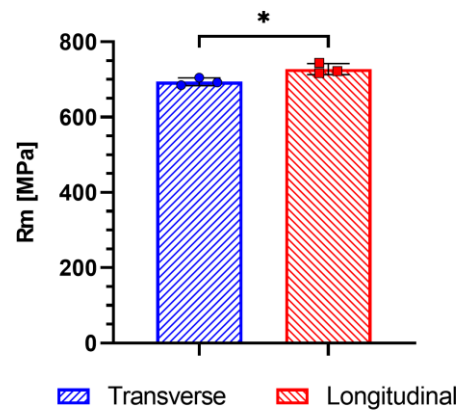
In contrast to 0.2 yield strength and tensile strength, the difference in impact energy of heat-treated samples with different annealing times was statistically significant. The greatest significance was between samples with annealing times of 60 and 120 minutes (Fig. 9).

The impact energy of the sample annealed for 60 minutes was only 9% higher compared to the non-heat-treated sample. However, this difference was not statistically significant.

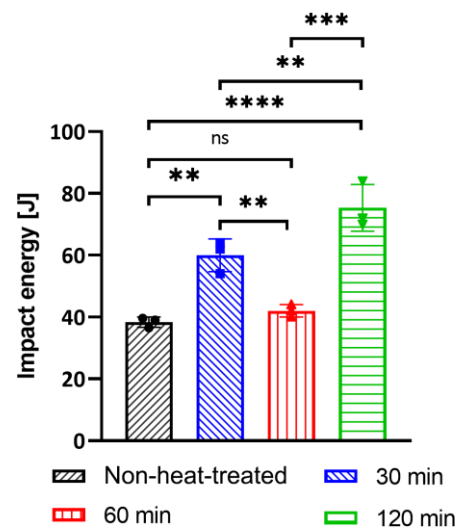
Nevertheless, the difference in impact energy between non-heat-treated samples and samples annealed for 30 and 120 minutes was statistically significant.



**Fig. 7.** t-test comparison of 0.2 yield strength between transverse and longitudinal samples orientation



**Fig. 8.** t-test comparison of tensile strength between transverse and longitudinal samples orientation



**Fig. 9.** ANOVA analysis of impact energy

## 4 Conclusions

The results showed that heat treatment of the samples made by the WAAM method changed their mechanical properties compared to non-heat-treated samples.

The heat treatment resulted in decrease of both the 0.2 yield strength and the tensile strength in comparison to non-heat-treated samples. The 0.2 yield strength was reduced by approximately 30% and the tensile strength by approximately 15%. These values differed only minimally for the samples located in the transverse and longitudinal directions, except for the annealing time of 60 minutes. The analysis of the measured data further confirmed that the annealing time was not statistically significant in terms of the achieved 0.2 yield strength and tensile strength values.

In contrast to the tensile characteristics obtained by the static tensile test, in the case of the Charpy impact test, the impact energy values increased after heat treatment. In the case of an annealing time of 30 min, the impact energy increased by 56%, with a time of 120 min up to 96%. Even in this case, the annealing time of 60 minutes showed an anomaly, as there was an increase in impact energy by only 9% compared to the non-heat-treated samples. When comparing the variance of impact energy, the variance of samples thermally treated for 60 minutes were the smallest compared to the samples processed for 30 and 120 minutes. This means that the decrease in impact energy cannot be attributed to the high variance of data. If we also take into account the statistical significance between transverse and longitudinal samples in terms of 0.2 yield strength and tensile strength of samples annealed for 60 minutes, it is clear that this anomaly will have to be paid attention to in the following research. The samples will therefore be analysed by scanning and transmission electron microscopy.

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## Acknowledgement

This work was supported by Slovak Research and Development Agency under the contract No. APVV- 20-0259.