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# Application of high-strength steel in the Wire Arc Additive Manufacturing (WAAM) process

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**Abstract:** The work deals with the application of high-strength structural steel in the process of *wire arc additive manufacturing* (*WAAM*). In this work, layers are welded by the cold wire *TIG* method. The aim of the work is to analyse the effect of process parameters and layering on the resulting geometry and mechanical properties of the experimental welds. The results showed that the mechanical properties of the welds are dependent on the direction of loading as well as on the welding thermal cycle.

**Keywords:** high-strength steel, manufacturing process, *WAAM*.

## INTRODUCTION

One of the most important aspects of sustainable development in the rapidly evolving sector of industrial production is the application of technological innovations and advanced process optimization. Owing to evolving consumer demands, complicated product designs, and novel materials, traditional manufacturing processes are either approaching the end of their lifespan or are becoming prohibitively expensive. This makes an opportunity for the development of novel, as-yet-undiscovered production concepts. Among the most popular developments in production today are additive and hybrid technologies.

*Wire Arc Additive Manufacturing* (*WAAM*) using the *Cold Wire Tungsten Inert Gas* (*TIG*) method represents a significant advancement in the field of metal additive manufacturing. *WAAM* is an innovative process that combines traditional welding techniques with modern additive manufacturing principles, enabling the creation of large, complex metal components layer by layer. In the *Cold Wire TIG* method, a cold wire feed is introduced into the *TIG* welding process, providing several advantages over conventional wire feed techniques.

The *Cold Wire TIG* process enhances control over the deposition rate and heat input, resulting in finer microstructures and improved mechanical properties in the fabricated components. This method is particularly beneficial for producing high-quality, structural parts with reduced residual stresses and minimal distortion [1, 2]. Additionally, the *Cold Wire TIG* approach allows for better management of material properties and geometric precision, making it ideal for applications in aerospace, automotive, and other high-performance industries [1, 3-5].

As *WAAM* continues to evolve, the integration of *Cold Wire TIG* technology opens new possibilities for manufacturing efficiency and material optimization. This introduction explores the principles, benefits, and potential applications of *WAAM* using the *Cold Wire TIG* method, highlighting its role in advancing additive manufacturing capabilities and addressing current industrial challenges.

In this work, the possibility of applying a filler metal intended for high-strength steels is investigated. Considering that the high strength of the used filler metal is achieved by martensitic transformation, the possibility of decreasing the heat input was investigated to increase the mechanical properties of the welded component.

## 1 MATERIALS AND METHODS

### 1.1 Materials

The base plate for both experimental welds was structural steel *S*355*JR* with a dimensions 150 mm × 300 mm × 5 mm. As filler metal, a metal-cored wire *BÖHLER X*96 *L-MC* with a diameter of 1 mm, classified as *T*89 4 *TMn*2*NiCrMo M M*21 1 *H*5 according to *EN ISO* 18276-A was used. Chemical composition and mechanical properties of filler metal according to manufacturer is given in Tab. 1 and Tab. 2.

**Tab. 1. Chemical composition of filler metal (wt.%)**

| | *C* | *Si* | *Mn* | *Cr* | *Mo* | *Ni* |
|---|---|---|---|---|---|---|
| ***Böhler X*96 *L-MC*** | 0.06 | 0.70 | 1.90 | 0.60 | 0.50 | 2.20 |

**Tab. 2. Mechanical properties of filler metal**

| | min. *YS* [MPa] | min. *UTS* [MPa] | min. *A* [%] |
|---|---|---|---|
| ***Böhler X*96 *L-MC*** | 980 | 1020 | 16 |

## 1.2 Welding procedure

The welding process was performed using the cold wire *TIG* method on a *Fronius MagicWave* 2200 device with a *Fronius KD* 4000*D*-11 *wire feeder*. The torch was clamped on a *Fanuc LR Mate* 200*iD* robotic arm. Two experimental welds marked *Weld-L* (longitudinal) and *Weld-T* (transverse) were made. The reason for such designation is the direction of planned loading during the static tensile test. Table 3 shows welding parameters for both experimental welds. Both welds were shielded by *Ar* 4.6 shielding gas.

**Tab. 3. Welding parameters of *WAAM* process**

| Weld | *WFS* | *I* | *U* | *TS* | $Q_p$ |
|---|---|---|---|---|---|
| | [m·mm$^{-1}$] | [A] | [V] | [mm·s$^{-1}$] | [kJ·cm$^{-1}$] |
| ***Weld-L*** | 1.0 | 80 | 18 | 3.0 | 2.88 |
| ***Weld-T*** | 1.0 | 80 | 18 | 2.5 | 3.46 |

For *Weld-T*, the length of one layer was 80 mm, and 84 layers were cladded to make a wall shaped experimental part. Likewise, for *Weld-L*, the length of one layer was 150 mm, and total number of 73 layers was cladded.

## 1.3 Mechanical testing

The mechanical tests consisted of a static tensile test and hardness test. The samples for the static tensile test were provided auxiliary gripping plates (Fig. 1). These plates were used to grip the jaws of the tensile test device, and were welded to avoid affecting the tested welds. The test samples were not machined; that is, the notch effect of the individual layers was preserved. Specimens were taken from *Weld-L* in the direction of the welded layers and from *Weld-T* perpendicular to the direction of welded layers.

Hardness was measured by the *Vickers* method with a load of 1 kg (*HV*1) on the *Innovatest 412D device*. Hardness measurements were carried out in a line drawn through the center of the sample thickness with a mutual distance of 2 mm between indentations.

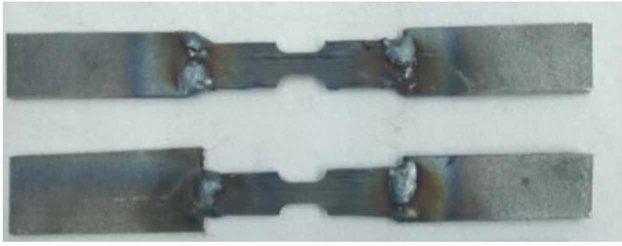


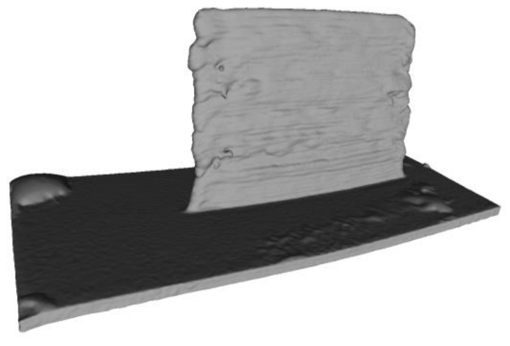
**Fig. 1. Samples for static tensile test**

## 1.4 Macrostructural analysis

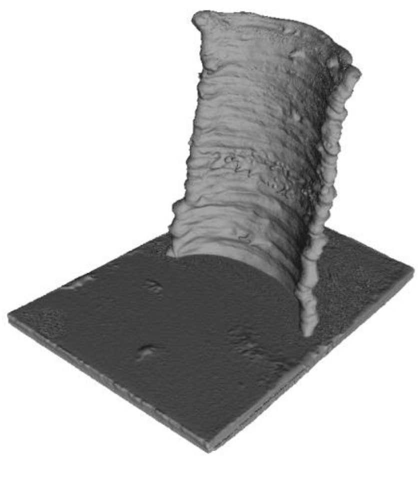
Macrostructural analysis was performed on cross-sections of welded parts. The samples were prepared by grinding and etched with 10 % *Nital*. The images were taken on an *Olympus SZX*16 *device.*

## 2 RESULTS AND DISCUSSION

The manufactured welded parts were subjected to a 3-*D* scan, which made it possible to evaluate their geometry alongside manufacturing precision. Images from this analysis are shown in Fig. 2.



a)



b)

**Fig. 2. 3-*D* images of welded parts: a) Weld-*L*; b) Weld-*T*.**

Based on the 3-*D* images, the total wall height was determined for *Weld-L* $h$ = 71 mm and for *Weld-T* $h$ = 110 mm. Maximum measured wall width was for *Weld-L* $w$ = 6.49 mm and for *Weld-T* $w$ = 6.25 mm.

## 2.2 Hardness distribution

Hardness tests showed relatively consistent hardness distribution in the welded parts (Fig. 3). An increase or decrease in hardness was noted only in the base plate due to the use of *S*355*JR* and in the last 5 layers, which were less thermally affected. This was demonstrated by an increase in hardness by 20 % and 37 %, respectively. The average hardness of the *Weld-T* sample was 305 *HV*1, and the average hardness of the *Weld-L* sample was 342 *HV*1, indicating that the hardness values also demonstrate the effect of heat input. Furthermore, the strength of the welded parts was also considerably impacted.

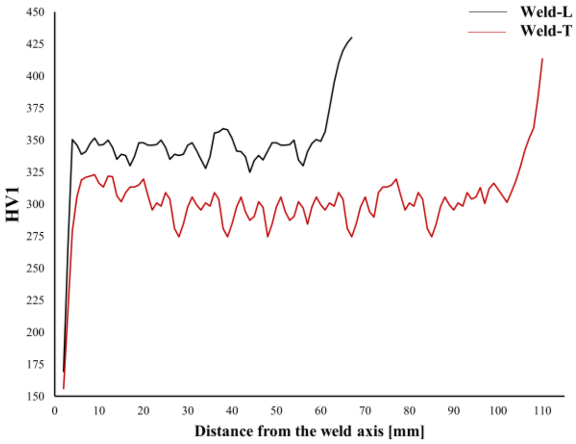



**Fig. 3. Hardness distribution in the welded parts**

## 2.3 Macrostructural analysis

The macrostructural analysis was focused on the observation of internal defects and weld geometry (Fig. 4, Fig. 5).

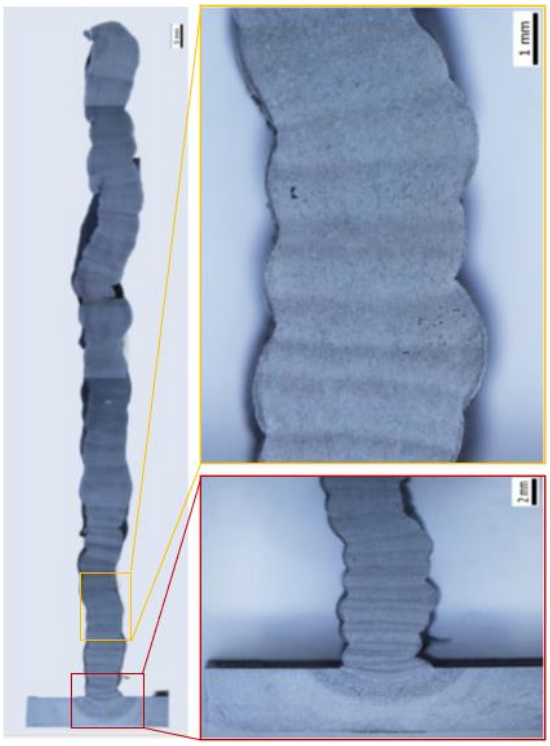



**Fig. 4. Macrostructure of *Weld-L***

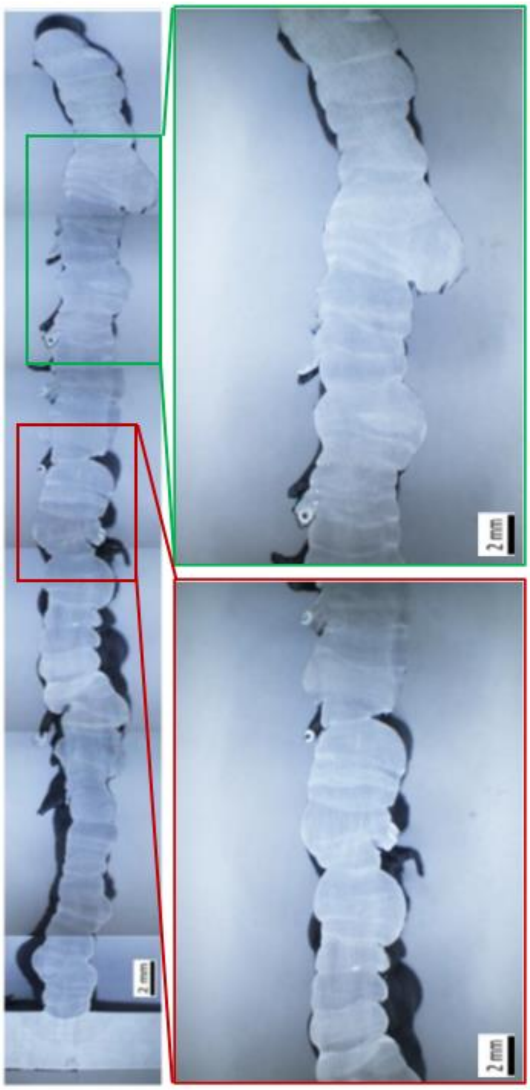



**Fig. 5. Macrostructure of *Weld-T***

Only microporosity and lack of fusion were observed in the analysed parts. Furthermore, it is possible to observe a significant side deviation from the line of layers (especially in the *Weld-T*).

## 2.4 TENSILE TEST

The results of the static tensile test showed a significant difference between *Weld-L* and *Weld-T* (Table 4). All samples were ruptured at the point of smallest cross-section. The fracture point was located on each sample and the initial surface of the sample was determined using a 3-*D* model, from which the *YS* and *UTS* values were determined (Fig. 6).

From the above results, it follows that by applying a lower heat input and longitudinal oriented loading direction (referred to the welding direction), it is possible to achieve more than twice the values of *YS* and *UTS*. Despite the high values obtained during welding with lower heat input, it can be concluded that the obtained values do not reach the minimum values guaranteed by the manufacturer of the filler metal (Tab. 2).

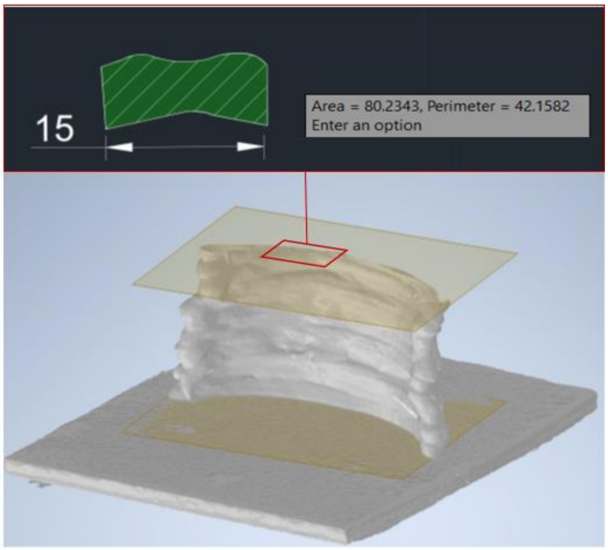



**Fig. 6. Determination of fracture area in static tensile test**

**Tab. 4. Results of the static tensile test**

| Weld | *YS* [MPa] | Avg. *YS* [MPa] | *UTS* [MPa] | Avg. *UTS* [MPa] |
|---|---|---|---|---|
| ***Weld-L*** | 899 | 866 | 1131 | 1102 |
| | 832 | | 1073 | |
| ***Weld-T*** | 494 | 422 | 552 | 462 |
| | 349 | | 372 | |

## CONCLUSION

In the work, two experimental welded parts were made and analysed. According to the findings, there would be a certain reduction in the expected mechanical properties of high-strength steel welded in multiple layers (*YS*, *UTS*). The yield strength (*YS*) of the components produced by the cold wire *TIG* process, made of high-strength filler metal, varies from 35 % to 90 % based on the direction of loading and heat input (referred to the welding direction). The *UTS* values were in the range of 35 % to 110 %, while it should be considered that higher values can be achieved by reducing the heat input. Many issues related to the wire feeding into the welding pool in the cold wire *TIG* process were identified by the geometrical analysis. The overflow of the weld at the layer's ends makes this evident.

Given that the high strength of the filler metal used is achieved by martensitic transformation, it is possible to increase the strength by increasing the cooling rate in the welding process (for example by interpass cooling). It is also advised to consider how the load direction in operating conditions relates to the layer orientation. In this manner, the structure's carrying capacity can be increased or decreased up to twice.

## Acknowledgement

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