Analysis of strength, microstructure and hardness of the butt-welded K-joint

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Abstract: *It is well known that there are several ways to make a butt weld depending on the thickness of the plates to be welded. This paper shows how important it is to prepare the surfaces to be joined by welding. In this paper, the 15 mm thick plates, made of mild steel S235JR, were welded face-to-face with a K-weld using the MIG welding method. The preparation of the plates before welding was not satisfactory, according to empirical instructions, and the resulting weld has defects. Four plates were welded face to face, resulting in two welds. The welds cooled in different ways after welding, one was cooled more slowly in air, and the other was cooled more quickly in water. After welding and cooling the welds, a metallographic analysis of the microstructures of the welds was carried out, and then their hardness was measured using the Vickers method. The conducted metallographic tests concluded that the heat-affected zone has a fine-grained structure, and the melting zone has a cast structure. After the hardness measurement, it can be seen that the hardness values in both the melting zone and the heat-affected zone increase from the root to the surface of the weld. Finally, a strength calculation was performed to determine how much static and dynamic alternating force the realized welded K-joint can withstand compared to the ideal value with good surface preparation.*

Keywords*: STRUCTURAL STEEL, BUTT-WELDED K-JOINT, VICKERS HARDNESS, METALLOGRAPHIC ANALYSIS, STRENGTH CALCULATION*

1. Introduction

Welded joints belong to non-separable joints and are mainly used above all for joints supporting machine parts and structures. Welding can be done by pressure with or without additional material by melting. It is known that in butt welds there is no redirection of the force flow in the welding zone and there are several possibilities of butt welds depending on the thickness of the plates to be welded. Butt welds are a type of weld formed by joining two materials along their interface or edge. This welding process is often used to join metal plates or pipes that are opposite each other. Care should be taken in the design of welded structures to avoid notch effects (stress peaks). The poor joining of parent and filler materials will result in large notch effects in the root and face of the weld. Under dynamic loading, such poor bonding of base and filler material leads to a drop in dynamic strength and failure due to material fatigue. The quality of the weld depends on the skill of the welder [1-3]**.**

The butt welding process includes the following steps: (I) Material preparation: The plates or pipes to be joined must be clean and prepared to ensure good weld quality. This may include cleaning the surface, removing oxides or grease, and smoothing the edges. (II) Placement of Materials: Materials are placed opposite each other so that their interfaces are aligned. Depending on the type of joint, clamps, guides or other tools may be used to ensure proper alignment. (III) Welding: After the materials are properly placed, the welding process is performed. The welder applies heat and filler material along the interface, creating a permanent joint. (IV) Re-welding: After welding, the joint may undergo a re-welding process to improve the properties of the weld. This may include heat treatment, weld testing, grinding, or other treatments [1]. Butt welds can be very strong and durable, but it is important to ensure proper alignment and weld quality to achieve the desired result. In addition, specific welding guidelines and procedures may vary depending on the material being joined and the application conditions [3].

In this paper, steel specimens were welded using the MIG welding method, with a melting electrode with the addition of material in an inert gas atmosphere, where the metal electrode and base material were melted by the heat of the arc.

This paper shows the importance of preparing the surfaces to be joined by welding. In this paper, the 15 mm thick plates of mild steel S235JR with a K-joint were welded face-to-face using the MIG welding method. The preparation of the plates before welding was not satisfactory, according to the empirical instructions, and the resulting welded joint has defects. Four plates were welded face to face resulting in two welds.

The welds were cooled in different ways after welding, one was cooled more slowly in air and the other more quickly in water. After welding and cooling of the welds, a metallographic analysis of the microstructure of the welds was performed, and then their hardness was measured by the Vickers method [4]. The metallographic examinations carried out showed that the heat-affected zone has a fine-grained structure, and the melting zone has a cast structure. After measuring the hardness, it can be seen that the hardness values increase from the root to the face of the weld in both the melting zone and the heat-affected zone. Finally, a strength calculation [5] was performed to determine how much static and dynamic alternating force the realized welded K-joint can withstand compared to the ideal value achieved by good surface preparation.

2. Prerequisites and means for the analysis of a weld seam

2.1. Properties of mild steel S235JR

The basic material of this butt-welded joint is mild steel S235JR, which is often used in construction. Steel S235JR can be welded without restrictions, without subsequent heat treatment, and without heating. When welding thicker steel products, the risk of cold cracking increases. Table 1 shows the chemical composition of S235JR steel.

Table 1. *Chemical composition of steel S235JR*

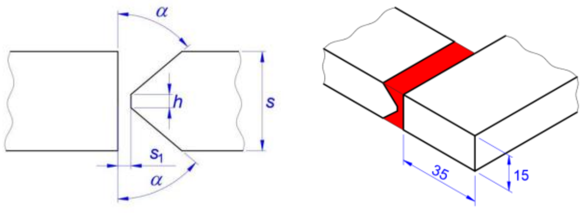
C	Mn	P	S	N	Cu
≤0.17	≤1.40	≤0.035	≤0.035	≤0.12	≤0.55

From the Smith diagram for mild steel S235JR, values of yield strength (R_e) of 235 MPa and dynamic strength (R_d^{-1}) for an asymmetry factor of -1 of 120 MPa can be read [3]. The read values of yield strength and dynamic strength are used for strength calculation.

2.2. Material preparation for welding

Preparation of steel specimens for butt welding begins with cutting on a band saw. The base material with dimensions 35x15 mm was placed in the stationary lower jaw of the saw to fix it for cutting. A total of four specimens with a length of 65 mm were cut. A belt sander was used to clean the specimens and prepare them for butt jointing. Since the sheet of the base material is thicker than 15 mm, it must be prepared from above and below. When preparing the *K*-seam, only one side of the plate may have a slope, while the other side is without a slope.

A properly prepared weld, shown in Fig. 1a, is used for plates thicker than 15 mm (dimension s), and the dimensions are as follows: s_1 = 2-4 mm, h = 0-3 mm, and α = 50-55°. Four plates are welded face to face so that two welds are obtained (Fig. 1b).



a) b)

Fig. 1. *a) Preparation of material for K-joint welding, b) Welded K-joint*

The geometry of the specimen preparation was not fully considered in this paper. The slope and the distance between the plates were not within the limits. Material preparation was followed by MIG welding. The specimens were first spot-welded at the ends of the ground grooves to bring the pieces closer together to fully weld them to the electrode. The two L-shaped specimens were welded as shown in Fig. 2. One piece of the welded mild steel was left on the table to cool gradually to room temperature in the air while the other piece was cooled in water.

a) b)

Fig. 2. *Specimens: a) cooled in air and b) cooled in water*

2.3. Preparation of specimens for metallographic analysis

Because of the metallographic analysis and hardness testing, the butt-welded parts must be cut so that the K-weld can be seen in the section. The cut specimens are shown in Fig. 3.

a) b)

Fig. 3. *Cut specimens: a) air-cooled joint, b) water-cooled joint*

The cutting of the specimens is followed by grinding and subsequent polishing, which was performed on the BUEHLER Phoenix Beta unit.

The grinding is done with water-based sandpaper in different gradations. It starts with the coarsest grit and ends with the smallest grit to obtain a finely polished surface of the specimens. The procedure starts with the use of 400-grit sandpaper, and then 600 and 800 grits are used. During grinding, the specimens should be constantly cooled with water so that the microstructure of the specimens does not change.

After grinding, all specimens were polished again to a mirror-like surface (without scratches) on a microfiber cloth (so-called felt) at a speed of 150 rpm with the occasional addition of an aqueous Al_2O_3 suspension. The grinding and polishing parameters are listed in Table 2. After grinding and polishing, the specimens are etched with Nital (a 5% solution of nitric acid in alcohol).

Table 2. *Parameters of grinding and polishing of steel specimens by hand*

Grinding				
Base	Grain granulation	Media	Plate rotation speed, rpm	Time, min
SiC-paper	400	water	150	6
	600			5
	800			5
Polishing				
Base	Grain granulation	Media	Plate rotation speed, rpm	Time, min
fabric	microfiber	water + Al_2O_3 (0.3μm)	150	5

2.4. Light microscopy

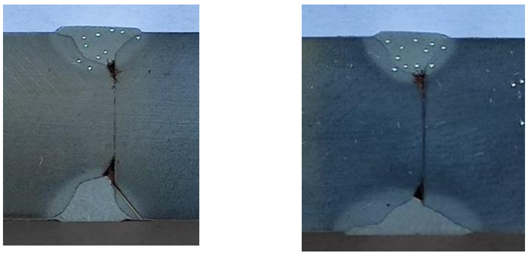
A light microscope was used to obtain information about the appearance of the surface and phenomena in the sample, such as inclusions, porosity, cracks, and others. Metallographically prepared samples were used for this purpose.

In this paper, the specimens were observed at 50x magnification using an Olympus GX 51 light microscope. The surfaces of the welded steel test specimens were photographed under the conditions of metallographic preparation using an Olympus DP 70 digital camera connected to the light microscope.

2.5. Hardness measurement

Hardness is a mechanical property that indicates the resistance of a material to penetration by another, harder material into its surface or structure. Hardness is influenced by the chemical composition of the material as well as by mechanical and heat treatment. In addition, hardness is closely related to yield strength, modulus of elasticity, ultimate strength, tensile strength, and toughness [4,6,7].

In this paper, the hardness of experimental welded steel specimens was measured by the Vickers method on a Mitutoyo hardness testing machine with an indentation force of 10 kg and with an indentation time of 10 seconds. HV10 hardness measurements were performed 1 to 3 times at random points on the polished surface: in the melting zone and in the heat-affected zone at the surfaces, center and root of the weld (Fig. 4.).



a) b)

Fig. 4. *Imprints of the indenter by the specimens: a) cooled in air, b) cooled in water*

2.5. Strength calculation

In order for the welded joint to withstand the tensile load, the strength condition must be satisfied. The strength condition is represented by the following equation

$$\sigma_{\mathrm{weld}} \leq \sigma_{\mathrm{allow,weld}}\ , \qquad (1)$$

where are σ_{weld} stress of welded joined and $\sigma_{\mathrm{allow,weld}}$ allowed the stress of welded joined. The stress in the weld is equal to the ratio between the axial force F and the bearing surface of the weld A_{weld}

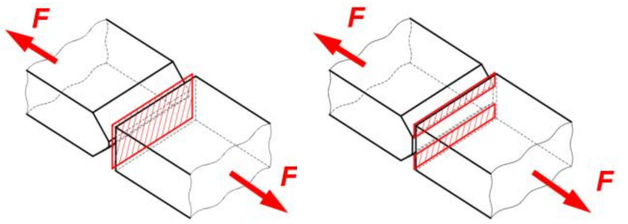
($\sigma_{\text{weld}}=F/A_{\text{weld}}$). A force, F, can be static (F^{stat}) or dynamic (F^{dyn}). The strength calculation can be performed both for a static force and for a variable dynamic force. Then the allowable stresses are calculated according to different expressions

$$\sigma^{\text{stat}}_{\text{allow, weld}} = \frac{b \cdot b_1 \cdot R_e}{S}, \tag{2}$$

$$\sigma^{\text{dyn}}_{\text{allow, weld}} = \frac{b_1 \cdot b_2 \cdot b_3 \cdot b_4 \cdot R_{\text{d}}^{-1}}{S_{\text{dyn}}}, \tag{3}$$

where are b the value of the strength reduction factor in the welded machine part in relation to the non-welded part (static), b_1 the value of the weld quality factor, b_2 the value of the shape factor, and the method of loading the weld, b_3 the value of the size factor of the machine part, b_4 the value of the material quality factor, S a safety factor for static load and S_{dyn} safety factor for dynamic loading.

When preparing the specimens for metallographic analysis, it was found that the welding was not done correctly. The bearing surface of the weld was significantly reduced. This strength calculation was used to calculate the maximum force (static and dynamic) with which the butt-welded joint can be subjected to tensile loading. Figure 5 shows the load-bearing surfaces of a well-designed weld and a poorly-designed weld. The load-bearing surface of the weld is marked with a red shaded field.



a) b)

Fig. 5. *Bearing surface (A_{weld}) of a butt-welded joint: a) well and b) poorly executed joint.*

The values of the required parameters are taken from [3] and shown in Table 3. The required safety factor is 1.5 for the static load (S) and 2.5 for the dynamic alternating load (S_{dyn}). The bearing surface of a poorly designed connection is only 40% of a well-designed connection.

Table 3. *Required parameters*

Welded joint	Parameter				
	b	b_1	b_2	b_3	b_4
WELL	0.75	1	0.45	1	1.1
POORLY		0.8			

3. Results and discussion

3.1. Light microscopy results

Images of the surface of the specimens after grinding, polishing, and etching are shown in Fig. 6.

The metallographic images show the gaps at the weld root, which should not have happened. The poor penetration of the weld root is very noticeable in both specimens. It is the initiation for the crack propagation when the weld is loaded and at the same time the reason for the corrosion formation.

From the metallographic images provided, it can be seen that the material in the melting zone has the structure of cast iron. The specimen cooled in water after welding has finer grains in the center of the surface of the weld than the specimen cooled in the air after welding. The grains are elongated towards the heat-affected zone.

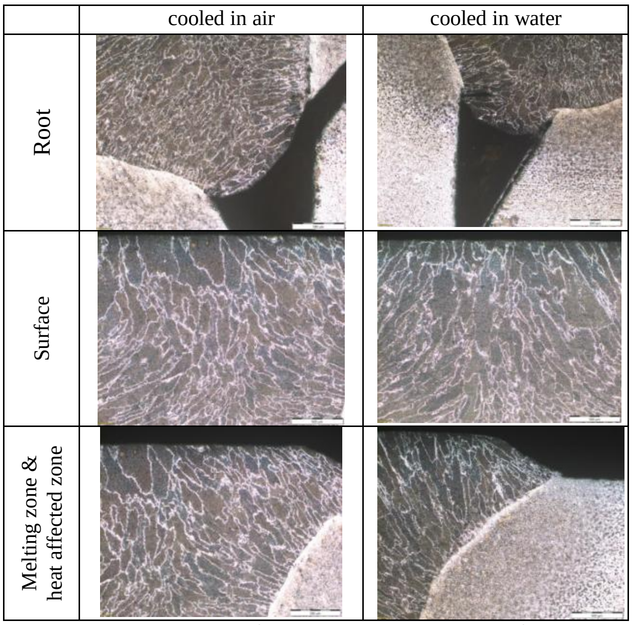


Fig. 6. *Microstructure of the welded joint at 50x magnification*

3.2. Hardness measurement results

The results of the hardness measurement are shown for the samples cooled in the air in Table 4, and for the samples cooled in water in Table 5.

Table 4. *Results of hardness measurement for the air-cooled samples after welding (HV 10)*

BASIC MATERIAL	First plate	Second plate	
	179.6	181.9	
	178.6	180.5	
HEAT AFFECTED ZONE	Root	Centre	Surface
	177.2	184.4	213.2
MELTING ZONE	Root	Centre	Surface
	249.6	261.9	263.2
	249.7	259.1	265.1
			263.8

Table 5. *Results of hardness measurement for a samples cooled in water after welding (HV 10)*

BASIC MATERIAL	First plate	Second plate	
	177.6	181.1	
	179.3	183.8	
HEAT AFFECTED ZONE	Root	Centre	Surface
	206.3	210.2	225.5
MELTING ZONE	Root	Centre	Surface
	253.3	258.0	270.1
	252.1	262.0	262.9
		263.7	272.3

The tables show that several measurements were made in a given area. The measured values per area are averaged and represented by the hardness dependence diagram per area for the melting zone (Fig. 7) and for the heat-affected zone (Fig. 8). The dependencies of the hardness change on position are shown in the same diagram for both specimens for better comparison.

From both diagrams, it can be seen that the hardness values increase from the root to the surface of the weld, both in the melting zone (Fig. 7) and in the heat-affected zone (Fig. 8). The hardness increase in the melting zone is similar for both the air-cooled and water-cooled specimens after welding.

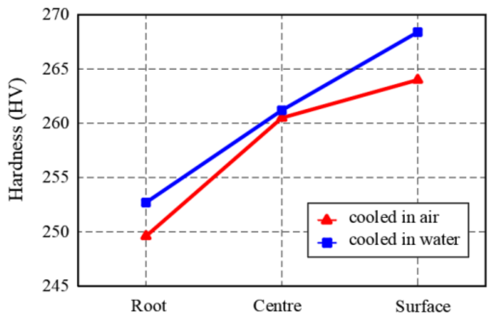


***Fig. 7.** Average measured hardness values by position in the melting zone*

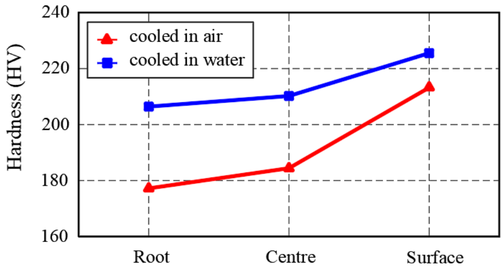


***Fig. 8.** Average measured hardness values by position in the heat-affected zone*

From the comparison of metallographic analysis and hardness measurement, it can be concluded that the finer the grain size structure, the higher the hardness in both the melting zone and the heat-affected zone.

3.3. Strength calculation results

Using the strength conditions and all the given parameters, it is possible to calculate the maximum force that a butt-welded joint can withstand under tensile load. The amounts of calculated maximum forces are shown in Table 6.

***Table 6.** Results of the maximum forces of a butt-welded joint under tensile load*

Welded joint	Force [kN]	
	Static (F^{stat})	Dynamic (F^{dyn})
WELL	61.69	12.47
POORLY	19.74	3.99

From the results shown in Table 6, it can be concluded that the capacity of a poorly butt-welded joint is reduced by 68% compared to a well-designed welded joint under both static and dynamic tensile loading.

4. Conclusion

The aim of this paper was to analyze butt-welded specimens that were welded using the MIG method and cooled differently after welding. One specimen was cooled in air after welding, while the other was suddenly cooled in water. The analysis of the two specimens revealed their differences. The analysis included a metallographic examination, a hardness measurement, and a strength calculation.

The investigations carried out revealed the following:

- the butt-welded joints were not well prepared before welding according to the standard for K weld, therefore there was a poor penetration of the roots on both sides of the weld and thus an accumulation of air in the middle of the welded plates, which can be the starting point for the beginning of corrosion and the starting point for the beginning of crack propagation due to high stress concentrations caused by the loading;
- the strength analysis showed that the maximum force of a tensile-loaded welded joint with this type of poor weld preparation was reduced by 68% compared to a good preparation;
- the metallographic analysis showed that the grain in the melting zone was finer for the specimen cooled in water than for the specimen cooled in air;
- the metallographic analysis showed that the grain in the melting zone is elongated in the direction of the heat-affected zone in both specimens;
- the metallographic analysis showed that the specimen cooled rapidly in water has a finer-grain structure in the heat-affected zone that the specimen cooled in the air;
- the metallographic analysis showed that the structure in the heat-affected zone is finer-grained than that of the base material in both specimens;
- by measuring the hardness, it was found that the hardness increases from the root to the face of the weld, both in the melting zone itself and in the heat-affected zone;
- by measuring the hardness, it was found that the increase in hardness in the melting zone and in the heat-affected zone is approximately the same for both specimens;
- the results of the metallographic analysis and the hardness measurement show that the hardness is higher with a finer-grained structure.

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5. References

1. M. Gojić, Tehnike spajanja i razdvajanja materijala, Sveučilište u Zagrebu, Metalurški fakultet, Sisak, 2008.
2. D. Jelaska, Elementi strojeva, Sveučilište u Splitu, FESB, Split, 2005.
3. L. Lazić, Elementi strojeva, Sveučilište u Zagrebu, Metalurški fakultet u Sisku, Sisak, 2001.
4. I. Vitez, Ispitivanje mehaničkih svojstava metalnih materijala, Sveučilište Josipa Jurja Strossmayera u Osijeku, SFSB, Slavonski Brod, 2006.
5. I. Alfirević, Nauka o čvrstoći I, Tehnička knjiga – Zagreb, Zagreb, 1995.
6. Mechanical Testing and Evaluation, ASM Handbook Volume 8, ASM International, Materials Park, (2000).
7. P.M. Talarico, Y.W. Kwon, Hardness and tensile properties of metals subjected to aging conditions, Multiscale and Multidisciplinary Modelling, Experiments and Design (2020) 3:187-200.