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THE INFLUENCE OF TIG WELDING TECHNOLOGY ON THE PROPERTIES AND QUALITY OF JOINTS MADE OF DISSIMILAR STEELS

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Abstract: The paper presents a new technology for welding dissimilar steels using the TIG method. Following the welding, the joint was subjected to non-destructive testing, and subsequently a Vickers hardness measurement. The tests were intended to determine whether the newly developed welding technology was properly prepared and if such joints were feasible. This particularly applies to dissimilar materials joined by welding.

Keywords: welding technology, 13CrMo4-5 steel, K18 steel.

1. INTRODUCTION

During dissimilar steel welding, one needs to consider the tendency of welds to harden and crack, and prevent the diffusion processes in welded components during long-term operation at high temperatures. For this reason, the chemical composition of the weld should be as close as possible to the material being welded. Making mixed welds by welding steels designed for use in elevated temperatures is not an easy issue to solve. Component diffusion in a weld made of materials with different compositions may lead to reduced resistance to prolonged loads and to brittleness. The differing chemical compositions at the joint result in a risk of a heterogeneous structure forming at the fusion line during heat treatment or prolonged use. A symptom of heterogeneity is the emergence of a large-grained carbon-depleted zone on one side of the fusion line, and a hard, carbonised zone on the other side. Carbon diffuses from the material with the higher carbon potential to the material having a lower carbon potential.

To avoid carbon migration within the fusion line, steels of differing chemical compositions are joined using fillers having an approximate composition of: 20% Cr, 70% Ni, 3-6% Mn, up to 5% Fe, 2% Nb, up to 1% Mo. The advantages of fillers with compositions similar to the above stem from the following properties [Łomozik 1997; Tasak 2002; Pilarczyk 2014]:

- in the intermediate zone, mixing of this filler with the native material leads to the forming of brittle (martensitic) structures;
- carbon activity in nickel and high-nickel alloys is high, so the development of a carbon-depleted zone is limited even after a long time of usage at high temperatures;
- they have high plasticity and strength at ambient temperatures;
- they have good creep resistance at high temperatures;
- these joints are resistant to corrosion at ambient temperatures and to oxidation at high temperatures;
- they maintain good plasticity at low temperatures;
- brittleness caused by the forming of a sigma phase does not occur (this brittleness occurs in austenitic steels).

In certain cases, due to the very high prices of such joints, their use is limited as much as possible. One method of reducing the need to use the above joints is to use 'buffer layers'. To protect against carbon diffusion by extending the diffusion distance from the low-alloy material to the high-alloy material by using one or more layers where the carbon activity is higher. If the buffer layer is on the higher-alloy material, the weld is made using a material with a chemical composition suitable for the lower-alloy material. If the buffer layers are made on a lower-alloy material using high-nickel joints, then the weld joint is made with a filler selected to match the higher-alloy material. For welding two ferritic or martensitic steels with an austenitic weld, buffer layers are applied to the edges of both materials to be joined [Gourd 1997; Łomozik 1997; Tasak 2002; Ferenc 2013].

Welding of dissimilar steels, as done in practice, covers 3 types of joints:

- parts welded for structural purposes are made of steels or alloys that differ or significantly differ in their chemical composition;
- regular carbon steels or low-alloy steels are surfaces with corrosion-resistant austenitic steels or alloys to protect the surface from corrosive agents;
- the parts to be joined are made of the same material, but for whatever reason it is necessary to use a filler of a different kind than the native material.

Selecting a filler with the right chemical composition is important when making welded joints between dissimilar steels. Another important issue in welding dissimilar steels is choosing the welding method [Gourd 1997; Klimpel 2013].

2. PREPARATION OF SAMPLES FOR TESTING

Sample 1A, 1B is a dissimilar combination of A106 (K18) steel with 13CrMo (15HM) steel in the form of a ø114.3 pipe with a wall thickness of 11.5 mm, as illustrated in Figure 1.

Fig. 1. Prepared sample 1A and 1B

This type of joint is an example of a practical application in the power engineering industry. Steam boilers use such joints when connecting pipe lines of the convection section with the steam superheater section. Non-alloy carbon steels, such as A106 (K18), are used in the boiler's convection section. In this part of the boiler, temperatures range from 130°C (feed water temperature) to 340°C (wet steam temperature in the drum). With these parameters, the A106 (K18) steel has suitable mechanical properties. An additional advantage of A106 (K18) steel is its good weldability. In a steam superheater, the temperature of the superheated steam often ranges from 500°C to 540°C. This leads to the need for using alloy steels resistant to such operating conditions. The 13 CrMo 4-5 (15HM) steel is often used for such purposes. Thanks to its chemical composition, it is resistant to the effects of high temperatures [Kamiński 2021].

The chemical composition and mechanical properties of A106 (K18) steel are based on the material certification, provided in Table 1.

Table 1. Chemical composition and mechanical properties of A106 (K18) steel

A106 (K18) according to PN-EN 10028-2:2017-09 **Certificate no.** 7198/W/96								
R_e [MPa]	**R_m [MPa]**		**A [%]**		**KV [J]**			
405	530		30		-			
C	**Cr**	**Mo**	**Si**	**Mn**	**A**	**S**	**Ni**	**V**
0.21	0.02	-	0.24	0.59	0.019	0.014	0.03	-

Table 2 shows the chemical composition and mechanical properties of the other test steel 13CrMo 4-5 (15HM), based on the material certificate.

Table 2. Chemical composition and mechanical properties of 13CrMo 4-5 (15HM) steel

13CrMo 4-5 (15HM) according to PN-EN 10028-2:2017-09 **Certificate no.** 200672								
R_e [MPa]	**R_m [MPa]**		**A [%]**		**KV [J]**			
280	530		22		27			
C	**Cr**	**Mo**	**Si**	**Mn**	**A**	**S**	**Ni**	**Cu**
0.18	1.13	0.53	0.25	0.96	0.0082	0.002	0.03	0.019

Before welding, the sample was properly treated, the edges were chamfered as per PN-EN ISO 9692 "Welding and allied processes. Recommendations for joint preparation", as illustrated in Figs. 2 and 3.

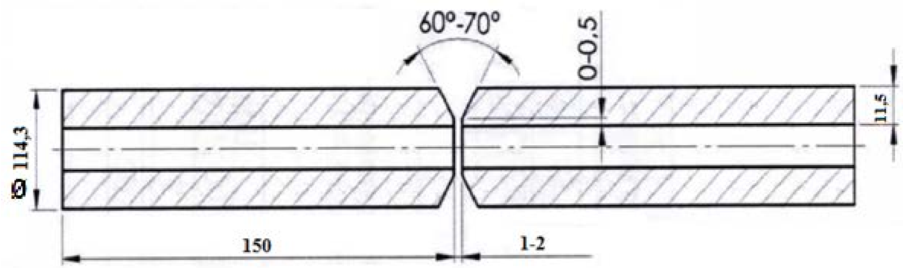


Fig. 2. Sketch showing the dimensions of sample 1A and 1B

Fig. 3. Sample preparation for the welding process

3. WELDING TECHNOLOGY

The additional welding material was a copper-plated, low-alloy chromium-molybdenum (1% Cr, 0.5% Mo) OK Tigrod 13.12 welding rod. Designed for welding using method 141 - with a non-consumable tungsten electrode in an inert gas shield (TIG – Tungsten Inert Gas) – of creep-resistant steels (same type), such as pipes used in pressure vessels and boilers. It can also be used for welding low-alloy, high-strength steels whose minimum tensile strength is approx. 550 MPa.

Table 3 shows the chemical composition of the filler used, which was produced by ESAB.

Table 3. Chemical composition of the filler

Filler name	C	Si	Mn	Cr	Mo	**Mechanical properties**			
						Rm [MPa]	Re [MPa]	A_5 %	KV (J)
OK Tigrod 3.12-ESAB	0.10	0.60	1.00	1.10	0.50	650	560	26	180

The prepared technology assumes:

The WPS (Welding Procedure Specification) – welding method using a non-consumable tungsten electrode in an inert gas shield (TIG), where an OK Tigrod 13.12-ESAB rod was used as the filler, requiring pre-heating of the filler to 250°C with a gas burner before welding. To maintain the pre-heating temperature and avoid the sample from cooling, thermal blankets and heating the elements with a gas burner was used. The heating process is illustrated in Figure 4 [Klimpel 2013; Wieczorska and Domżalski 2021].

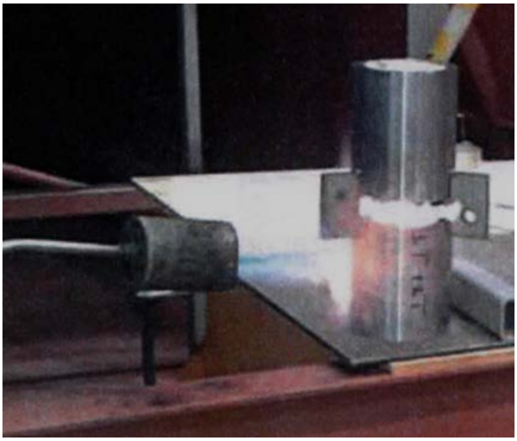


Fig. 4. Heating the welding sample

At the beginning of the welding process, a positional weld had to be made. This involved positioning the samples properly, then welding three metal plates to them at equal distances so that the root, or the first layers of the weld, could be made. To protect against the phenomenon of root layer oxidation, a “pad” of forming gas – argon – was used to cut off the flow of air using a thermal insulation material and feeding argon in the space thus formed. Very frequently this method is used in welding pipe joints to produce a weld with high purity on the root side.

Figure 5 shows the sample with the positioning plates and the thermal insulation material “pad” visible in a top view [Łabanowski 2010; Ferenc 2013; Wieczorska and Domżalski 2021].

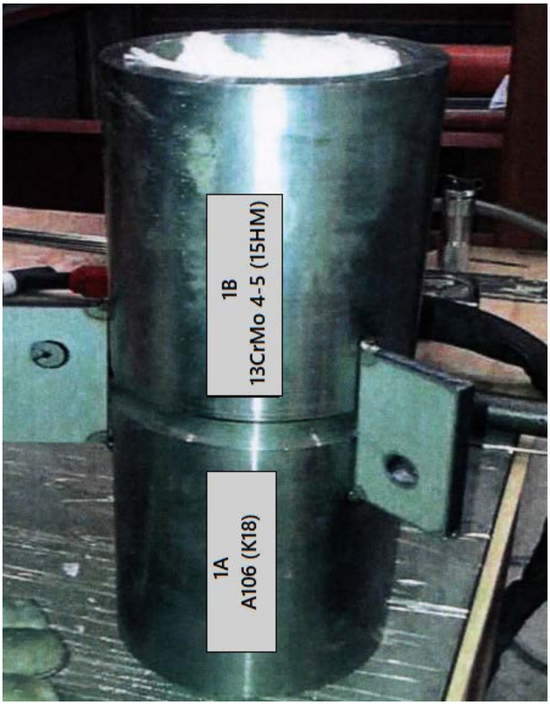


Fig. 5. Positioning welds with visible positioning plates and a thermal insulation “pad”

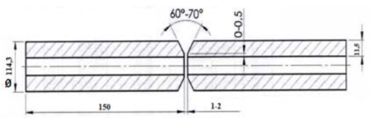
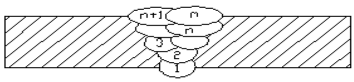
The root, or the first layer of the weld, was made using ø2.0 OK Tigrod 13.12 – ESAB filler. Once the first weld layer was done, the positioning weld plates were cut away and further layers were made with ø2.4 OK Tigrod 13.12 – ESAB filler. After each layer was completed, the slag had to be removed and the weld cleaned. During welding, the temperature in each run was measured using a Cyclops 160L pyrometer, the temperature between the runs should be at most 250˚C. Once the welding process was complete, relief annealing was performed.

Table 4 shows the welding specification. Figure 6 shows the sample after the welding process [Łabanowski 2010; Ferenc 2013; Pilarczyk 2014].

Table 4. Welding Procedure Specification (WPS)

WPS Welding Procedure Specification	No./Nr **141/20/1**	Rev./zm. **-**
	Page / strona 1	Pages / stron 1

1. WPQR no. : 1	1. Method of preparation for welding: machining / washing
2. Standard No. : PN-EN ISO 15609-1	2. Base material: A: 13CrMo4 (15HM) B: K18 (A106) – pos. 1 **material group** : 5.1 – pos. 2 **material group** : 1.1
3. Manufacturer :	3. Thickness of material [t-mm]: : 3 - 12
4. Welder qualifications : FM3-EN ISO9606-1	4. Outer diameter [d-mm] : ø ≥ 25
5. Welding process : 141	5. Welding position : PA, PC, PH, H-LO45
6. Joint type : BW	

Preparation for welding	Run sequence
	

Current characteristics								
Run	Welding process	Size of filler mat. [mm]	Current [A]	Voltage [V]	Type of current / Polarity	Wire speed [m/min]	Welding speed [mm/s]	Linear energy [kJ/mm]
1	141	2.0	80-95	12-13	DC -	-	45-60	0.96-1.65
2-n	141	2.4	95-115	13.5-14.5	DC -	-	60-90	0.86-1.67

1. Filler material - type: 141-W Cr Mo 1Si wg EN ISO 21952-A - brand : 141-OK. Tigrot 13.12 - manufacturer : 141-ESAB 2. Shield gas acc. to EN ISO 14175 - type : 141 – I1-Ar 99.99% - flow : 141 - 10-12 l/min 3. Forming gas - type : I1-Ar 99.99% - flow : 4-6 l/min 4. Tungsten electrode brand / Size: N/A : Wth-2,4X125 Pn-EN 26848	**Preheating for welding / Podgrzewanie do spawania** - preheat temperature : **min 250^{o}C** - type of pre-heating : furnace - temperature between runs : **max 250^{o}C** **Post weld heat treatment / Obróbka cieplna po spawaniu** - type : stress reliving - heating rate [^{o}/h] : **max. 150** - holding temp. [^{o}C] : **740+/-10** - holding time [h] : **2** - cooling rate [^{o}/h] : **max. 100**

Remarks, additional information / Uwagi, informacje dodatkowe: Weld with shorting arc, do not allow local superheating of material. Thoroughly clean each run. Multilayer welding. After welding, cool to 100±10°C, maintain this temp. for at least 0.5 h and begin stress relief annealing		
Prepared by Date	Approved by Date	Approved by Customer Date

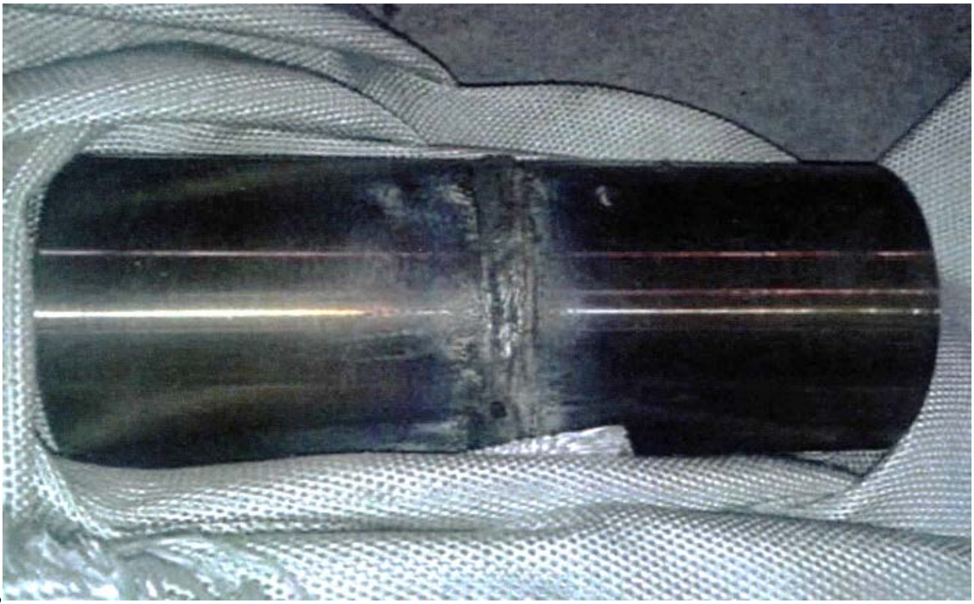

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Fig. 6. Sample after the welding process

4. STRESS RELIEF ANNEALING

Annealing is a heat treatment process involving heating the charge to a specific temperature, holding it at this temperature, then slowly cooling it in air.

The purpose of this treatment was to bring the material closer to equilibrium conditions [Cicholska and Czechowski 2013].

Heat treatment was performed in a DLR-61 electric chamber furnace. Sample heating rate was 150°C/h, then after reaching a temperature of 740 ±10°C the holding time was 2 hours, followed by cooling the sample at a rate of 100°C/h.

Once the heat treatment was complete, which was intended to remove welding stresses, non-destructive testing was performed, which included:

- visual testing (VT);
- penetration testing (PT);
- radiographic testing (RT).

Following the non-destructive testing, a Vickers joint hardness measurement was conducted.

Figure 7 illustrated the heat treatment process.

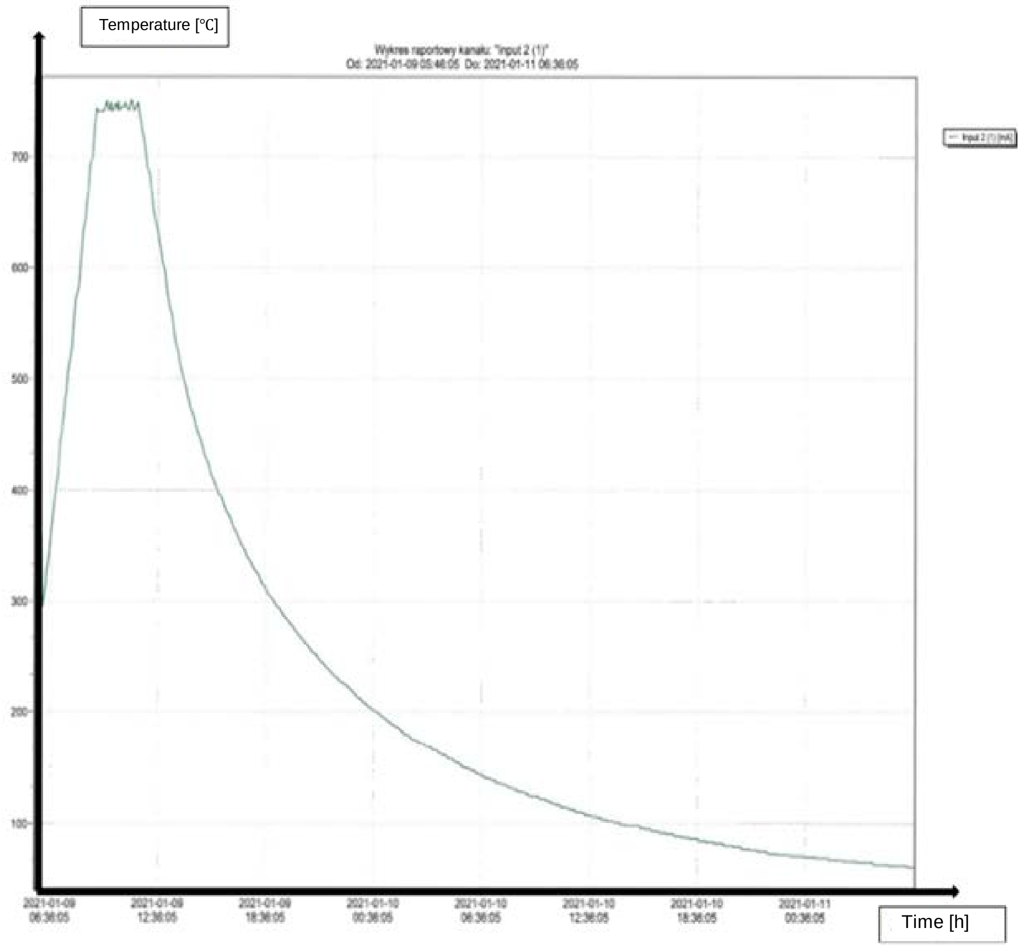

Fig. 7. Heat treatment process chart

5. TEST RESULTS

Once cooled, the sample was handed over for non-destructive testing. The scope of testing, equipment used and test documentation is summarised in Table 5.

Visual testing was performed using a calliper and a weld gauge, measuring the geometric dimensions of the weld. Using a looking glass, the joint was inspected for cracks, undercuts, lack of weld groove filling, pores, overlaps and excess penetration beads. Visual observations found no irregularities. An acceptable level was found, weld quality B. The tests were performed in accordance with PN-EN ISO 5817: 2014-05. Next, the sample was subjected to penetration testing according to PN-EN ISO 5817 and PN-EN ISO 3452-1: 2021-12. The penetration test was performed across the entire surface of the weld, with background lighting intensity of 990 lx, using a MR Chemie set. The penetration test also demonstrated weld class B with a positive result for the weld joint [Pilarczyk 2014; Czuchryj and Sikora 2018].

Table 5. Test methods, test equipment, standards

No.	Test method	Equipment Test equipment	Testing conditions	Testing standards and instructions
1	Visual	Weld gauge, Calliper	[Lx] 990 - Levy Hill Mk VI No 6500 18°C - TES1361	PN-EN ISO 13018:2016-4 PN-EN ISO 17637:2017-02
2	Penetration	MR Chemie set	[Lx] 990 - Levy Hill Mk VI No 6500 18°C - TES1361	PN-EN ISO 3452-1:2013-08 PN-EN ISO 13480-5:2017-10 PN-EN ISO 23277:2015-05
3	Radiographic	Developing machine – Compact2 Camera – RTG ICL CP200D	Temp. 26°C. Duration 8 min, Anode voltage - 180 [kV], anode current – 4.5 [mA]	PN-EN ISO 13480-5:2017-10 PN-EN ISO 10675:2017-02
4	Vickers hardness test	HPO-10	Load 98.1 N	PN-EN ISO 16859-1:2015-12

The radiographic test results are provided in Table 6. The test sample attained a positive result, achieving weld class B in accordance with PN-EN ISO 5817: 2014-05. The quality level B corresponds to the highest requirements for welds.

Table 6. Radiographic testing results

Weld no.	Section	Rod no.	Blackening	Acceptance level	Acceptance	
					Yes	No
1A-1B	32-4	W13	3.1	B	**X**	
1A-1B	2-10	W13	2.9	B	**X**	
1A-1B	6-16	W13	3.0	B	**X**	
1A-1B	14-22	W13	3.0	B	**X**	
1A-1B	20-28	W13	3.1	B	X	
1A-1B	26-34	W13	3.0	B	X	

The sample hardness test was performed using the Vickers method, in accordance with PN-EN 1043-1:2000. The hardness measurements were performed in the joint and in the native material.

The hardness test results are provided in Table 7. The test sample attained a positive result.

Table 7. Hardness test results

Weld no.	HV10 Hardness Native material 1A			HV10 Hardness Weld measurement			HV10 Hardness Native material 1B		
	1	2	3	1	2	3	1	2	3
1A-1B	132	134	135	195	190	191	137	140	142

6. CONCLUSIONS

The conducted non-destructive tests showed that a weld joint between k18 steel and 13CrMo4-5 steel, made using method 141 – a non-consumable tungsten electrode in an inert gas shield (TIG – Tungsten Inert Gas) – achieved weld class B, which confirms a well-developed welding technology. The quality level B corresponds to the highest requirements for welds. The Vickers hardness test for the native material and for the weld confirms the good quality of the weld, which achieved a positive result. Welding dissimilar materials together is feasible, the weld for dissimilar joints should be selected according to the principles for selecting the welding wire with a chemical composition similar to the composition of the nobler grade of the steels to be joined.

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