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MECHANICAL PROPERTIES OF DISSIMILAR METAL BUTT JOINT

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Abstract: The paper present some mechanical properties of dissimilar metal butt joints, performed between structural steel S355J0 and abrasion-resistant steel Hardox 450, using welding processes of MMA (111) and MAG (135). Taking advantage of this approach, it would be possible to replace the lining elements of the mining skip buckets in areas most exposed to the abrasive-dynamic degradation with Hardox 450 steel having better performance properties. Both dissimilar steel butt joints have tensile strength values higher than those of S355J0 steel. Heat input values that allow to the formation of high-quality joints by MMA method are higher than those required for MAG method. The metal-mineral abrasion resistance of dissimilar butt joints, performed by MMA and MAG welding procedures, is about 70% of those corresponding to Hardox 450 steel components.
Keywords: dissimilar metal joint, structural steel, abrasion-resistant steel, welding, coal mines, mine skip buckets.

1. INTRODUCTION

Mineshaft hoists belong to the most complex electrical power and mechanical systems in underground mining. Most of the mineshaft hoists have the long-term operation history, resulting in the need for regeneration of the degraded parts. As of today, one of the main problems limiting the continuation of the technological mining process is the periodic replacement of the skip vessel elements exposed to abrasion and dynamic loads. The lining plates in this type of machinery are mostly made from S355 steel. It seems justified to explore possibilities of replacement of the material of elements loaded most with materials with better abrasion resistance than the commonly used S355 steel. The contemporary Hardox 450 micro-alloyed, martensitic steel with such properties is presented. Due to Hardox 450 substantial cost (about three times higher than of the S355 steel) replacement of lining elements in most loaded areas only is considered [1-8].
Mineshaft hoist is a complex system designed for the vertical transport of workers, excavated output, materials and equipment in the underground mines. Coal transport to the surface is performed by devices called skips. The loading of skip material with crashes into the inner lining of the container with high kinetic energy leads to plastic deformation of the lining plates destroying them. The area most prone to this kind of loading is top plates, placed in front of the transported material inlet into the skip bucket, which is shown in Figure 1 [7].

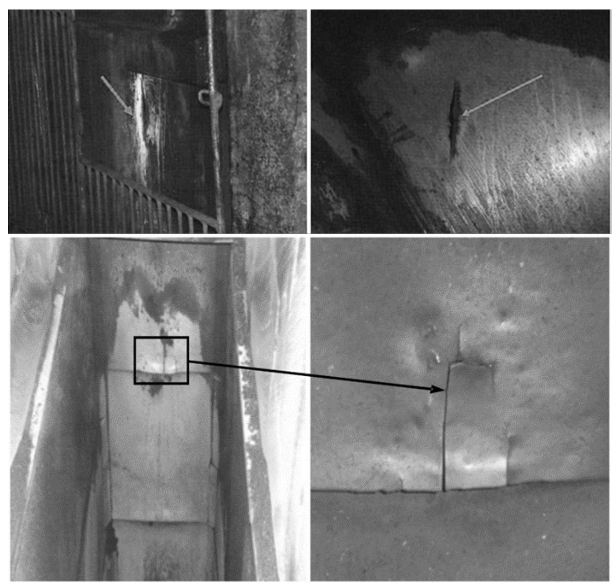

Fig. 1. Damage of lining plates in the skip with the payload of 22 [Mg] caused by the stream of material during loading [7]

Repairs in this area call for lots of maintenance staff and considerable financial investments. The criterion for material choice for the lining elements of the skip bucket in areas of the significant dynamic-abrasive degradation is, aside from the favorable mechanical properties, good weldability including arc joining of said steel with S355 steel [8, 10].
Good weldability aside from abrasive resistance is one of the main advantages of Hardox steel, according to producer [10]. Welded joints have

a higher yield strength than S355 steel (up to 700 MPa). This property is extremely vital in the assessment of the use of steel for machine and device welded parts possibility. Depending on cumulative material thickness and steel grade, in some cases, use of pre-heating is recommended to minimise the likelihood of cracking, especially delayed cold cracking [11]. Steels with the postmartensitic structure according to their manufacturers' guidelines should be welded with low heat input and with use of filler material with hydrogen content under 5ml for 100 g of weld material.

Table 1. Chemical composition of base materials and carbon equivalent values

Steel grade	Alloying elements content wt. [%]										Carbon equivalent C_E [%]
	C	Si	Mn	P	S	Cr	Ni	Mo	B	N	
Hardox 450	0.20	0.3	1.25	0.01	0.002	0.2	0.04	0.009	0.001		0.45
S355J0	0.19	0.36	1.20	0.03	0.02	-	-	-	-	0.009	0.39

Table 2. Mechanical properties of base materials

Steel grade	Hardness [HBW]	R_m [MPa]	R_e [MPa]	A_5 [%]	KV [J]	Impact test temperature [°C]
Hardox 450	461	1430	1210	10	40	-40
S355J0	-	595	365	22	27	0
Note: R_m – ultimate tensile strength, R_e – yield strength, A_5 – elongation, KV – impact energy.						

2. EXPERIMENTAL

The aim of the study was to perform the welding procedure for repairing of the skip vessel of mine shaft lift. Welding included joining of steel plates 200x400x8mm from Hardox 450 steel with plates made from S355J0 steel by MMA welding, as well as MAG welding. Eight plate fragments (4 of each type) were prepared according to ISO 15614-1:2017 standard [12]. In Tables 1 and 2 chemical composition and basic mechanical properties, based on producer attest, of welded plates are presented.

2.1 Welding test joints

Welding was carried by MMA and MAG method. Filler materials were chosen from ESAB (Gothenburg, Sweden) product line. For manual metal arc welding, the basic electrodes OK 48.00 with low diffusing hydrogen (under 5 ml per 100g of weld metal) were used. In case of metal active gas welding copper plated, low alloyed solid wire OK Autorod 13.25 was used. Chemical composition and basic mechanical properties of the filler materials are presented in Table 3.

Table 3. Chemical composition and mechanical properties of filler material

Filler material	Alloying elements content, [%]								Minimal mechanical properties			
	C	Si	Mn	P	S	Ni	Mo	Ti	R_m [MPa]	R_e [MPa]	A_5 [%]	KV_{-40} [J]
OK. 48.00	0.06	0.5	1.2	0.02	0.015	-	-	-	540	445	29	70
OK Autrod 13.25	0.08	0.6	1.8	-	-	1.0	0.4	0.15	700	620	20	90
Note: R_m – ultimate tensile strength, R_e – yield strength, A_5 – elongation, KV – impact energy at -40°C.												

Plate edges were prepared according to ISO 9692--1:2013 standard [13], with beveling shown in Figure 2. For industrial welding the lining plates of the mining skip bucket, the highest heat input position is generally vertical-up position (PF). Therefore, in order to determine the critical properties of the joints, welding was carried out in the above-named position. The base materials were welded without pre-heating in accordance with the manufacturers' recommendations. The interpass temperature was limited to 150°C. In Figure 3, the seam order in both welding methods is presented. The weld was done as a multipass one, and process parameters (shown in Table 4) were obtained during the preliminary welding tests.

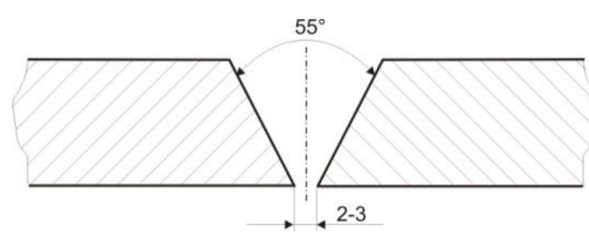

Fig. 2. Joint preparation

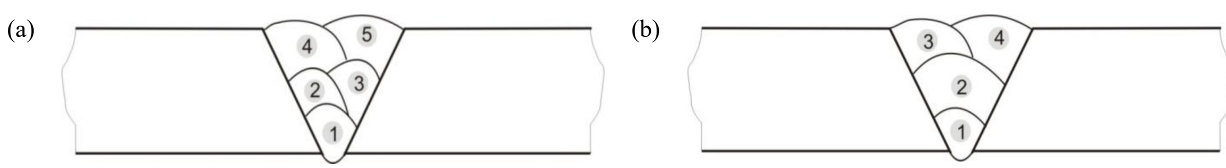

Fig. 3. Cross sections of seam order in: (a) manual metal arc welding, (b) metal active gas welding

Table 4. MMA and MAG welding parameters

Seam	Electrode diameter [mm]		Welding current [A]		Welding voltage [V]		Welding speed [mm/min]		Heat input [kJ/mm]	
	MMA	MAG	MMA	MAG	MMA	MAG	MMA	MAG	MMA	MAG
1	2.50	1.2	75	132	21	18.7	75	240	1.008	0.555
2	3.25		120	235	22	26.0	150	460	0.845	0.717
3	3.25		130	241	22	26.3	140	440	0.981	0.778
4	4.00		160	238	24	26.1	210	430	0.878	0.780
5	4.00	-	170	-	24	-	210	-	0.933	-

Note: covered electrodes were dried for 2 hours at a temperature of 350°C. DC (+) current was used for welding. Gas flow rate in MAG welding was ~15 [l/min] (mixture gases 82%Ar and 18%CO_2). Welding speed value was determined on the basis on average time of made particular weld bead.

2.2 Destructive and non-destructive weld examinations

Welded joints, shown in Figures 4 and 5, were subjected to visual inspection and radiographic testing. Tests were carried 72 hours after welding. No defects were found that would eliminate the welded joints from further examinations. Non-destructive radiographic examinations of welded plate joints were made by ISO 17636-1:2013 standard [14]. This way, radiograms shown in Figure 6, were obtained. Based on radiograms, presence of singular gas pores in welded joints with dimensions allowable in quality level B were found.

Static tensile testing was carried according to ISO 6892-1:2019 standard [15] on samples obtained from the welded joint following ISO 4136:2012 [16]. During all tensile tests, samples fractured outside of the welded joint area in S355J0 steel base material. Results of the carried tensile test of MMA and MAG butt joints are shown in Tables 5 and 6.

Charpy impact tests were carried at a temperature of 20°C (acc. to ISO 148-1:2016 [17]) on samples with the V-shaped notch. As a result of the plate thickness of 8 mm and the need for machining as a part of sample preparation, smaller dimensions samples with a thickness of 5 mm were prepared. Notch was cut both in the weld metal and heat-affected zone. Samples were etched in Nital agent. Results of impact tests of butt joints made by MMA and MAG method are presented in Tables 7 and 8.

(a)
(b)

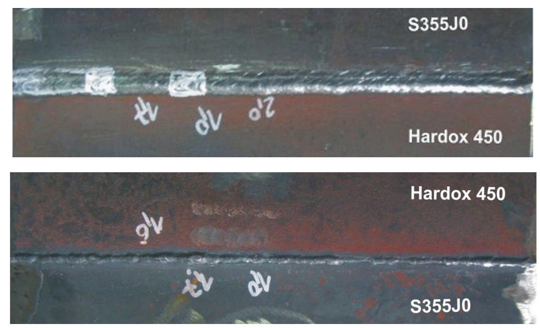

Fig. 4. MMA joint: (a) from face side, (b) from root side

(a)
(b)

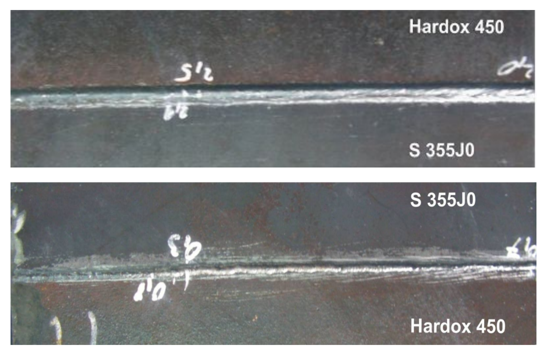

Fig. 5. MAG joint: a) from face side, b) from root side

(a)
(b)

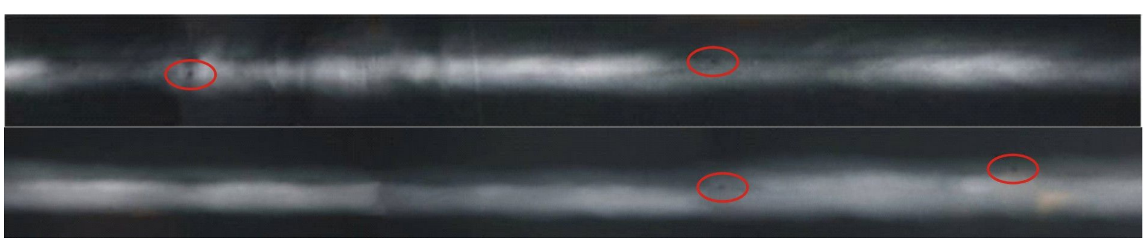

Fig. 6. Radiograms of plate butt joint made with the use of: (a) MMA and (b) MAG welding. In figure areas of welding imperfections occurrence were marked

Table 5. Results of MMA welded butt joins tensile tests

Specimen number	a [mm]	b [mm]	S_0[a] [mm^2]	F_m [kN]	R_m[b] [MPa]	l_0 [mm]	l_k [mm]	A_5[c] [%]
1_1	7.14	25.14	179.57	106	590.30	100.0	119.7	19.7
1_2	6.93	25.06	173.66	101	581.60	100.0	120.3	20.3

Note: a – nominal thickness of specimen before testing, b – nominal width of the sample before testing, S_o – cross-section area, F_m – maximum force, R_m – ultimate tensile strength, l_0 – gauge length, l_k – final gauge length, A_5 – elongation, [a]$S_o=a \cdot b$, [b]$R_m=F_m/S_o$, A_5[c]$=[(l_k - l_o)/l_0] \cdot 100\%$.

Table 6. Static tensile test results of the butt joints of the steel sheets made with MAG method

Specimen number	a [mm]	b [mm]	S_0^a [mm^2]	F_m [kN]	R_m^b [MPa]	l_0 [mm]	l_k [mm]	A_5^c [%]
1_1	7.16	25.05	179.36	105	585.41	100	120.8	20.8
1_2	7.30	25.12	183.38	106	578.03	100	120.1	20.1

Note: a – nominal thickness of specimen before testing, b – nominal width of the sample before testing, S_o – cross-section area, F_m – maximum force, R_m – ultimate tensile strength, l_0 – gauge length, l_k – final gauge length, A_5 – elongation, $^aS_o=a\cdot b$, $^bR_m=F_m/S_o$, $A_5^c=[(l_k - l_o)/l_0]\cdot 100\%$.

Table 7. MMA welded plate butt joint impact test results

Specimen number	Notch placement	Specimen geometry (in notch cross-section)			Results	
		h [mm]	b [mm]	S_0^a [mm^2]	KV [J]	KCV^b [J/mm^2]
3_1	Joint	3	10	0.3	73	-
3_4					71	-
3_7					78	-
3_2	HAZ S355J0				39	-
3_5					35	-
3_8					28	-
3_3	HAZ Hardox 450				65	-
3_6					57	-
3_9					57	-

Note: h, b – thickness and width of the specimen in notch cross-section, S_0 – cross-section area, KV – impact energy, KCV – V-notch impact strength, ^{a} $S_0=a\cdot b$, ^{b} $KCV = KV/S_0$.

Table 8. MAG welded plate butt joint impact test results

Specimen number	Notch placement	Specimen geometry (in notch cross-section)			Results	
		h [mm]	b [mm]	S_0^a [mm^2]	KV [J]	KCV^b [J/mm^2]
3_1	Joint	3	10	0.3	51	-
3_4					62	-
3_7					68	-
3_2	HAZ S355J0				23	77
3_5					22	73
3_8					23	77
3_3	HAZ Hardox 450				74	-
3_6					72	-
3_9					71	-

Note: h, b – thickness and width of the specimen in notch cross-section, S_0 – cross-section area, KV – impact energy, KCV – V-notch impact strength, ^{a} $S_0=a\cdot b$, ^{b} $KCV = KV/S_0$.

Bending tests of butt joints with face tension (FBB) and root tension (RBB) were based on ISO 5173:2009 standard [18]. Tests were performed with the use of former selected based on ISO 15614-1:2017 standard [12]. Results of the bending test of the butt joint made by MMA and MAG are presented in Tables 9 and 10. Results of bending tests were similar for both welding methods. The bending angles obtained were ranging from 130° to 155° (with higher angles corresponding to root bending) without any fractures in the joint.

Table 9. MMA welded joint bending test with face tension and root tension results

Specimen number	Test type	Bending angle [°]	Mandrel diameter [mm]
2_1	FBB	130	72
2_2		125	
2_3	RBB	150	
2_4		145	

Hardness tests were performed using Vickers method according to ISO 6507-1:2018 [19]. Tests were performed on the cross-section of butt welded joint made by MMA and MAG. Test points placement is shown in Figures 7 and 9. In Table 11 results of hardness test in MMA welded joints are presented. Table 12 presents MAG welded joints hardness tests.

Table 10. MAG welded joint bending test with face tension and root tension results

Specimen number	Test type	Bending angle, [°]	Mandrel diameter, [mm]
2_1	FBB	130	72
2_2		130	
2_3	RBB	160	
2_4		155	

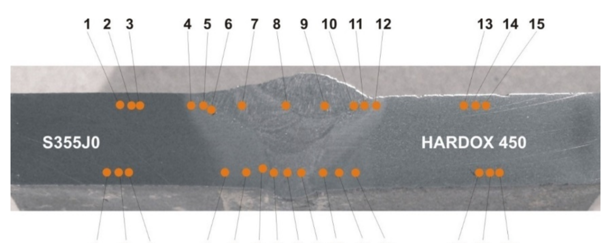

Fig 7. Hardness test points placement on MMA joint cross-section

Table 11. MMA welded joint hardness test results

Test point number	Tested zone	Face side		Root side	
		Hardness [HV10]	Average hardness [HV10]	Hardness [HV10]	Average hardness [HV10]
1		192		172	
2	S355J0	193	192.3	173	172.3
3		192		172	
4		199		181	
5	HAZ S355J0	222	218.7	186	184.7
6		235		187	
7		206		196	
8	Joint	202	204.3	194	196.0
9		205		198	
10		206		189	
11	HAZ Hardox 450	281	259.7	188	189.3
12		292		191	
13		394		413	
14	Hardox 450	397	395.0	413	409.0
15		394		401	

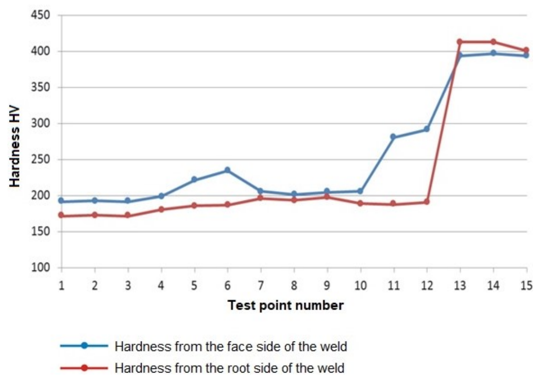

Fig. 8. MMA welded joint hardness plot

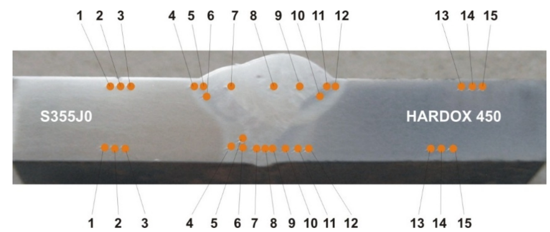

Fig. 9. Hardness test point placement on MAG joint cross-section

In Figures 8 and 10, hardness distributions on measurement lines are presented for MMA and MAG welded joints accordingly.

Table 12. MAG welded joint hardness test results

Test point number	Tested zone	Face side		Root side	
		Hardness, [HV10]	Average hardness, [HV10]	Hardness, [HV10]	Average hardness, [HV10]
1		187		182	
2	S355J0	186	186.7	183	182.7
3		187		183	
4		206		196	
5	HAZ S355J0	233	228.7	199	197.3
6		247		197	
7		210		187	
8	Joint	212	211.3	189	188.0
9		212		188	
10		283		198	
11	HAZ Hardox 450	319	306.3	198	205.0
12		317		219	
13		468		429	
14	Hardox 450	464	466.7	425	429.0
15		468		433	

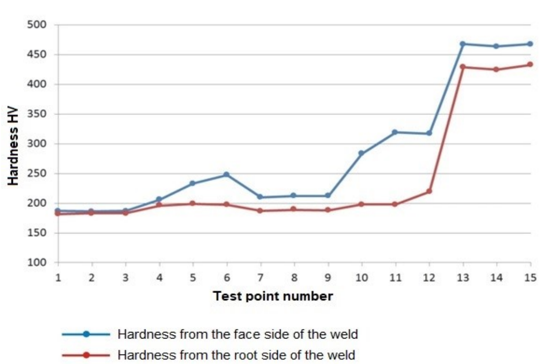

Fig 10. MAG welded joint hardness plot

2.3 Metallographic weld examinations

Macro- and microscopic metallographic examinations were performed using a light microscope equipped with a camera and macrophotography adapter. As a result of the examinations carried out, macro- and microstructures of welded joints were obtained. Macro- and microstructures of welded joints are presented in Figures 11-14. The metallographic examinations did not reveal the presence of welding defects in both welded joints.

(a) (b)

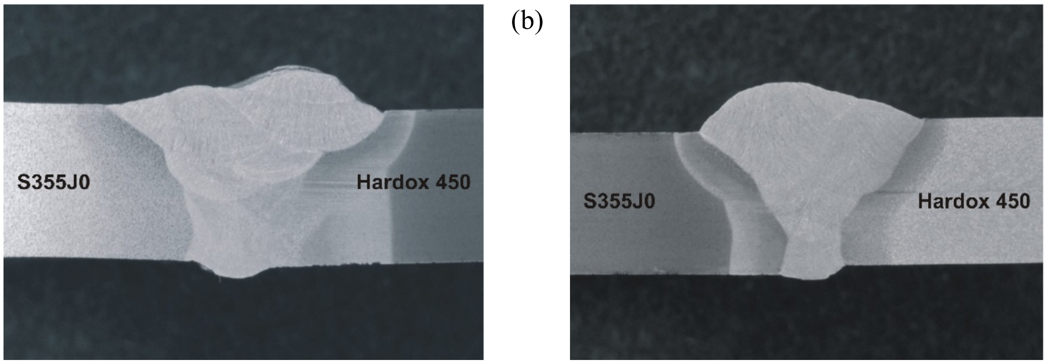

Fig. 11. Macrostructure of welded joints: (a) by MMA method,
(b) by MAG method. Etching agent 10% solution of HNO_3. Mag. 3x

(a) (b)

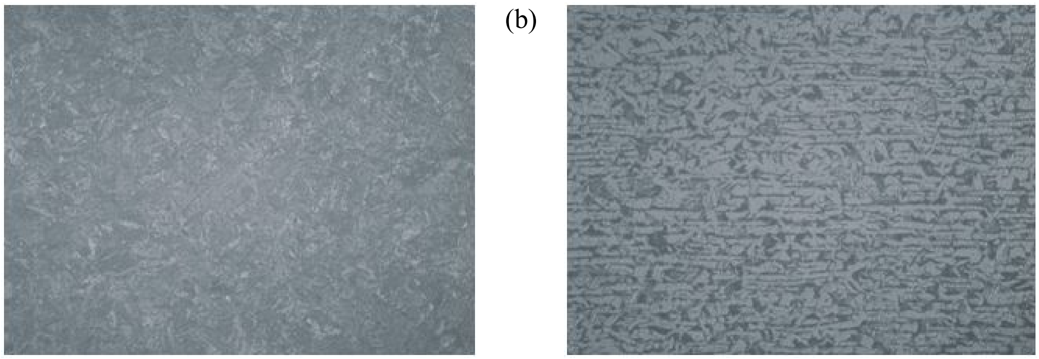

Fig. 12. The microstructure of base material: (a) Hardox 450 steel – high quenched martensite structure,
b) S355J0 steel – ferritic-pearlitic structure. Etching agent Mi1Fe. Mag. 200x

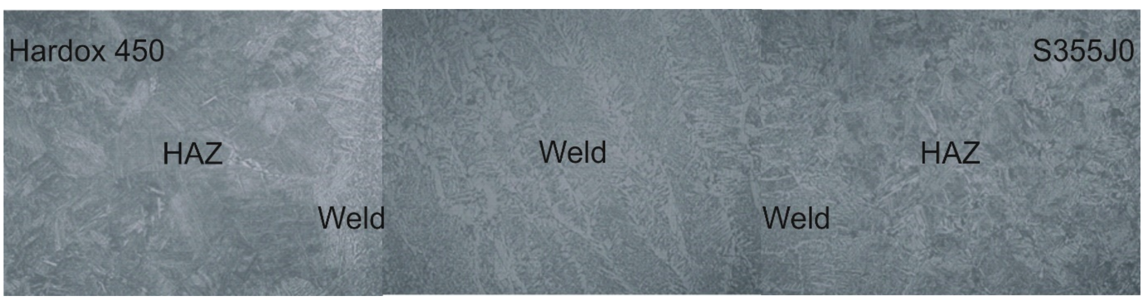

Fig. 13. The microstructure of MMA welded joint. Etching agent Mi1Fe. Mag. 200x

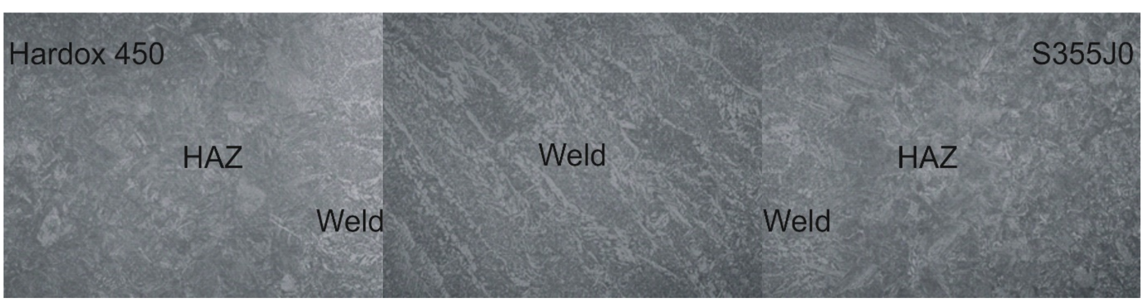

Fig. 14. The microstructure of the MAG welded joint. Etching agent Mi1Fe. Mag. 200x

2.4 Results of wear resistance test on the weld

Abrasive wear tests were performed according to ASTM G 65-00 standard [20], according to procedure A recommendations. Two samples with dimensions of 75x25x8 mm were prepared to perform the test. Faces of welded joints were ground flat. Two samples with the same dimensions were cut both from Hardox 450 and S355J0 sheets of steel. All samples were weighed before and after abrasive wear testing on a scale with 0.0001 g precision, as described in procedure from ASTM G 65-00 [20]. Mass reduction from weld metal and S355J0 steel caused by abrasive wear were compared to Hardox 450 steel mass reduction. Wear tests were performed with the abrasive material rate of 355 g/min and 130 N of downforce. In table 13, results of mass reduction during wear tests are presented, as well as the relative abrasive metal-mineral wear resistance of welded joints in comparison to steel Hardox 450.

Table 13. Results of mineral-metal type abrasive wear test of samples of MMA, MAG welded joints and steel S355J0 in comparison to wear resistance of Hardox 450 steel were carried according to ASTM G 65-00 [20]

Specimen source	Specimen number	Weight prior testing [g]	Weight after testing [g]	Mass reduction [g]	Average mass reduction [g]	Relative wear resistance [%]
MMA joint	$1S_1$	117.1719	115.1279	2.0440	2.0423	72.53
	$1S_2$	116.8654	114.8248	2.0406		
MAG joint	$3S_1$	115.5903	113.5186	2.0717	2.0704	71.54
	$3S_2$	115.8544	113.7852	2.0692		
S355J0	P_1	115.3390	113.5577	1.7813	1.7960	82.47
	P_2	116.4360	114.6254	1.8106		
Hardox 450	H_1	116.2391	114.7533	1.4858	1.4812	100
	H_2	117.1134	115.6368	1.4766		
Note: Results are referred to specimens from Hardox 450 sheet. The test load was 130 [N].						

3. CONCLUSIONS

Results of the analysis of the repair welding technology of mineshaft lift skip vessel, with use of two welding methods MMA welding by basic OK 48.00 electrode and MAG welding with wire OK Autrorod 13.25 provide the basis for the formulation of the following conclusions:

1. It is possible to join Hardox 450 steel plates with S355J0 steel plates using the manual metal arc welding and gas metal arc welding using active gas.
2. Both dissimilar steel butt-joints have tensile strength values higher than those of S355J0 steel.
3. The metal-mineral abrasion resistance of butt joints performed by use of MMA method by OK 48.00 electrode and MAG method with the use of OK Autorod 13.25 is about 70% of the relative abrasion resistance in comparison to Hardox 450 steel.
4. Heat input values that allow to the formation of high-quality joints by MMA method are higher than those required for MAG method and approach limit set by steel manufacturer for 8 mm thick plates. This limit is 1.0 kJ/mm.

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