Acta Mechanica Slovaca
ISSN 1335-2393
www.actamechanica.sk

Analysis of CMT weld Clads for High-pressure die Casting Mold Restoration

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Abstract: The paper presents results of the research focused on the possibility of restoration of the shape parts of molds made of X15CrNiSi20-12 heat resistant austenitic chromium-nickel-stainless steel working in high-pressure die casting of aluminum alloys by clad welding. There were tested two welding wires - Thermanit 625 and Thermanit X, deposited on X15CrNiSi20-12 tool steel using cold metal transfer (CTM) welding in protective atmosphere of Ar. Two important properties of welded clads were tested - resistance of welds against dissolution in molten aluminum alloy AlSi8Cu3 and wear resistance of welds. Resistance of welds against dissolution were assessed by exposition of welded clads in aluminum melt for 120 and 300 minutes. The EDX semiquantitative microanalyses of element distribution were performed at the welding-melt interface, also build-ups were observed on the surface of welded clads. Wear resistance of the welded clads was tested using pin-on-disk test at room temperature. Results were compared to reference material – base tool steel X15CrNiSi20-12.

Keywords: *high pressure die casting; wear; dissolution; CMT welding.*

1. Introduction

Shape mold parts and mold cores for high-pressure die casting (HPDC) of aluminum alloys must possess suitable physical and mechanical properties at elevated temperatures. These properties are essentially defined by the thermal and mechanical stresses as well as by the interaction at the interface between the mold and the aluminum alloy melt. In particular the high velocities of the turbulent to dispersive filling of the mold cavity by the aluminum alloy melt, the high hydrodynamic pressures generated by the melt on the shape part of the mold and relatively high temperatures on the surface of shape parts of molds can significantly shorten lifespan of molds and cores. All these phenomena cause degradation of the surface of mold shape parts by mechanisms of erosion, abrasion, corrosion and heat fatigue of the mold, which co-act at the same time. [1-3].

Since molds and dies work under heavy mechanical and thermal conditions, they are made of complex alloyed steels with the main alloying elements being: Cr, V, Mo, or W, or a combination of these and, in some cases, contain a considerable amount of Co. Detailed analysis of the wear of different types of molds and dies was performed by Chander [4] and Jhavar [5]. As the main mechanisms of

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mold damage they identified wear (abrasive, adhesive, according to the purpose of the mold: mold for casting or die forging), erosion and mechanical and thermal fatigue. Chander [4] identified wear-influencing factors as follows: temperature, atmosphere, contact area, load, material properties, finish, velocity, lubrication, shape, vibration, sliding distance, type of motion. The material characteristics of molds and dies are also important, especially: hardness, yield strength, elastic modulus, ductility, toughness, work-hardening characteristics, fracture toughness, microstructure, corrosion resistance, and in case of molds and dies in high-pressure die casting also resistance against solution in melt [3].

Examples of high-pressure die damage after a certain lifetime period are shown in Figure 1.

Fig. 1: *Detail of damage on surface of high pressure casting die after 800 000 working cycles.*

One of the possibilities of restoring functional surfaces of injection molds or coremakers is with arc welding by CMT (Cold Metal Transfer) [6]. Damaged parts of the molds are machined and consequently the layers are welded and deposited on these surfaces. Molds renovated this way are heat-treated and machined to the required dimensions and surface quality. Such layers will withstand the presented combinations of tribodegradation factors while being resistant to the action of the injected liquid.

In the CMT process, as soon as the electrode makes contact with the molten pool, the welding torch is reversed, this causes the wire to retract promoting droplet transfer. During metal transfer, the current drops to near-zero and thereby any spatter generation is avoided. When the metal transfer is completed, the arc is re-ignited and the wire is fed forward once more with set welding current reflowing. The procedure is continually repeated and automated [7-12].

The aim of the work is to verify the use of Thermanit 625, Thermanit X welding on high-pressure casting die restoration from point of view of their solubility in AlSi8Cu3 aluminum alloy melt and wear resistance.

2. Materials and Methods

Thermanit 625 and Thermanit X welds were produced on steel plates with thickness of 10 mm from AISI/SAE 309 material using welding equipment Fronius Trans Puls Synergic 5000 by CMT - Cold Metal Transfer (Fronius International GmbH, Wels, Austria) in argon protection atmosphere (Figure 2). The welding parameters were: 155A, 16.5 V, 8.5 $m \cdot min^{-1}$ with a wire feed of 8 $m \cdot min^{-1}$. The chemical composition of the base metal (AISI/SAE 309, Mat. No. 1.4828) and the two wired used (Thermanit 625 and Thermanit X) were analyzed using a spectral chemical analyzer Belec Compact Port (Belec Spektrometrie Opto-Elektronik GmbH, Georgsmarienhütte, Germany). The corresponding chemical compositions are shown in Table 1. Mechanical properties of used materials given by material producer are shown in Table 2.

2.1 Immersion test

In order to simulate real operating conditions, the weld resistance against dissolution was assessed in immersion in the melt of aluminum alloy EN AB 46200-EN AB AlSi8Cu3(DIN EN 1706). For stated

Tab. 1: *Chemical composition of used materials (wt. %)*

	C	Mn	Si	Cr	V	Mo	Nb	Cu	Ni	Ti	Co	Fe
AISI/SAE 309	0.075	0.408	1.153	19.48	0.058	0.071	-	0.079	13.92	0.011	0.035	Bal.
Thermanit 625	0.004	0.855	0.562	20.42	0.006	8.13	3.1	-	Bal.	0.004	0.004	0.9
Thermanit X	0.101	7.915	0.861	18.81	0.084	0.020	-	0.052	9.85	0.007	0.056	Bal.

Tab. 2: *Mechanical properties of used materials (average values)*

	Yield strength Rp0.2 [MPa]	Ultimate tensile strength Rm [MPa]	Elongation A5 [%]
AISI/SAE 309	260	750	30
Thermanit 625	420	760	30
Thermanit X	350	600	40

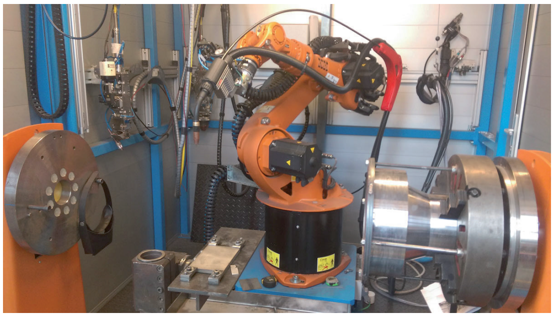


Fig. 2: *Fronius Trans Pulse Synergic 5000 CMT.*

tests, samples from welds Thermanit 625 and Thermanit X with dimensions of 20x20x10 mm were taken. The aluminum alloy melt was prepared from portions of AlSi8Cu3 aluminum alloy, which were embedded into ceramic crucibles and heated in a laboratory furnace to the melting point of alloy. The temperature of alloy was maintained at 680±20°C temperature. It is a casting temperature of EN AB AlSi8Cu3 alloy in pressurized casting on machines with cold filling chambers. All weld samples were completely immersed in the melt in ceramic crucibles. Samples were in vertical position during the tests and melt did not run over the sample surface. Test samples were exposed to the aluminum alloy melt for 120 and 300 minutes, then successively removed from the melt and cooled freely in the still air. On both surfaces of the samples solid aluminum alloy remained. For metallographic analyses, light optical microscope OLYMPUS GX71 (OLYMPUS Europa Holding GmbH, Hamburg, Germany) was used.

For the quality assessment, EDX microanalyses of element distribution at the weld interface of Thermanit 625 and Thermanit X in melt EN AB AlSi8Cu3 after 120 and 300 minute exposure (680±20°C) was performed using environmental scanning electron microscope SEM EVO MA15 (Carl Zeiss, Germany) with integrated analytical units EDX and WDX (Oxford Instruments, United Kingdom). Diffraction measurements were performed on a Philips X'Pert PRO device using Cu radiation. The phase composition of the samples was determined using the PDF2 database and the subsequent Rietveld structure refinement was performed using the MAUD software [25].

2.2 Wear resistance testing

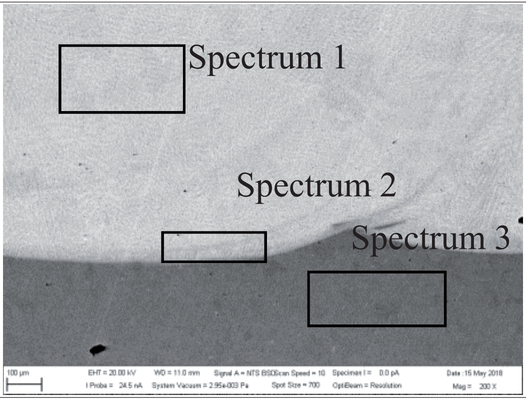
Surfaces of welds were ground to a surface roughness of less than 0.2 μm. Wear tests were performed on tribometer HTT by CSM Instruments Switzerland - ball-on-disc method under dry friction conditions, temperature of 23°C and 45% relative humidity. The static pin for test was a highly polished SiC ball of 6 mm diamete, radius of circle track 3 to 7 mm; linear ball velocity was 0.1 $m \cdot s^{-1}$, the normal load Fp was 3N, 5N and 10N, respectively. Tangential forces were experimentally measured during the tests, and friction coefficients were calculated. Worn surfaces were subsequently observed by scanning electron microscopy and wear patterns, type of damage, and wear micromechanisms were identified. The wear losses of the materials were measured by the confocal profilomether and the specific wear rates (W) were calculated based on the volume loss (V) at the distances (L) and the normal load (Fp) according to ISO 20808.

3. Results and Discussion

Information on the distribution of alloying elements in the Thermanit 625 and Thermanit X welds were obtained by EDX surface and point microanalyses of welds, mixing zone and base material (Table 3, 3a, 4, 4a).

Distribution of alloying elements in Thermanit 625 and Thermanit X welds before the immersion in the aluminum alloy melt was uniform with no locally increased concentration.

Tab. 3: *Thermanit 625 weld – EDX semiquantitative microanalyses*

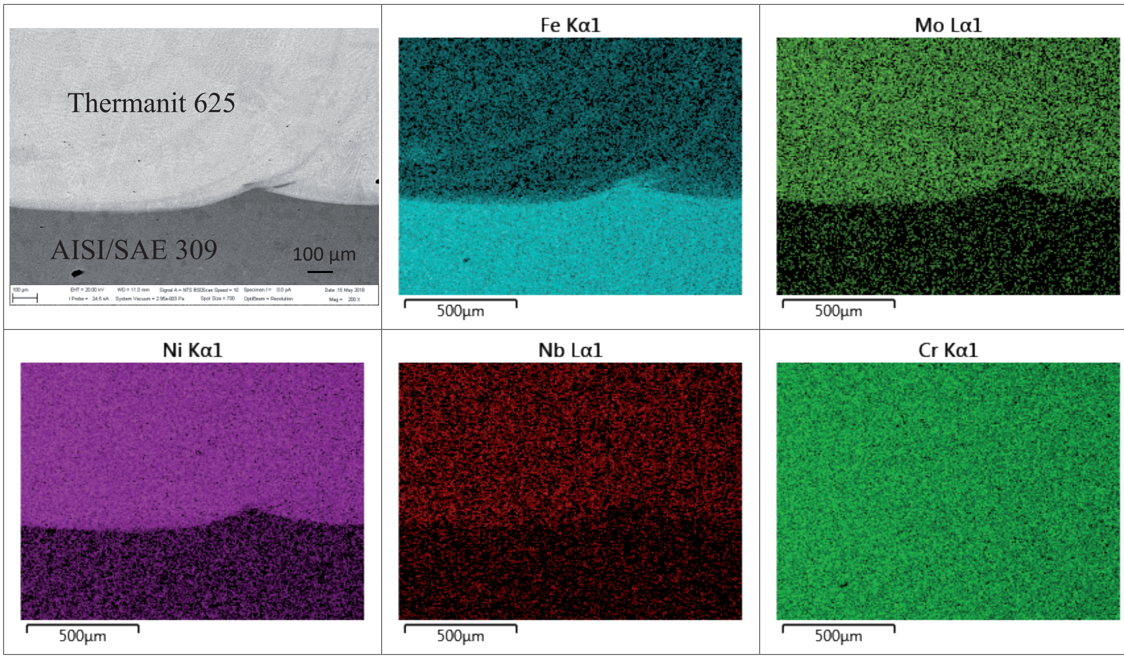


EDX-Spectrum 1	
Element	***Wt.[%]***
Si	0.26
Cr	22.98
Fe	7.88
Ni	57.76
Nb	3.19
Mo	7.94
Total	100

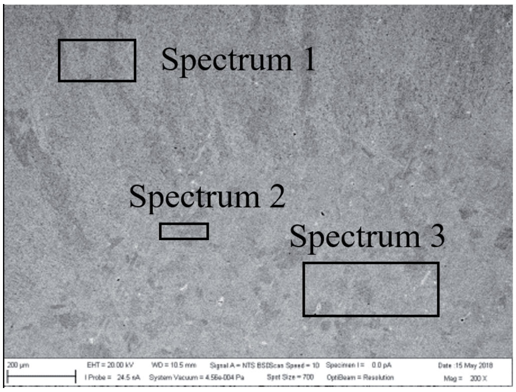
EDX-Spectrum 2	
Element	***Wt.[%]***
Si	0.34
Ti	0.20
Cr	22.54
Fe	10.79
Ni	55.18
Nb	3.12
Mo	7.84
Total	100

EDX-Spectrum 3	
Element	***Wt.[%]***
Si	1.43
Cr	19.94
Mn	1.59
Fe	65.74
Ni	11.29
Total	100

Tab. 3a: *Thermanit 625 weld - EDX semiquantitative microanalyses (mapping)*



Tab. 4: *Thermanit X weld - EDX semiquantitative microanalyses*

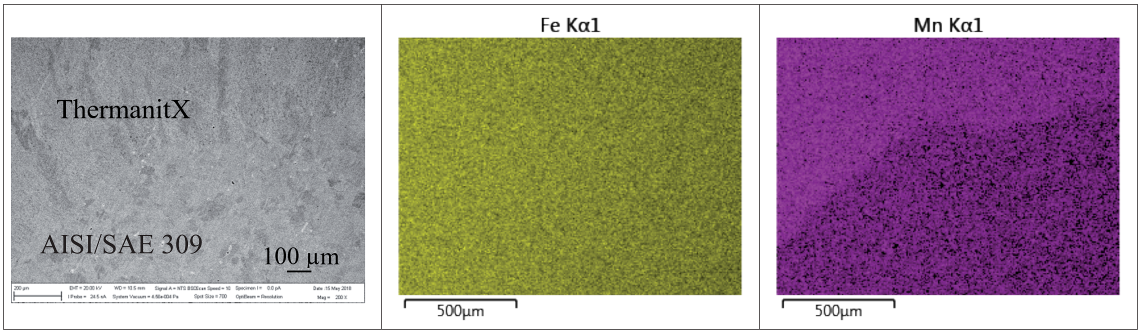


EDX-Spectrum 1	
Element	***Wt.[%]***
Si	1.00
Cr	20.03
Mn	6.38
Fe	63.85
Ni	8.74
Total	100

EDX-Spectrum 2	
Element	***Wt.[%]***
Si	1.31
Cr	19.99
Mn	3.12
Fe	65.41
Ni	10.17
Total	100

EDX-Spectrum 3	
Element	***Wt.[%]***
Si	1.45
Cr	20.28
Mn	1.60
Fe	65.41
Ni	11.26
Total	100

Tab. 4a: *Thermanit X weld - EDX semiquantitative microanalyses (mapping)*



Immersion test

The resistance of Thermanit 625 and Thermanit X welds on the base material of AISI/SAE 309 quality was tested by complete immersion in the aluminum alloy melt EN ABAlSi8Cu3 maintained at temperature of 680±20°C in laboratory resistance furnace for 120 and 300 minutes. In both cases welds reacted with the aluminum alloy melt with different intensity (Figures 3–8).

The intense reaction of aluminum melt with Thermanit 625 melt was at the areas of corners and edges of the samples (Figure 3, 4). Resistance of Thermanit X weld (Figure 5, 6) and base material AISI/SAE 309 in the aluminum alloy melt (Figure 7, 8) was higher than the resistance of Thermanit 625 weld.

During the 120 and 300 minutes exposures of Thermanit 625 weld in the aluminum alloy melt a complex reaction of aluminum alloy EN AB AlSi8Cu3 with alloying elements present in the welds was observed. Using the qualitative elemental EDX microanalysis on the surface of the Thermanit 625 weld an individual complex phases based on chromium, nickel, iron, molybdenum and niobium were observed (Table 5, 5a, 6, 6a).

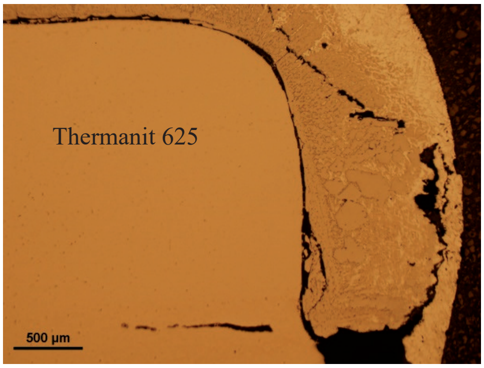


Fig. 4: *Thermanit 625 / 680°C / 120´ / AlSi8Cu3.*

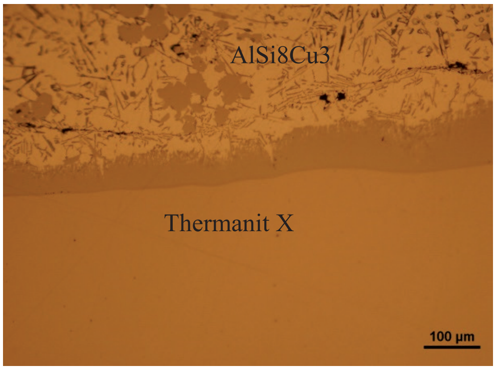


Fig. 5: *Thermanit X/680°C/300´/AlSi8Cu3.*

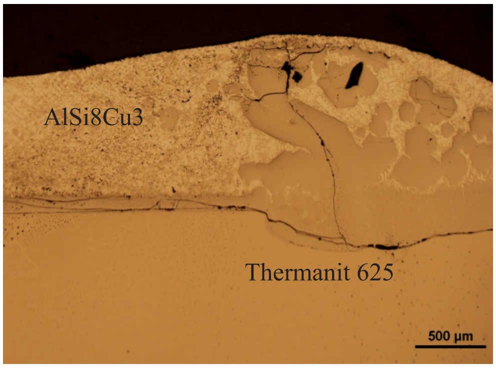


Fig. 3: *Thermanit 625 / 680°C / 300´ / AlSi8Cu3.*

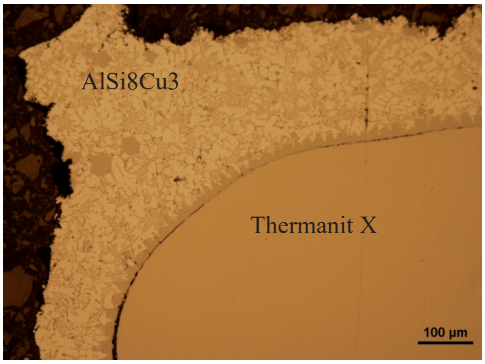


Fig. 6: *ThermanitX/680°C/120´/AlSi8Cu3.*

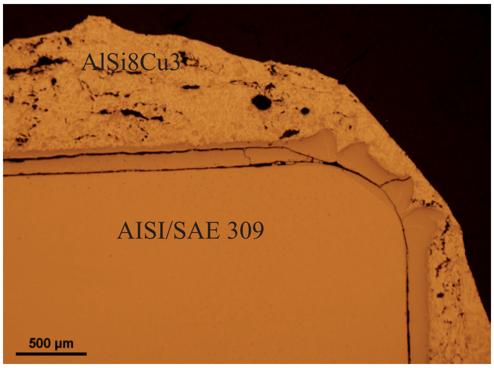


Fig. 7: *Base material 1.4823 / 680°C / 300´ / AlSi8Cu3.*

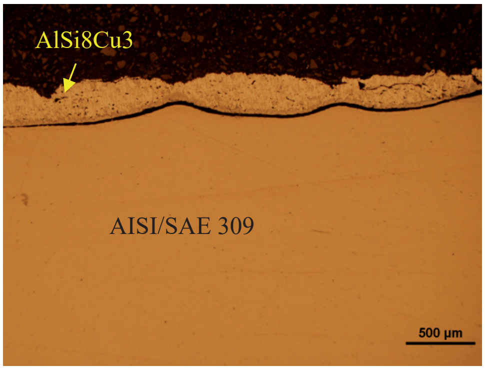
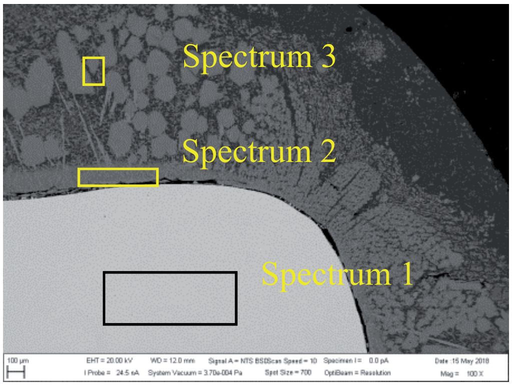


Fig. 8: *Base material 1.4823 / 680°C / 120´ / AlSi8Cu3.*

Tab. 5: *Thermanit 625/680°C/120´/AlSi8Cu3 - EDX EDX semiquantitative microanalyses*

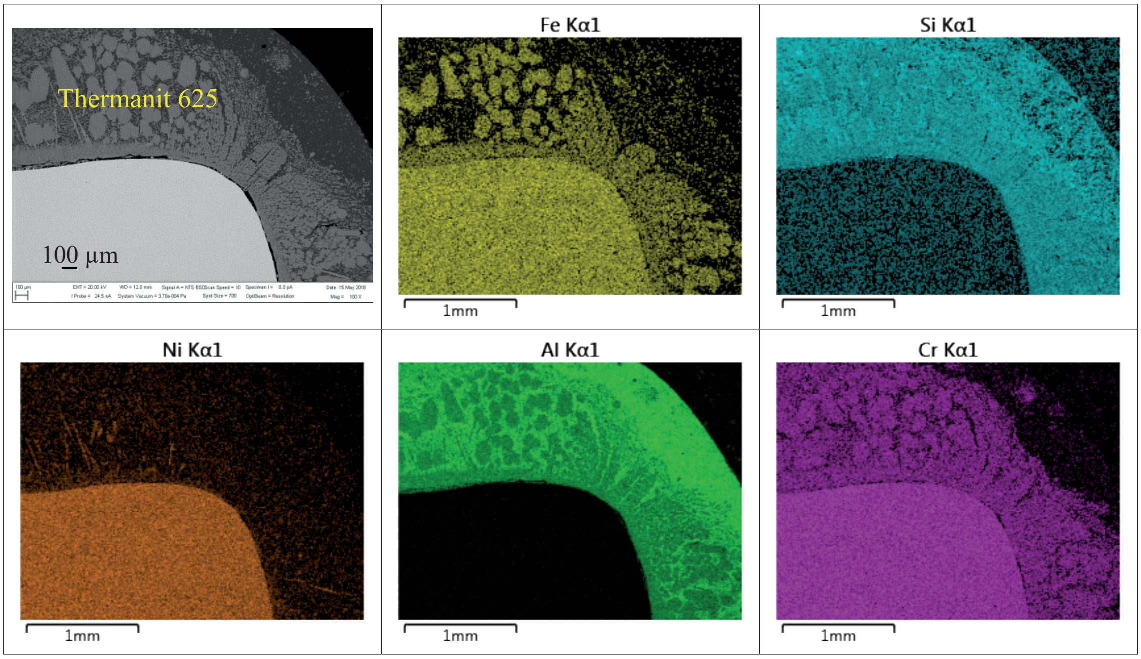


EDX-Spectrum 1	
Element	**Wt.[%]**
Si	0.39
Cr	22.69
Fe	13.37
Ni	53.20
Nb	2.97
Mo	7.37
Total	100

EDX-Spectrum 2	
Element	**Wt.[%]**
Al	54.28
Si	11.73
Cr	12.81
Fe	7.86
Ni	7.74
Nb	1.44
Mo	4.14
Total	100

EDX-Spectrum 3	
Element	**Wt.[%]**
Al	51.97
Si	12.89
Cr	13.66
Mn	0.64
Fe	12.02
Ni	2.44
Nb	1.38
Mo	5.00
Total	100

Tab. 5a: *Thermanit 625/680°C/120´/AlSi8Cu3 - EDX semiquantitative surface microanalyses (mapping)*



After the 120 and 300 minutes exposures of Thermanit X weld in the aluminum alloy melt a lower intensity of a reaction of aluminum alloy EN AB AlSi8Cu3 with alloying elements present in the welds was observed in the layer of solid aluminum alloy. Using the qualitative elemental EDX microanalysis on the surface of the Thermanit X weld an individual complex phases based on chromium, manganese, nickel and iron were observed (Table 6, 6a).

In Table 7 are shown results of phase analysis of welded layers. In Thermanit 625 there was identified one phase with a spatial group $Fm\bar{3}m$ that corresponds to the austenitic phase in steel.

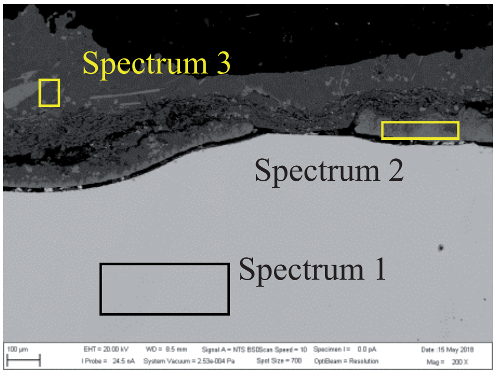
In Thermanit X two phases have been identified. The majority phase is the same as for Thermanit 625. The minority phase will need to be dealt with in more detail because there was not sufficient signal of weaker reflections to identify it. For fitting the structure, $Im\bar{3}m$ the phase corresponding to the α-Fe phase was used. Output fitted parameters are also shown in Table 7.

Wear resistance test

The results of the tribological tests and wear of the Thermanit 625 and Thermanit X are listed in Table 8.

In Figures 9-10 are shown SEI and BSE-detail analysis of wear tracks, EDX area and line spectrum through wear track on welded clads.

Tab. 6: *Thermanit X/680°C/120´/AlSi8Cu3. EDX semiquantitative microanalyes*

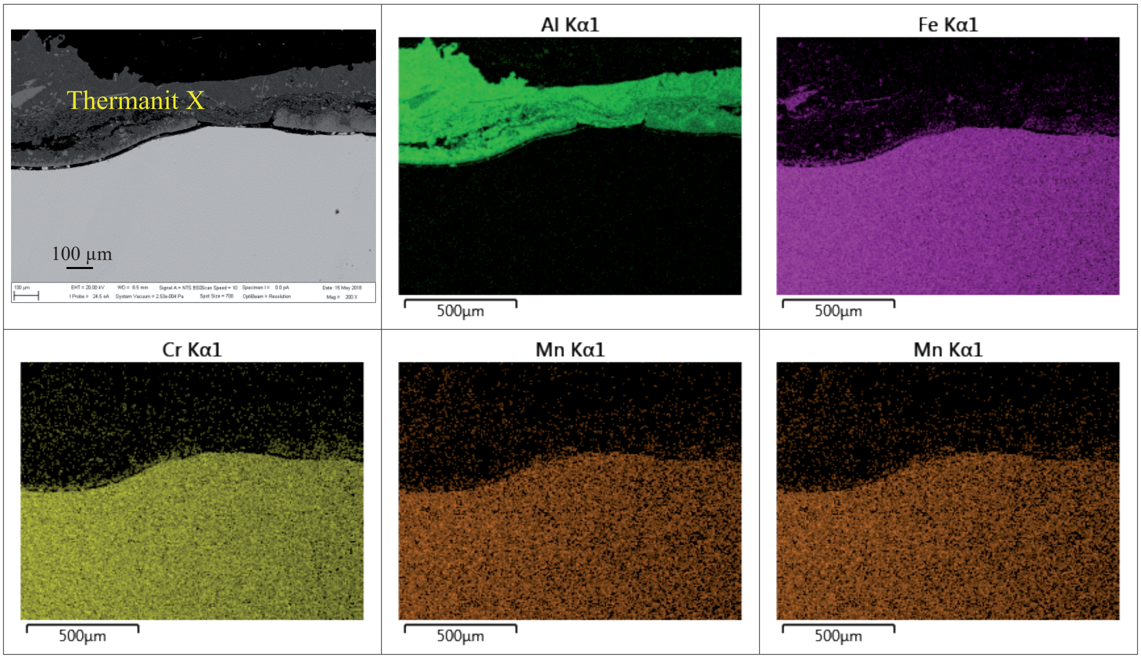


EDX-Spectrum 1	
Element	**Wt.[%]**
Si	0.92
Cr	20.21
Mn	5.88
Fe	64.09
Ni	8.90
Total	100

EDX-Spectrum 2	
Element	**Wt.[%]**
Al	58.56
Si	8.57
Cr	8.02
Mn	2.53
Fe	22.32
Total	100

EDX-Spectrum 3	
Element	**Wt.[%]**
Al	56.83
Si	13.64
Mn	0.59
Fe	28.93
Total	100

Tab. 6a: *Thermanit 625/680°C/120´/AlSi8Cu3 - EDX semiquantitative surface microanalyses (mapping)*

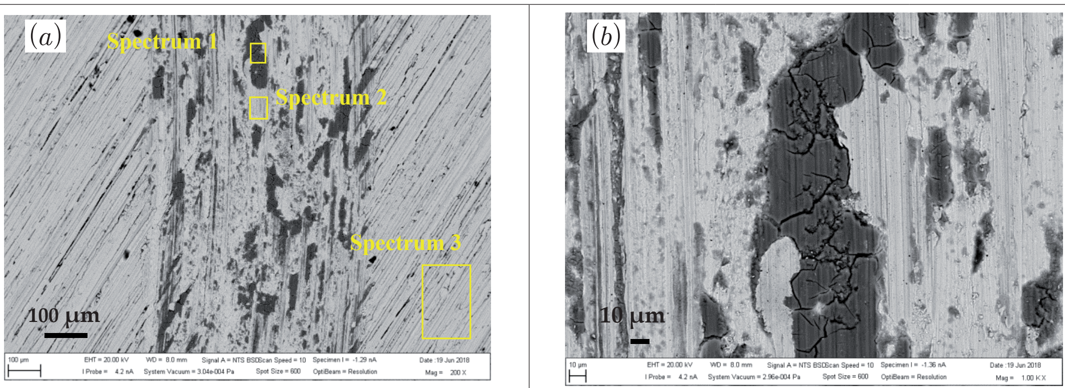


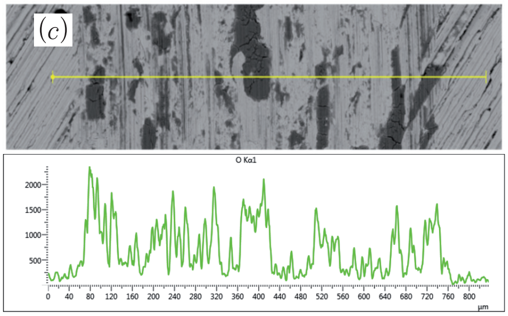
Tab. 7: *Parameters from refining diffraction spectra*

	aFeNi [Å]	*aFe [Å]*	*FeNi [wt. %]*	*Fe [wt. %]*	σ	*Rwp [%]*
Thermanit 625	3.5922	-	100	-	1.22	2.89
Thermanit X	3.5961	2.8735	94.8	5.2	1.2	2.76

Tab. 8: *Tribological and wear properties of investigated materials*

Experimental materials	*Applied load Fp [N]*	*Distance L [m]*	*Radius [mm]*	*Coefficient of friction [-]*					*Volume loss V [mm³]*	*Wear rate W [×10⁻⁶ mm³/m.N]*
				Start	*Min.*	*Max.*	*Mean*	*Std. Dev.*		
Thermanit 625	3	500	3.0	0.41	0.28	0.75	0.37	0.051	0.0272	18.13
	5	500	4.5	0.38	0.29	0.75	0.40	0.059	0.0510	20.40
	10	500	6.5	0.30	0,29	0.75	0.38	0.062	0.1255	25.10
Thermanit X	3	500	7.0	0.16	0,16	0.54	0.47	0.045	0.0236	15.73
	5	500	3.0	0.22	0,22	0.55	0.48	0.057	0.0117	4.68
	10	500	5.0	0.14	0,13	0.55	0.43	0.072	0.0477	9.54



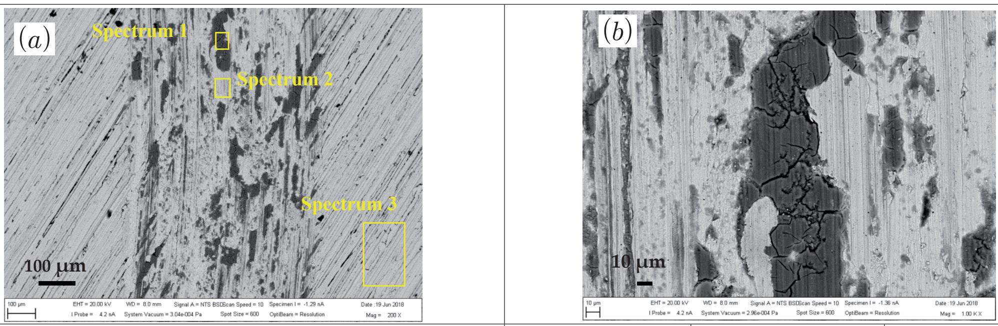


EDX-Spectrum 1	
Element	*Wt.[%]*
O	31.89
Si	1.19
Ti	0.19
Cr	15.18
Fe	8.85
Ni	36.27
Nb	1.65
Mo	4.79
Total	100.00

EDX-Spectrum 2	
Element	*Wt.[%]*
O	6.59
Al	0.17
Si	0.88
Ti	0.21
Cr	20.68
Mn	0.34
Fe	12.18
Ni	50.43
Nb	2.46
Mo	6.05
Total	100.00

EDX-Spectrum 3	
Element	*Wt.[%]*
O	2.13
Al	0.36
Si	0.34
Cr	21.64
Mn	0.56
Fe	13.05
Ni	53.30
Nb	2.39
Mo	6.23
Total	100.00

Fig. 9: *Wear track at normal load 10 N: (a) SEI smooth wear tracks and EDX spectra in Thermanit 625, (b) BSE-detail, (c) EDX line analysis.*



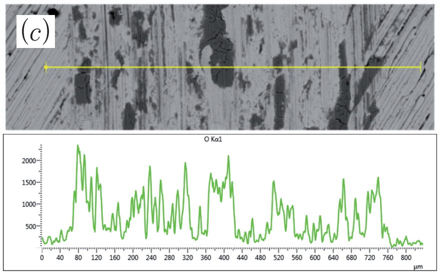
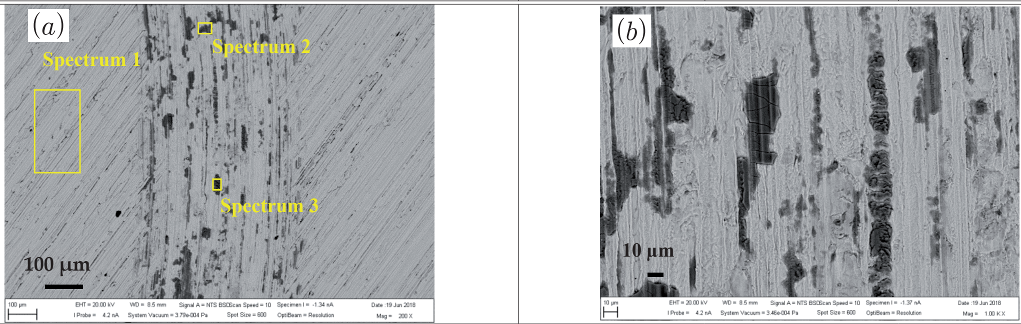


Fig. 9: *Wear track at normal load 10 N: (a) SEI smooth wear tracks and EDX spectra in Thermanit 625, (b) BSE-detail, (c) EDX line analysis.*

EDX-Spectrum 1	
Element	***Wt.[%]***
O	1.57
Si	0.87
Cr	19.81
Mn	6.04
Fe	62.91
Ni	8.80
Total:	100.00
Mo	4.79
Total	100.00

EDX-Spectrum 2	
Element	***Wt.[%]***
O	6.59
Al	0.17
Si	0.88
Ti	0.21
Cr	20.68
Mn	0.34
Fe	12.18
Ni	50.43
Nb	2.46
Mo	6.05
Total	100.00

EDX-Spectrum 3	
Element	***Wt.[%]***
O	2.13
Al	0.36
Si	0.34
Cr	21.64
Mn	0.56
Fe	13.05
Ni	53.30
Nb	2.39
Mo	6.23
Total	100.00



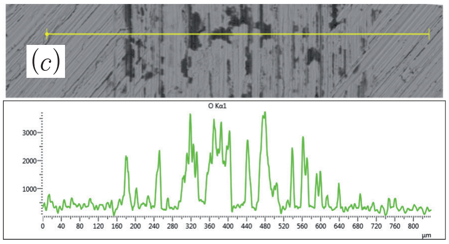


Fig. 10: *Wear track at normal load 10 N: (a) SEI smooth wear tracks and EDX spectra in Thermanit X, (b) BSE-detail, (c) EDX line analysis.*

EDX-Spectrum 1	
Element	***Wt.[%]***
O	1.57
Si	0.87
Cr	19.81
Mn	6.04
Fe	62.91
Ni	8.80
Total:	100.00

EDX-Spectrum 2	
Element	***Wt.[%]***
O	24.62
Si	2.74
Cr	15.13
Mn	4.49
Fe	46.89
Ni	6.13
Total:	100.00

EDX-Spectrum 3	
Element	***Wt.[%]***
O	32.88
Si	3.43
Cl	0.34
K	0.25
Ca	0.15
Cr	12.96
Mn	3.70
Fe	40.74
Ni	5.55
Total:	100.00

It is clear from the appearance of the wear track that adhesive wear was the dominant wear mechanism. Thermanit 625 and Thermanit X weld materials were pressed into the surface roughness of the static counterpart - SiC ball. The fragments of the intensively plastically deformed material Thermanit 625 and Thermanit X during the tribological test formed microbonds that were subsequently broken and formed a wear track pattern. The remains of the pressed material abraded the wear track. Part of energy generated during wear test was dissipated in tribo system and manifested by heat generation. As a result, the temperature of the tribo-couple increased locally. The intense plastic deformation of the surface of the tested clads and the local heating in the air created conditions for local oxidation of a part of the wear track, as evidenced by the high oxygen content in EDX analyses (Figures 9 and 10).

4. Conclusions

The paper presents the results of the research focused on the possibility of renovation of the shape parts of mold in the technology of aluminum casting under high pressure. The quality of two weld types - Thermanit 625 and Thermanit X in aluminum alloy melt EN AB AlSi8Cu3 was determined experimentally – resistance against dissolution in molten metal and wear resistance. For the production of welds the technology of CMT welding - Cold Metal Transfer in protective atmosphere Ar was used.

Experimental work confirmed that after 120 and 300 minute exposure of Thermanit 625 welds in aluminum alloy melt, a complex reaction of aluminum alloy EN AB AlSi8Cu3 with alloying elements present in the welds was observed. Using the qualitative elemental microanalysis EDX on the surface of the Thermanit 625 weld in individual complex phases chromium, nickel, iron, molybdenum and niobium were detected - elements present in the aluminum alloy and in Thermanit 625 and Thermanit X welds. Intense reaction of aluminum melt with Thermanit 625 weld occurred in the area of corners and edges of the sample. Resistance of Thermanit X weld and underlying material AISI/SAE 309 in aluminum alloy melt was higher than the resistance of Thermanit 625 weld.

Based on the experiments carried out it can be stated that the evaluated types of welds are not suitable for renovation of the shape parts of molds, because the elements are dissolved in contact with the aluminum alloy and degradation occurs in the areas of corners and edges. For this type of renovation a combination of welds and duplex PVD coating can be recommended.

Acknowledgments

This contribution is the result of the project implementation: „The utilization of innovative technology for repair functional surfaces of mold casting dies for castings in automotive industry" (APVV-16-0359) supported by the Slovak Research and Development Agency and „Study of the properties of newly constituted layers and coatings in tribological systems" (VEGA 1/0424/17).

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