Analysis of Weld Joint of DX51D Steel with $AlMg_3$ Alloy Made by CMT Welding Method

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The combination of steel and aluminum as a constructional material brings many benefits. Steel is characterized by strength and is suitable for components exposed to high stress. Aluminum is light and is suitable for less stressed parts. However, for technical and economic reasons, the arc welding of these materials has not been possible for a long time. The development of the technology that allows welding of steel with aluminum is linked to the requirements of the automotive industry. This is a process known as CMT – Cold Metal Transfer and refers to the low energy transition of the droplet during MIG/MAG welding. In this so-called "welding soldering", the base steel material is not melted, but merely wetted, whereas in the case of aluminum, a melt weld is formed. The advantage of this process is the lower heat input and consequently considerably less heat deformation. This paper deals with the analysis of the welded joint of the DX51D steel sheet with the Aluzinc layer and the $AlMg_3$ alloy sheet made by CMT welding using the digitized inverter welding power from Fronius company. An $AlSi_5$ welding wire of Ø 1.2 mm was chosen as an additive material. The used technology has led to the formation of a weld with a considerable porosity of the weld metal.

Keywords: CMT welding, steel DX51D, Aluzinc, Aluminum alloy $AlMg_3$, Porosity, $AlSi_5$

1 Introduction

At present, combinations of the specific properties of different materials promise interesting perspectives. The combination of materials imparts to the respective components or product the required properties of multiple materials, Sun et al. (2017). This kind of joints was previously possible only by mechanical means or as glued joints. But the greatest attention today is devoted the thermal joining of materials with different properties. The center of gravity is steel and aluminum joints. Aluminum joining with steel through the CMT process opens new design and technological possibilities, Gungor et al. (2014), Průša et al. (2015). It is mainly used in the automotive industry where is focused on weight reduction and increasing safety due to targeted strength improvement, Hagara (2000), Larsson (2003). Based on the different properties of steel and aluminum, their joints can provide optimal utility properties, Feng et al. (2009). The CMT process differs from other thermal techniques, such as MIG/MAG, WIG, or laser welding, in a few important parameters, by lower heat input to the welding and controlled reversible wire movement. The process brings about 20 – 30% less heat than MIG/MAG welding. CMT welding which was originated from the development of the of MIG/MAG welding branch, Schierl (2005), Talalaev et al. (2012), is based on controlled near-wire transfer of welded material, Kah et al. (2013). The result is a very uniform weld. This is one of the preconditions for joining aluminum and steel. Another requirement when using the CMT method is a material – the steel sheet must be galvanized, Zhang et al. (2009), Cao et al. (2014). The advantage of CMT welding is high bridgeability without the need for a welding pad, minimal welding deformation due to low heat input, highly stable arc, practically zero spatter and minimum finishing works, Schierl (2005), Lipiński (2015). However, with the welding method being evaluated, we can encounter some welding problems and defects, e.g. the porosity of the weld metal, Ahsan et al. (2016), Cong et al. (2015), and the formation of segregation cracks during solidification, Rush et al. (2010), Meško et al. (2014).

The paper deals with the evaluation of the welded joint of DX51D steel with the Aluzinc layer and the AlMg3 aluminum alloy formed by CMT welding. Both materials in the form of a 1 mm thick sheet metal were welded with overlapping, using a 1.2 mm thick $AlSi_5$ alloy welding wire. The Aluzinc layer on the steel sheet surface is formed of alloy from aluminum and zinc. Welding was carried out according to the conditions and parameters mentioned in Table 1.

***Tab. 1** Conditions and parameters of the welding process*

Welded materials	Steel sheet metal DX51D+Aluzinc and alloy sheet $AlMg_3$
Type of weld joint	Overlapped joint
Additional material	Welding wire Ø 1.2 mm, $AlSi_5$
Protective gas	100% Ar
Protective gas flow	$30\ l\cdot min^{-1}$

The weld joints created by the CMT method were performed on a welding machine from Fronius company. The entire welding process was digitally controlled, including the reverse motion of the wire, which took place at a frequency of 70 Hz. Chemical analysis of weld metals was performed by a spark optical emission spectrometer Q4 Tasman. The metallographic samples of the welds were prepared using MTH Micron 150 metallographic saw and Struers Labopol 60 grinder. Metallographic analysis was performed on the Olympus DSX100 opto-digital microscope and Olympus GX51 metallographic microscope. The microhardness measurement was performed by the Leco LM247AT automated hardness tester. The evaluated weld joint exhibited considerable porosity in the weld metal.

2 Experimental methods

2.1 Analysis of chemical composition

To analyze the chemical composition was used the Tasman Q4 spark optical emission spectrometer and the corresponding standards were selected based on the measured material (standard for steel, standard for aluminum alloy). The results of the chemical analysis of the steel sheet are shown in Table 2. Table 3 shows the results of the chemical analysis of the aluminum alloy sheet.

***Tab. 2** Chemical composition of DX51D steel [wt. %]*

C	Si	Mn	P	S	Cr	Mo	Ni	Cu	Al
0.068	0.013	0.323	<0.005	<0.15	0.0065	<0.01	0.0067	0.06	0.026

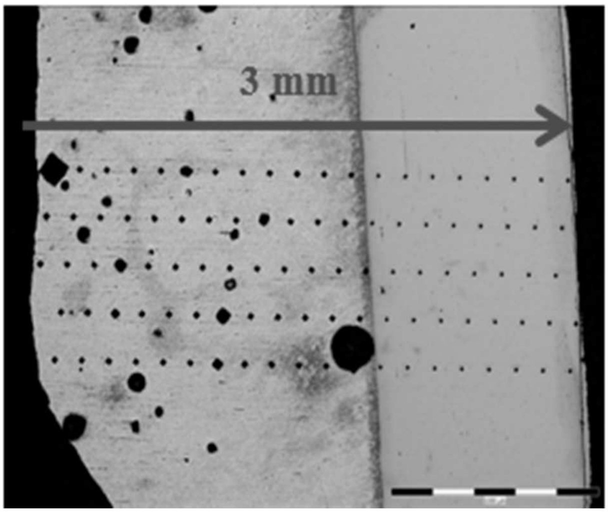
***Tab. 3** Chemical composition of $AlMg_3$ alloy [wt. %]*

Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	Al
0.144	0.406	0.016	0.220	2.792	0.115	0.0023	0.023	0.027	96.22

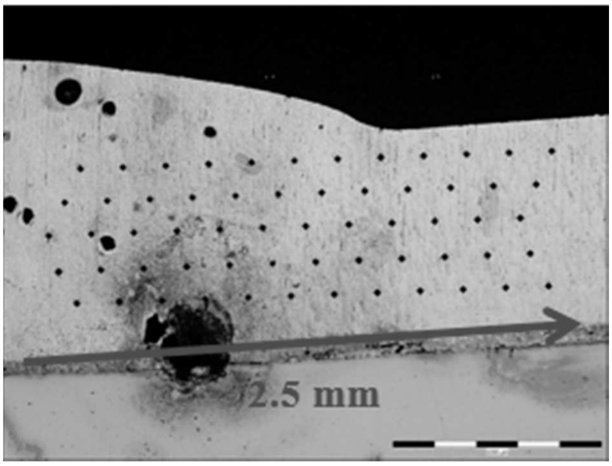
2.2 Metalographic analysis

The cuts of welds were prepared using the MTH Micron 150 precision metallographic saw, then were casted into methylacrylate Duracryl Plus self-curing resin, and after curing, they were hand grinded on the Struers Labopol 60 metallographic grinder. Grinding was performed on Hermes abrasive paper with a particle size of 80 – 4000 μm. The polishing of the samples was carried out on the Leco Brown Technotron abrasive cloth using a Leco diamond slurry with a particle size of 1 μm. A velvet polishing disc and a diamond suspension with a particle size of 0.5 μm were used to a finish polishing. 2% Nital was used to induce the steel sheet structure, the aluminum alloy was etched by immersion in NaOH and the surface of the sample was wipeded with a cotton swab soaked in a solution of 95% H2O + 5% HF. The structure of weld metal (AlSi5) was induced by HF. Macroscopic images were taken on an Olympus DSX100 optical microscope, the microstructure was evaluated using the Olympus GX51 inverted metallographic microscope.

2.3 Measurement of microhardness



a)



b)

***Fig. 1** Indentations after microhardness measurement. Measurement of the transition area at the contact of DX51D steel–weld metal $AlSi_5$ (a) and contact of $AlMg_3$ alloy–weld metal$AlSi_5$ (b)*

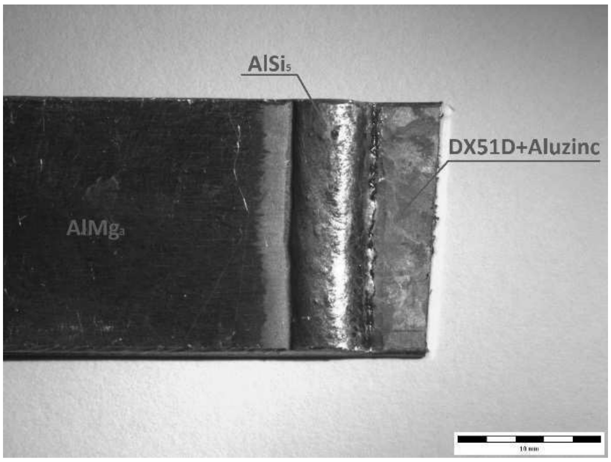
The microhardness measurement was performed by the Leco LM247AT automatic hardness tester. Measurement was done in 5 rows, 20 indentations, by Vickers method with load 50 g (HV 0.05). The principle of microhardness measuring the transition area on the contact of steel sheet – the weld metal is shown in Fig. 1 (a). The principle of microhardness measuring of the transition area of contact of weld metal – Aluminum alloy is shown in Fig. 1 (b). The red arrow shows the direction of measurement.

3 Results and discussion

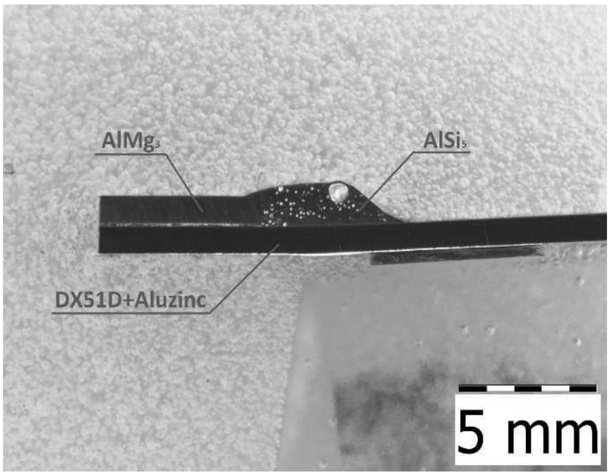
The picture of weld with the description of the individual parts is shown in Fig. 2 (a). Fig. 2 (b) documents the cross-sectional of the weld also with the description of the individual parts of the weld and visible numerous porosity in the weld metal. The porosity of the weld metal is documented in Figures 3 (a) and 3 (b). The formation of gas cavities and pores in CMT welding may be related to the absorption of gases by aluminum. The creation of gas cavities is most often caused by hydrogen, which is soluble in aluminum. Weld metal absorbs hydrogen, which diffuses through the entire volume of the welding bath. When cooling the weld metal, the solubility of hydrogen decreases. Because the cooling rate is high during welding, it is not enough to exclude all hydrogen from the liquid metal, hydrogen is staying there and forming gas cavities. When welding the CMT, the protective atmosphere is made up of 100% argon, so it is possible that the gas cavities creation is also join with presence of argon. Cais et al. (2014) documents the porosity in the case of pressurized die casting alloys AlSi7Mg0.3, which is created by the presence of hydrogen according to the equation:

$$2\,Al + 3\,H_2O = Al_2O_3 + 3\,H_2 \qquad (1)$$

Overheating of the aluminum melt causes excessive oxides formation, Novotný et al. (2014). During aluminum melting process, each temperature rise of 10 ° C above the melting point results in an increase of the gases in the melt by 0.1%, Michna et al. (2011), Żydek et al. (2010). According to a similar mechanism, welding pores can also be formed during the CMT welding process.

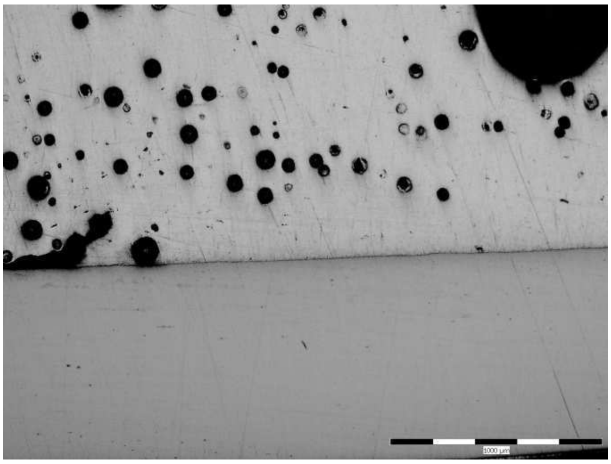


a) 3.15x

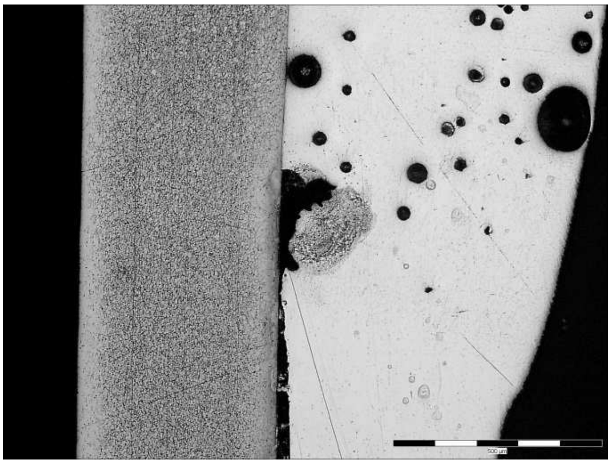


b) 6.25x

Fig. 2 A weld image with a description of the main parts (a) and a cross section of the weld (b)



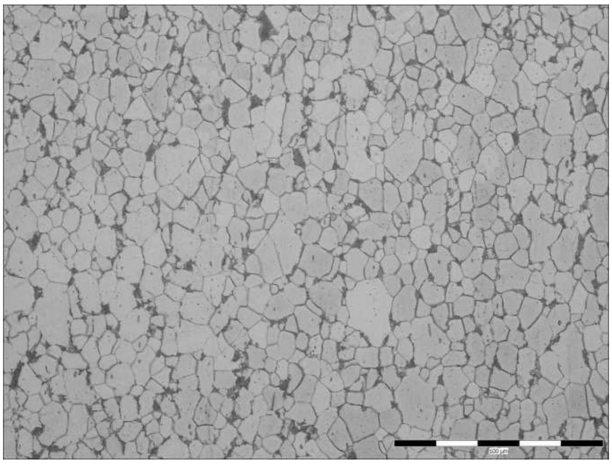
a) 50x



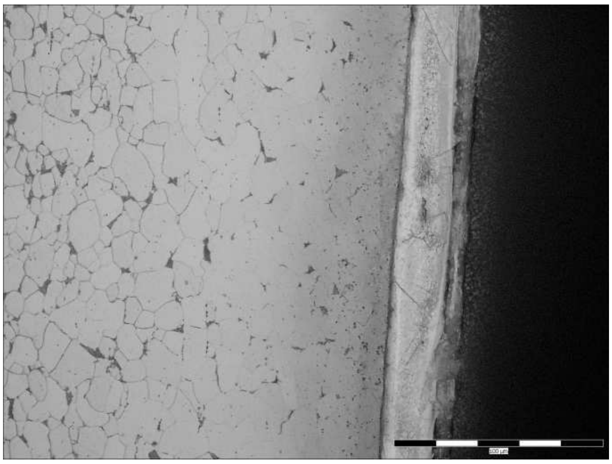
b) 100x

***Fig. 3** Porosity in transition area of weld metal $AlSi_5$ – DX51D steel (a) and in transition area of $AlMg_3$ alloy – weld metal $AlSi_5$ (b)*

The metallographic analysis of the metal sheet with an aluzinc layer is documented in Fig. 4 (a) and Fig. 4 (b). The core structure of the steel sheet consists of ferrite with a lamellar perlite. The aluzinc layer, which has a defined chemical composition of 55% aluminum, 43.4% zinc and 1.6% silicon, was applied to the steel sheet by a continuous hot-dip process, which corresponds to a significant heat-affected area of the base material under the aluzinc layer. The microstructure of the aluminum alloy $AlMg_3$ is shown in Fig. 5 (a). In the structure of the aluminum alloy, Mg_2Al_3 phase exclusion regions are visible. With less magnification, the aluminum alloy linearity is evident, as is visible from Fig. 5 (b). The metallographic analysis of the $AlSi_5$ weld metal is documented in Figure 6 (a). With smaller magnification, individual grains of aluminum alloy having a considerable size are visible, as shown in Figure 6 (b). The coarse grain structure may reduce the strength and plasticity of the weld metal. The microstructure in the transition zone of steel sheet - weld metal is documented in Fig. 7 (a). A thin layer of the intermetallic phase is visible on the contact of steel with weld metal, which is better visible at higher magnification; see Fig. 7 (b). The grains of steel are enlarged in contact area with the weld metal, which can again lead to deterioration of the mechanical properties of the weld joint. In the case of the transition zone aluminum alloy-weld metal they are visible the sharp grain boundaries, see Fig. 8 (a). With greater magnification of the transition area which is shown in Figure 8 (b), it is evident that the precipitating particles have been gradually softened and that the sharp grain boundaries have decreased.

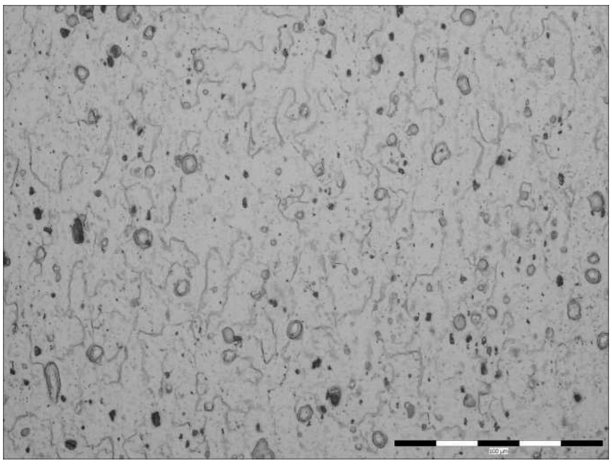


a) 500x

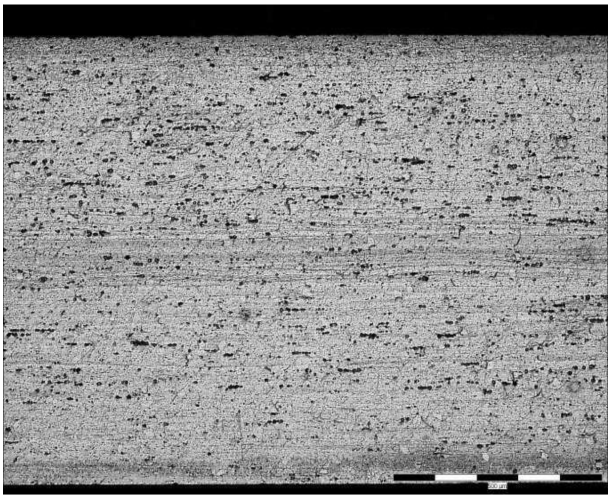


b) 500x

***Fig. 4** Microstructure of steel sheet (a) and aluzinc layer on steel surface (b)*

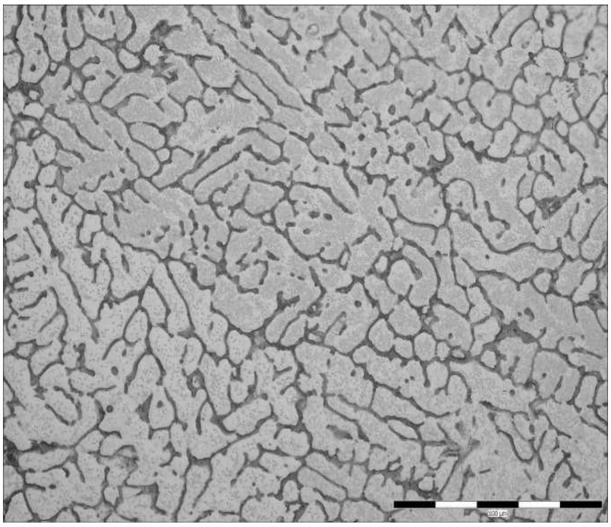


a) 500x

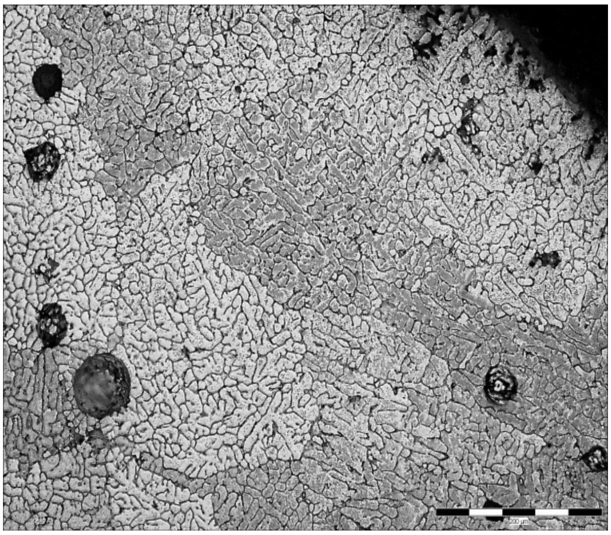


b) 100x

***Fig. 5** Microstructure of aluminum alloy (a) and its visible linearity (b)*

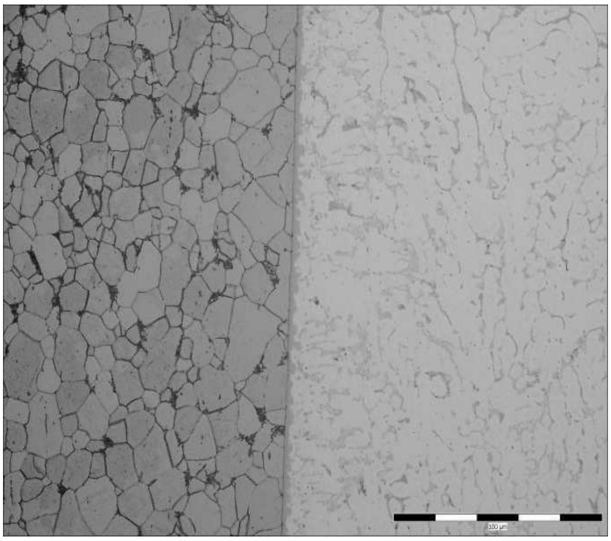


a) 500x

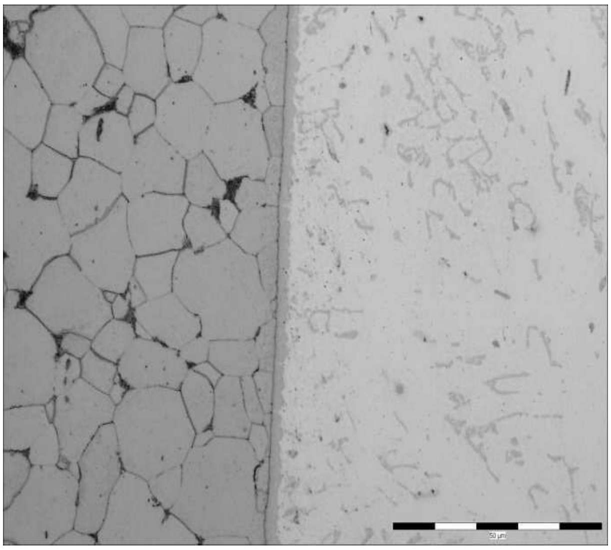


b) 500x

***Fig. 6** The weld metal microstructure (a) and the visible grains of the $AlSi_5$ additional material (b)*

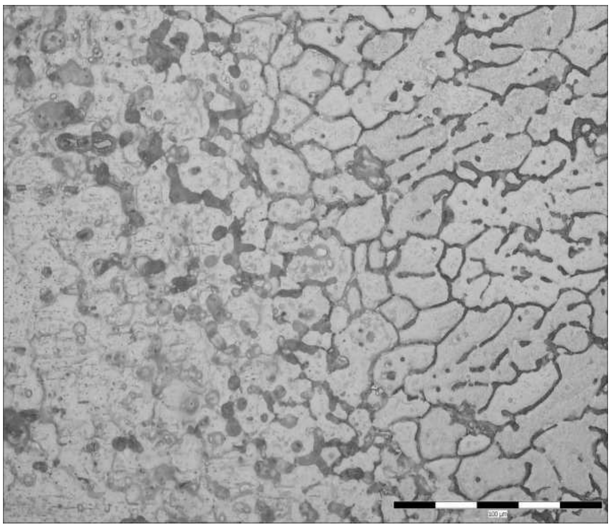


a) 500x

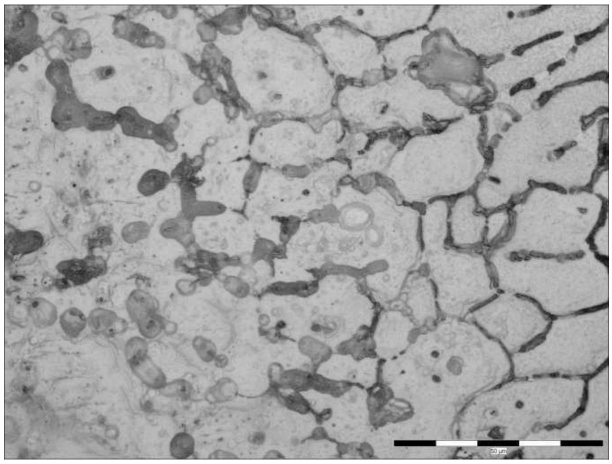


b) 1000x

***Fig.** 7 Microstructure of transition area of DX51D steel – AlSi5 weld metal (a) and visible layer of intermetallic phase (b)*



a) 500x



b) 1000x

***Fig. 8** Microstructure of transition area AlMg$_3$ aluminum alloy – AlSi$_5$ weld metal (a) and area of grain refinement (b)*

The microhardness measurement results show differences in microhardness of individual weld joint materials. Fig. 9 documents the results of microhardness measurements in transition area of weld metal – steel sheet. The results show that the microhardness of the weld metal is about 80 HV0.05, and there is a sharp transition to a steel sheet with a microhardness of about 180 HV0.05. The heat-affected area is not visible from the process of microhardness measurement. When measuring the microhardness at the transition area weld metal - aluminum alloy, the higher value of microhardness of the weld metal (about 80 HV0.05) is evident, as compared to the aluminum alloy (about 70 HV0.05), which is evident from Fig. 10. The transition area is not characterized by a more pronounced microhardness variation, from which it can be concluded that a welded joint has perfectly bonded the weld metal to the aluminum sheet. This was confirmed by metallographic analysis.

4 Conclusion

CMT belongs between arc-welding with a melting electrode in an inert gas, most commonly argon, which originates from MIG / MAG welding. When welding by CMT, the electric arc melts the wire electrode and the base material of the aluminum alloy. Usually there is no melting of the steel sheet. In this method, fusion welding of aluminum alloy is combined with hard brazing of steel sheet, the so-called overlapped joint. When welding two heterogeneous materials, one encounters a problem in the difference in physico-chemical properties. Weldability is greatly complicated by the limited solubility of both metals. The technological difficulty of welding is considerable, especially the intermetallic phases at the interface of both metals must be avoided. The effort is to bring as little heat to the joint as possible, shorten the welding process itself, reduce diffusion and intermetallic phase formation, in particular by selecting a suitable additive material. For the welding of selected materials, an additional AlSi$_5$ material was chosen, which very well compensates for the susceptibility of the weld metal to heat cracking and limits the formation of intermetallic phases. The evaluated welds exhibited slight deformations. The macrophotography shows a quality weld, without spraying, with a minimal heat-affected area. Metallographic analysis documents the considerable porosity of the weld metal. Between the weld metal and the steel sheet there is a thin layer of the intermetallic phase and the area of the coarse grain of the steel. The transition phase of the aluminum sheet and the weld metal was characteristic by area of fine grain of the weld metal. The results of the measurement of the microhardness of the transition region did not show any fluctuations in the microhardness values, i.e. no wider heat-affected area was created. In the transition steel sheet – weld metal, a sharp transition in microhardness values, which indicates the sharp interface of the solder joint, is visible. In the transition area, the aluminum alloy – weld metal exhibits microhardness similar to the two materials which is result of a welded joint with a diffusion bond between the two materials. The article confirmed the suitability of the CMT method for welding two heterogeneous materials. However, it should be remembered that even with this method, weld defects can occur which must be detected which was confirmed also in this work.

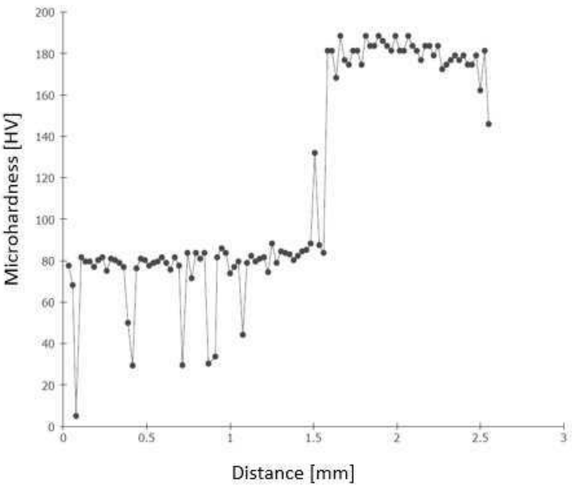


***Fig. 9** Microhardness measurement of the transition area of steel sheet – weld metal*

***Fig. 10** Measurement of microhardness of the transition area of aluminum sheet – weld metal*

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References

[1] SUN, Q.J., LI, J.Z., LIU, Y.B., LI., B.P., XU, P.W., FENG, J.C. (2017). Microstructural characterization and mechanical properties of Al/Ti joint welded by CMT method – Assisted hybrid megnetic field. In: *Materials and Design*, Vol. 116, pp. 316 – 324.

[2] GUNGOR, B., KALUC, E., TABAN, E., SIK, A. (2014). Mechanical and microstructural properties of robotic Cold Metal Transfer (CMT) welded 5083-H111 and 6082-T651 aluminum alloys. In: *Materials and Design*, Vol. 54, pp. 207 – 211.

[3] PRŮŠA, F., VOJTĚCH, D., BERNATIKOVÁ, A., DVORSKÝ, D. (2015). Mechanical Alloying: A Way How to Improve Properties of Aluminium Alloys. In: *Manufacturing Technology*, Vol. 15, No. 6, pp. 1036-1043.

[4] HAGARA, K. (2000). Strength properties of aluminum/aluminum and aluminum/steel joints for light weighting of automotive body. In: *Weld. World*, Vol. 44, No. 4, pp. 23 – 27.

[5] LARSSON, J.K. (2003). Overview of joining technologies in the automotive industry. In: *Weld. Res. Abroad*, Vol. 49, No. 6/7, pp. 29 – 45.

[6] FENG, J.C., ZHANG, H.T., HE, P. (2009). The CMT short-circuiting metal transfer proces and its use in thin aluminium sheets welding. In: *Mater. Des.*, Vol. 30, No. 5, pp. 1850 – 1852.

[7] SHIERL, A. (2005). The CMT proces – a revolution in welding technology. In: *Weld. World*, Vol. 9, No. 38.

[8] LIPIŃSKI, T. (2015). Influence of Surface Refinement on Microstructure of Al-Si Část Alloys Processed by Welding Method. In: *Manufacturing Technology*, Vol. 15, No. 4, pp. 576-581.

[9] TALALAEV, R., VEINTHAL, R., LAANSOO, A., SARKANS, M., (2012). Cold metal transfer (CMT) welding of thin sheet metal product. In: *Estonian Journal of Engineering*, Vol. 13, No. 3, pp. 243 – 250.

[10] KAH, P., SUORANTA, R., MARTIKAINEN, J. (2013). Advanced gas metal arc welding processes. In: *J. Adv. Manuf. Technol.*, Vol. 67, pp. 655 – 674.

[11] ZHANG, H.T., FENG, J.C., HE, P., ZHANG, B.B., CHEN, J.M., WANG, L. (2009). The arc

characteristics and metal transfer behaviour of cold metal transfer and its use in joining aluminium to zinc-coated steel. In: *Mater. Sci. Eng.*, Vol. A 499, No. 1, pp. 111 – 113.

[12] CAO, R., FENG, Z., LIN, Q., CHEN, J.H. (2014). Study on cold metal transfer welding – brazing of titanium to cooper. In: *Mater. Des.*, Vol. 56, No. 4, pp. 165 – 173.

[13] AHSAN, M.R.U., KIM, Y.R., KIM, C.H., KIM, J.W., ASHIRI, R., PARK, D. (2016). Porosity formation mechanisms in cold metal transfer (CMT) gas metal arc welding (GMAW) of zinc coated steels. In: *Science and Technology of Welding and Joining*, Vol. 21, No. 3, pp. 209 – 215.

[14] CONG, B., DING, J., WILLIAMS, S. (2015). effect of arc mode in cold metal transfer proces on porosity of additively manufactured Al-6.3%Cu alloy. In: *Int. J. Adv. Manuf. Technol.*, Vol. 76, No. 9. pp. 1593 – 1606.

[15] RUSH, M.T., COLEGROVE, P.A., ZHANG, Z., COURTOT, B. (2010). An investigation into cracking in nickel-base superalloy repair welds. In: *Advanced Materials Research*, Vol. 89 – 91, pp. 467 – 472.

[16] MEŠKO, J., ZRAK, A., MULCZYK, K., TOFIL, S. (2014). Microstructure Analysis of Welded Joints after Laser Welding. In: *Manufacturing Technology*, Vol. 14, No. 3, pp. 355-359.

[17] CAIS, J., WEISS, V., SVOBODOVA, J. (2014). Realtion between Porosity and Mechanical Properties of Al-Si Alloys Produced by Low-Pressure Casting. In: *Archives of Foundry Engineering*, Vol. 14, No. 1, pp. 97 – 102.

[18] NOVOTNÝ, J., CAIS, J., NÁPRSTKOVÁ, N. (2014). Analysis of Aluminium Alloys AlSi7Mg0.3 and AlMg3 by Means of X-Ray Diffraction. In: *Manufacturing Technology*, Vol. 14, No. 3, pp. 392-397.

[19] MICHNA, Š., NÁPRSTKOVÁ, N., LUKÁČ, I. (2011). Mechanical Properties Optimization of AlSi12CuMgNi Alloy by Heat during Annealing. In: *Archives of Foundry Engineering*, Vol. 11, No. 4, pp. 163 – 166.

[20] ŽYDEK, A., KAMIENIAK, J., BRASZCZYŃSKA-MALIK, K.N. (2010). Microstructural stability of Mg-5Al-0.4Mn-3RE alloy Treatment. In: *Mettalofizika i Noveishie Teknologii*, Vol. 11.

10.21062/ujep/80.2018/a/1213-2489/MT/18/2/215