Paweł Irek

Laser surface alloying of AlSi7Cu4MgMn aluminium alloy with silicon carbide

Abstract: The article presents the results of tests on the laser surface alloying of AlSi7Cu4MgMn aluminium alloy using silicon carbide. The objective of the tests was to establish the influence of laser beam power and travel rate, ceramic powder feeding rate and presence of activating flux on the quality of seams surface alloyed with an HPDDL laser using SiC particles as well as to determine the optimum technological process conditions. The assessment of the quality of surface alloyed seams was carried out using macro and microscopic examination verifying the proper generation of a composite layer on the surface and the percentage fraction of SiC particles in the root run. The article also presents the results of microhardness measurements in the cross-sections of laser-processed layers.

Keywords: laser surface alloying, AlSi7Cu4MgMn aluminium alloy;

Introduction

The popularity of welded structures made of aluminium alloys continues to enjoy significant popularity due to its numerous advantageous properties including high strength in relation to weight, good corrosion resistance and high workability. However, constant technological development and the pursuit of increased efficiency of materials for welded structures is accompanied by a decrease in the use of aluminium alloys in favour of composite materials based on aluminium alloys. This approach results from the low tribological properties of aluminium alloys. In turn, composites based on aluminium alloys with additions of other metal or ceramic particles enable the improvement of the tribological properties of aluminium alloys. Composites are an answer to a growing demand for materials characterised by better mechanical and operational properties at the same time making it possible to intentionally shape desirable properties. Aluminium alloys have proved unable to fully satisfy the needs mentioned above. The formation of composite layers based on aluminium alloys can be achieved by means of laser technologies. This process, referred to as laser surface alloying, consists in enriching a remelted surface layer with metallic or ceramic alloying agents, usually with the simultaneous change of the matrix structure. Aluminium-based composite layers [1,2] are characterised by high strength and rigidity in relation to specific gravity at ambient or elevated temperatures, good fatigue properties, high plasticity and improved abrasive wear resistance. A newly formed surface layer differs both from the base and filler metals as regards its chemical composition, physical properties and structure. Owing to dispersive carbide particles or ceramic particles having appropriate granularity, it is possible to freely control the phase composition of surface layers

mgr inż. Paweł Irek (MSc Eng.) – Instytut Spawalnictwa, Centre for Education and Welding Supervision

subjected to surface alloying. Such effects enable the formation of surface layers having diverse properties such as resistance to aggressive chemicals, abrasion, corrosion and erosion, as well as high hardness, heat resistance and significant fatigue strength [3,4].

Laser surface alloying enables the formation of very thin surface layers over small and great areas. The scheme of laser surface alloying is presented in Figure 1.

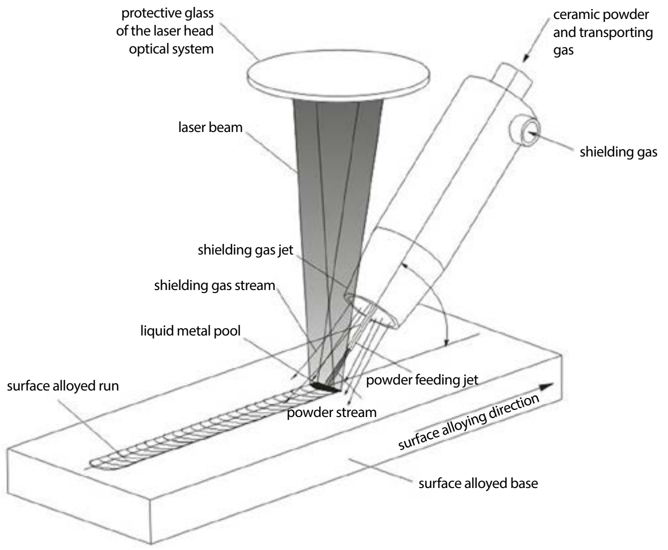

Fig. 1. Laser surface alloying [5]

Exemplary applications include surface alloying of tools made of high-speed steel or surface alloying of matrix edges and of the work surface of hot-rolling roller etc. The process requires the access of a laser beam to an area subjected to surface alloying. The dimensions or the mass of an object being surface alloyed are of no importance. Owing to an advanced technique Nd:YAG fibre and disk diode lasers can provide a laser beam via optical fibres to a working head as far as approximately 100 metres from the laser source. During surface alloying the powder must be fed coaxially along with the laser beam by means of a specially adjusted head [4,6].

Table 1. Chemical composition of AlSi7Cu4MgMn alloy [8]

Grade		Alloying components,%				
Designation	Symbol	Si	Mg	Cu	Mn	Al
AlSi7Cu4MgMn	AK74	6.5-8.0	0.3-0.6	3.0-4.0	0.2-0.5	rest

Objective and scope of tests

The research involved carrying out initial diagnostic laser surface alloying tests of AlSi7Cu4MgMn aluminium alloy with SiC particles using a high power direct-diode laser (HPDDL) and an ActivaTec 500 activating flux in order to determine the effect of the basic laser surface alloying process parameters on the properties of surface layers.

Test pieces and testing methodology

The tests of laser surface alloying were carried out on an AlSi7Cu4MgMn aluminium alloy base (Table 1). A 10 mm thick plate was used to prepare test pieces (60×20×10 mm) for surface alloying. The surfaces of the test pieces underwent milling and chemical cleaning. The tests involved the use of powdered silicon carbide having a granularity of 100÷125 μm. The powder was fed to the laser beam affected area with a powder feeding jet at an angle of 45°. In addition, in order to fully protect the liquid metal against the access of air it was necessary to

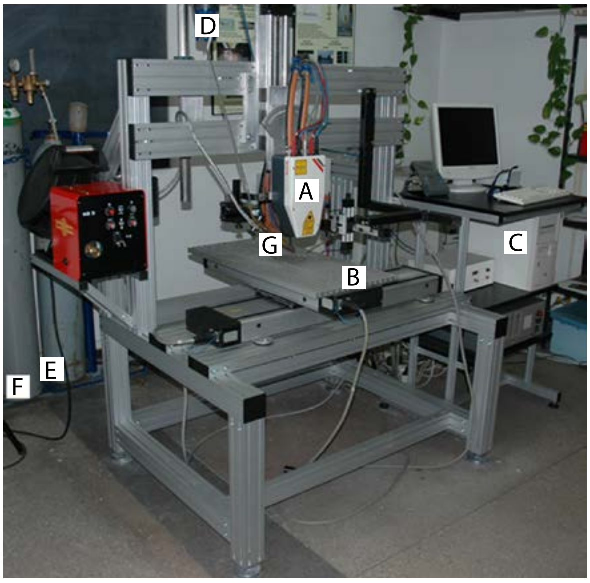

Fig. 2. Numerically controlled experimental laser stand composed of a ROFIN SINAR DL 020 high power direct-diode laser and a CNC ISEL AUTOMATION positioning system: A – laser head, B – CNC table, C – stand-controlling computer, D – disk powder feeder, E – powder-transporting gas cylinder (argon), F – shielding gas cylinder (argon), G – powder-feeding jet positioning system and shielding gas jet.

use an additional gas shielding jet for supplying argon at a flow rate of 10 l/min.

Laser surface alloying using SiC ceramic powder was carried out on a stand provided with a ROFIN SINAR DL-020 high power direct-diode laser (Fig. 2). The maximum power of a laser beam is 2.2 kW (Table 2).

Table 2. HPDDL ROFIN SINDAR DL 020 characteristics

Parameter	Size/quantity
Laser radiation wavelength	808 ± 5, nm
Maximum laser beam output power (continuous operation)	2200, W
Scope of power stepless adjustment	100 – 2200, W
Power efficiency	35 – 50,%
Laser beam focal length	82 / 32, mm
Laser beam focus dimensions	1.8×6.8, mm 1.8×3.8, mm
Range of power density in laser beam focus plane	0.8 – 36.5, kW/cm2

The activating flux used in the tests was ActivaTec 500 produced by Castolin and intended for GTA welding of plates/sheets made of austenitic steels. In the TIG method this flux is used to increase the depth of penetration by changing convective motion in the liquid pool of the weld. In the case of laser welding, this flux is used to increase the absorption of laser radiation by a surface undergoing surface alloying, strongly reflecting laser radiation. The purpose of using the flux is to facilitate the commencement of surface alloying (the formation of a liquid metal pool) and stabilise the surface alloying process [7]. It was expected that the flux would improve the wettability of SiC particles and, through the convective motion of liquid metal, would facilitate spreading of the particles in the aluminium alloy matrix.

The laser surface alloying tests were carried out in the direction of the shorter side of the laser beam rectangular focus for various values of laser beam power (P), surface alloying rate (v), powder feeding rate (Q) and the presence of an activating flux (Table 3).

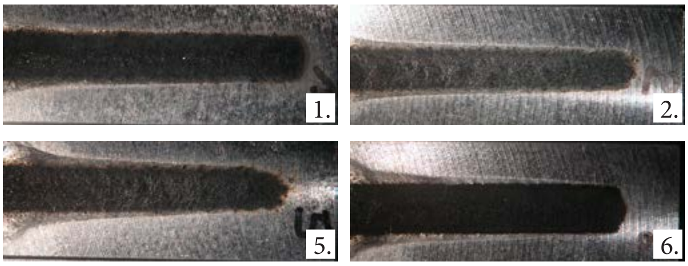

Fig. 3. Examples of test piece faces after surface alloying with a ROFIN SINDAR DL 020 HPDDL; tests piece designations as in the Table 3

Tests and results

The tests pieces were subjected to visual and metallographic tests as well as microhardness measurements. Each surface alloyed run underwent visual testing. All the runs were characterised by a uniform face (Fig. 3) indicating that the process of surface alloying was stable.

Table 3. Surface alloying process parameters and the results of penetration shape measurements

Test piece no.	P, W	v, m/min	E, J/cm²	Q, g/min	AT500	b, mm	h, mm	S, mm²
1	2000	0.25	4.8	1.5	-	8.3	2.9	18.89
2	2000	0.25	4.8	1.0	-	8.3	2.7	17.59
3	2000	0.25	4.8	1.0	YES	9.6	3.3	24.87
4	2000	0.25	4.8	0.5	-	8.3	2.9	18.79
5	2000	0.20	6	0.5	-	9.8	3.7	28.46
6	2000	0.25	4.8	0.5	YES	9.7	3.5	27.65
7	2000	0.30	4	1.5	-	7.7	2.5	15.11
8	2000	0.30	4	1.5	YES	7.7	1.7	11.28
9	2000	0.20	6	1.0	-	10.8	3.8	32.21
10	2000	0.20	6	1.0	YES	19	6	89.49
11	1500	0.15	6	1.0	-	11.7	4	36.74
12	1200	0.15	4.8	1.0	-	6.3	1.5	14.84
13	1200	0.15	4.8	1.0	YES	10.1	3.5	27.75
14	1500	0.15	6	1.0	YES	18	5.5	77.71

Note: Other surface alloying parameters: shielding gas blow-in – 10 l/min, laser beam focus dimensions– 1.8 x 6.8 mm, laser beam focal length – 82 mm, AT500 - ActivaTec 500.

For some specific parameters the run axis had a characteristic sign, i.e. a slight thickening indicating the significant concentration of alloying particles in the weld axis. It was presumed that the area in question might be characterised by the incomplete fusion of the layer with SiC particles (Fig. 6). Due to its very small dimensions, the thickening observed in the weld axis could be properly assessed and interpreted only after carrying out macro- and microscopic tests.

The macrostructural tests of alloyed surfaces were carried out using an Olympus SZX9 stereoscopic microscope; images were magnified 8x and 10x (Fig. 5-8.). The microstructural tests were conducted with an Olympus PME3 microscope and the magnification of 50x (Fig. 9-13). The measurement of the shape of surface alloyed runs was carried out using Auto CAD 2012 software and the digital metallographic photographs with the macrostructures of penetrations (Table 3.) according to the scheme presented in Figure 4.

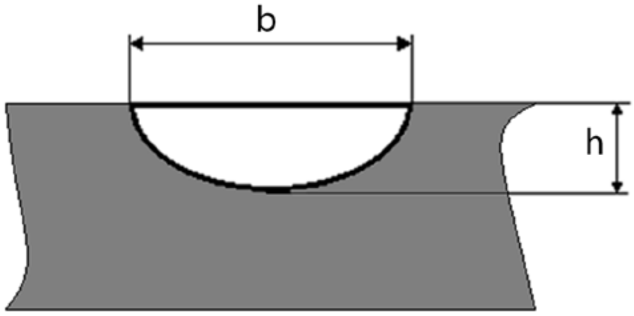

Fig. 4. Measurement of the penetration shape; b – penetration width, mm, h – penetration depth, mm, Grey colour – base metal

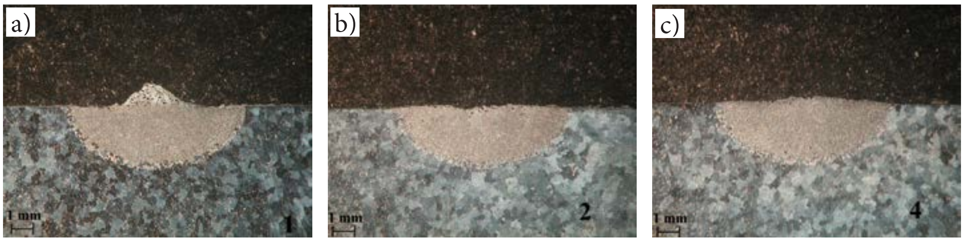

Fig. 5. Macrostructure of the cross-section of surface alloyed runs made with a HPDDL laser on an AlSiCu4MgMn aluminium alloy base. Surface alloying parameters: laser beam power 2000 W, surface alloying rate 0.5 m/min, powder feeding rate: a) 1.5 g/min; b) 1 g/min; c) 0.5 g/min Note: test piece designations as in Table 3

Without activating flux	With activating flux

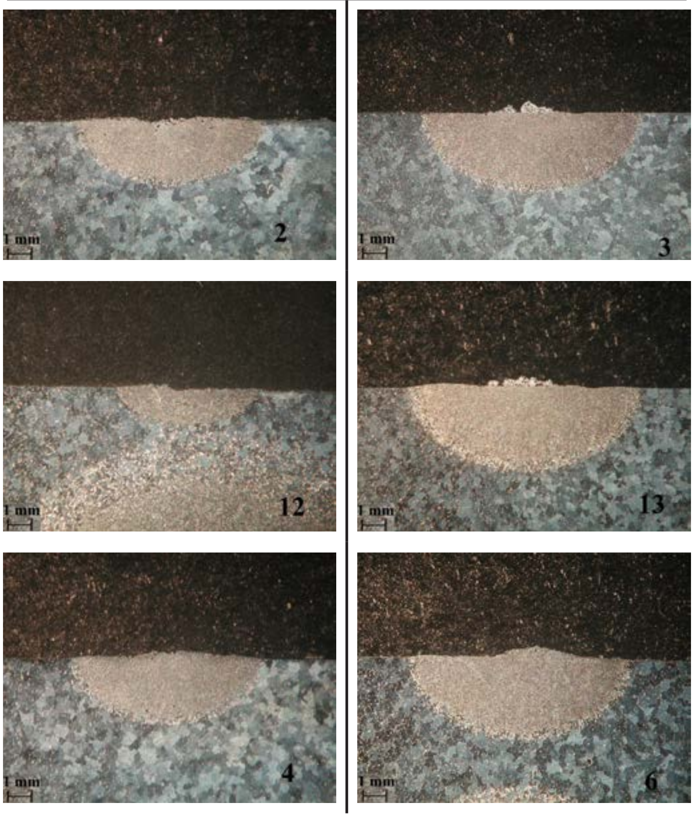

Fig. 6. Effect of an activating flux addition on the shape of surface alloyed runs with other parameters constant Note: test piece designations as in Table 3

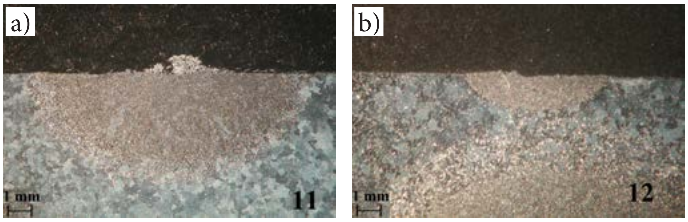

Fig. 7. Effect of HPDDL beam power in laser surface alloying of an AlSiCu4MgMn aluminium alloy base with SiC powder at the powder feeding rate of 0.15 g/min and the surface alloying rate of 0.15 m/min on the shape of surface alloyed runs: a) 1500 W; b) 1200 W. Note: test piece designations as in Table 3

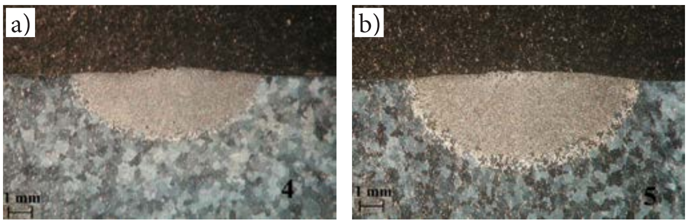

Fig. 8. Macrostructure of the cross-section of surface alloyed runs made with a HPDDL on an AlSiCu4MgMn aluminium alloy base. Surface alloying parameters: the laser beam power of 2000 W, the powder feeding rate of 0.5 g/min, the surface alloying rate of: a) 0.25 m/min; b) 0.20 m/min Note: test piece designations as in Table 3

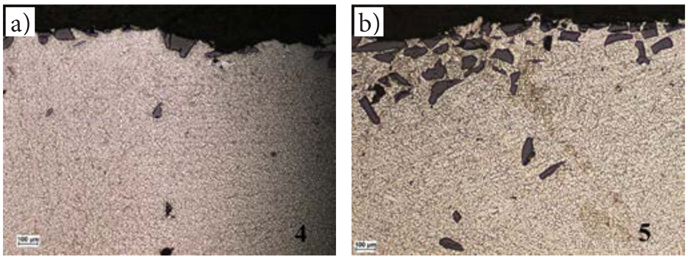

Fig. 9. Microstructure of the cross-section of surface alloyed runs made with a HPDDL on an AlSiCu4MgMn aluminium alloy base. Surface alloying parameters: the laser beam power of 2000 W, the powder feeding rate of 0.5 g/min, the surface alloying rate of a) 0.25 m/min; b) 0.20 m/min Note: test piece designations as in Table 3

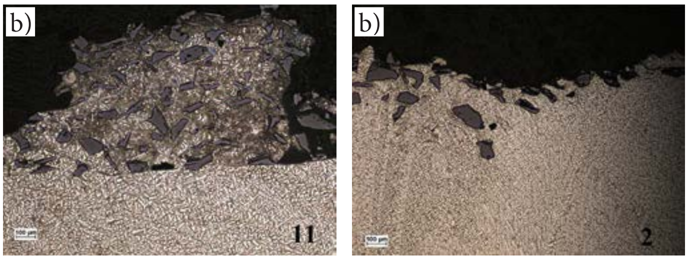

Fig. 10. Effect of HPDDL beam power in laser surface alloying of an AlSiCu4MgMn aluminium alloy base with SiC powder at the powder feeding rate of 0.15 g/min and the surface alloying rate of 0.15 m/min on the microstructure of surface alloyed runs: a) 1500 W; b) 1200 W. Note: test piece designations as in Table 3

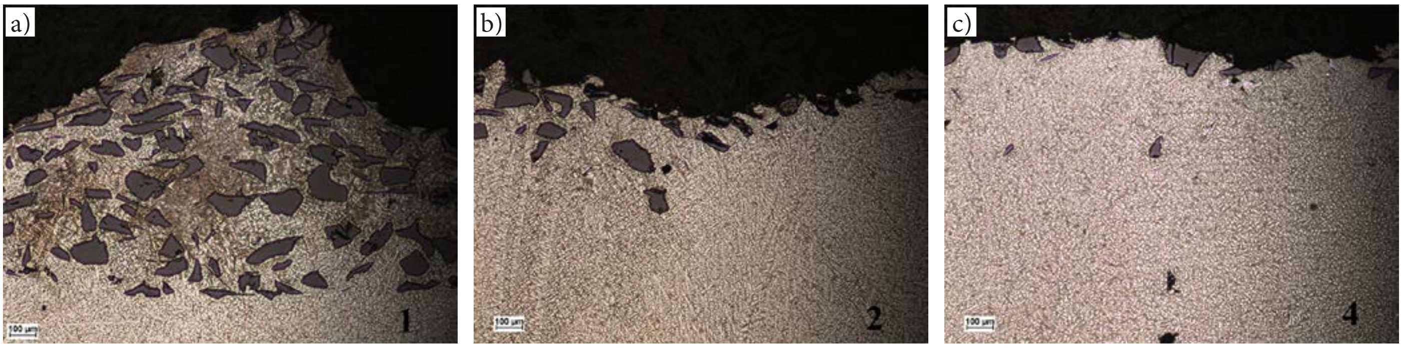

Fig. 11. Microstructure of the cross-section of surface alloyed runs made with a HPDDL on an AlSiCu4MgMn aluminium alloy base. Surface alloying parameters: the laser beam power of 2000 W, the surface alloying rate of 0.25 m/min, the powder feeding rate of: a) 1.5 g/min; b) 1 g/min; c) 0.5 g/min. Note: test piece designations as in Table 3

Without activating flux	With activating flux

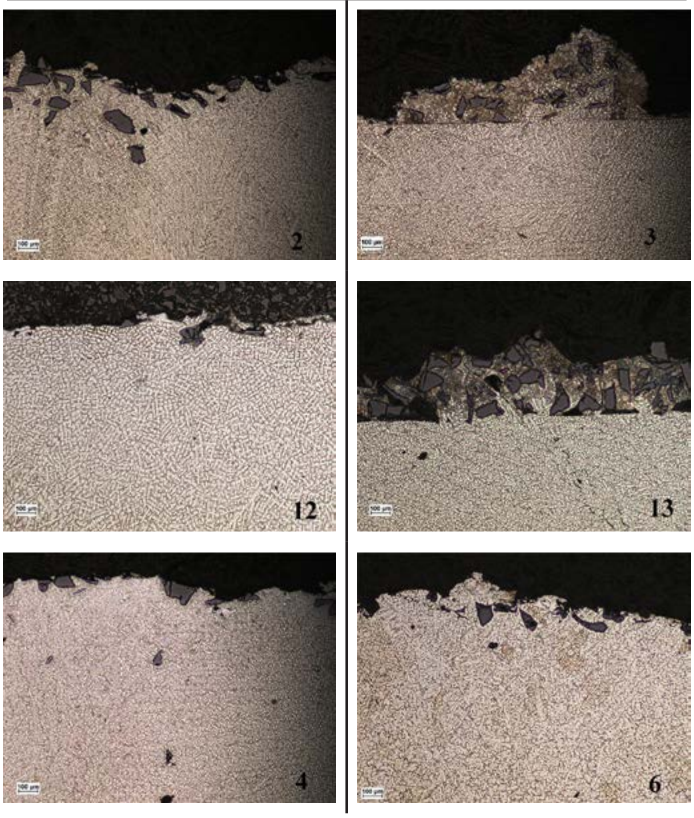

Fig. 12. Effect of an activating flux addition on the microstructure of surface alloyed runs with other parameters constant. Note: test piece designations as in Table 3

Table 4. Number of SiC particles measured on the area of 0.5 mm²

Test piece no.	Volume of SiC particles on the area of 0.5 mm²,%
2	13.55
4	5.24
5	17.19
6	4.83
7	10.37
9	13.38
10	3.21
12	1.98
14	7.46

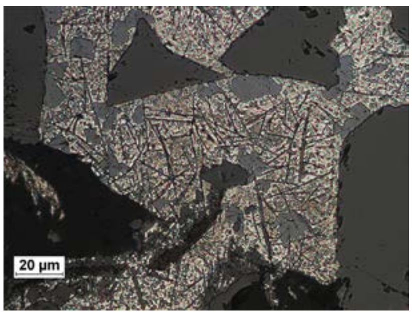

Fig. 13. Microstructure of the alloyed surface in test piece no. 8 at the magnification of x500

The volume of particles which penetrated the matrix was measured using Auto CAD 2012 and digital metallographic photographs with the microstructure of penetrations over an area of 0.5 mm2 (Table 4).

The microhardness measurements were carried out using a WILSON WOLFPERT MIKRO-VICKERS 401 MVD microhardness tester under a load of HV 0.1. The microhardness of surface alloyed runs was measured starting from the face. The investigation involved 9 microhardness measurements every 0.5 mm (Fig. 14), out of which 4 in the penetration zone, 3 in the Heat Affected Zone and 2 in the base metal area. Table 10 presents the results of hardness measurements.

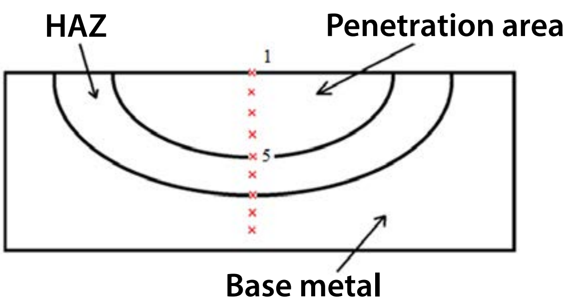

Fig. 14. Places of microhardness measurements in the test pieces. A red “x” signifies the place of testing whereas numbers signify the direction of successive measurements

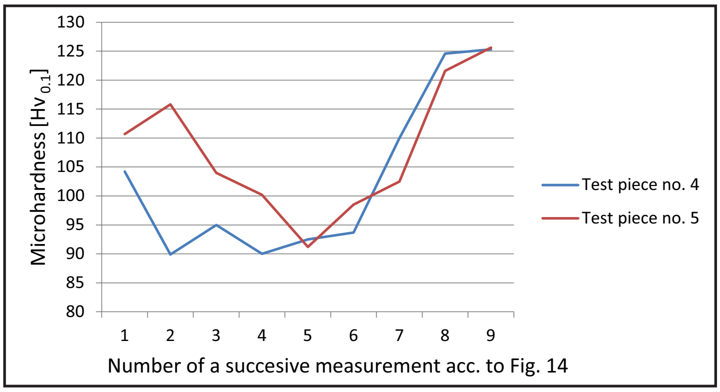

Fig. 15. Microhardness measurement results for test pieces nos. 4 and 5. Surface alloying parameters: the laser beam power of 2000 W, the powder feeding rate of 0.5 g/min, the surface alloying rate of: test piece no. 4 – 0.25 m/min; test piece no. 5 – 0.20 m/min

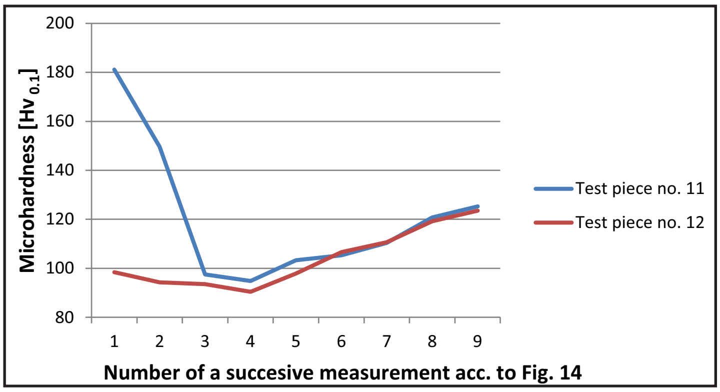

Fig. 16. Microhardness measurement results for test pieces nos. 11 and 12, for the powder feeding rate of 0.15 g/min and the surface alloying rate of 0.15 m/min on the microhardness of the matrix of surface alloyed runs: test piece no. 11 - 1500 W; test piece no. 12 - 1200 W

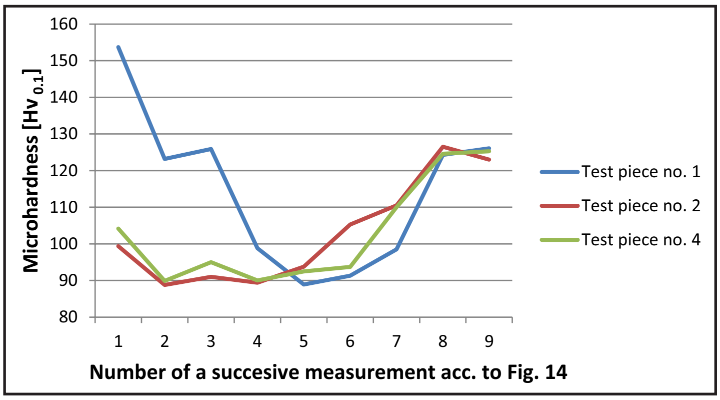

Fig. 17. Microhardness measurement results for test pieces nos. 1, 2 and 4. Surface alloying parameters: the laser beam power of 2000 W, the surface alloying rate of 0.25 m/min, the powder feeding rate of test piece no. 1 – 1.5 g/min; test piece no. 2 - 1 g/min; test piece no. 4 – 0.5 g/min

Analysis of test results

The macroscopic tests of surface alloyed runs revealed that in test pieces nos. 1, 3, 6, 8, 11 and 13 a layer containing a significant number of SiC particles was formed. However, such layer fails to form a metallurgical joint on the whole width of the run with the base.

The laser beam power of 2000 W, the surface alloying rate of 0.25 m/min and the powder feeding rate of 1.0 g/min ensured the greatest number of SiC particles in the penetration area (Fig. 5.). The tests revealed that too high or too low powder feeding rates result in the formation of surface alloyed runs representing worse quality. The powder feeding rate of 1.5 g/min resulted in the formation of a layer containing a significant content of SiC particles, yet without the metallurgical joint of this layer on the whole width of the run with the base metal. In turn, the powder feeding rate of 0.5 g/min led to the formation of an MMC layer characterised by a very low content of SiC particles. The addition of an ActivaTec 500 activating flux significantly increased the depth and width of penetration, on the average by 27% but failed to ensure the proper wettability of SiC particles (Fig. 6), which resulted in the formation of a layer lacking a metallurgical joint on the whole width of a run. The surface alloyed runs made without the activating flux were characterised by the greatest content of SiC particles.

The highest matrix hardness was measured in the layers lacking a metallurgical joint on the whole width of a run. The average hardness in these layers was 174 $HV_{0,1}$. The microhardness increase can probably be ascribed to the formation of Al_4C_3 and Al_4SiC_4 phases visible in the microscopic photograph as acicular formations (Fig. 13). A lower surface alloying rate (Fig. 15), tantamount to a greater linear energy, resulted in the microhardness increase in the matrix. The highest matrix hardness was measured in test piece no. 10 (135 $HV_{0,1}$), which had a proper metallurgical joint. This indicates the dissolving of SiC particles in the matrix. The greatest content of SiC particles (17.19%) was observed in test piece no. 5. The surface alloying parameters for test piece no. 5 proved the best result of the tests conducted and were the following:
- laser power of 2000 W,
- surface alloying rate of 0.20 m/min,
- powder feeding rate of 0.5 g/min,
- lack of an ActivaTec 500 activating flux.

The above parameters led to the formation of a composite layer, which was a desirable result of the tests. The microhardness of test piece no. 5 did not increase, which indicated that SiC particles had not undergone excessive dissolving in the matrix.

Concluding remarks

The tests of a HPDDL surface alloying on an AlSiCu4MgMn aluminium alloy with SiC powder revealed as follows:
- ActivaTec 500 activating flux addition increases the depth and width of penetration by about 27% on average,
- activating flux addition caused the formation of layers having a significant content of SiC particles, yet lacking a metallurgical joint on the whole width of runs,
- matrix microhardness in the layers lacking metallurgical joint on the whole cross-section of a joint increased on the average by 40%. In most cases, in the test pieces with a proper metallurgical joint the microhardness of matrix did not increase, yet it contained numerous SiC particles in its volume.
- parameters used for test piece no. 5 proved the most efficient. The amount of SiC particles measured on the area tested amounted to 17.19%, which indicates the formation of a composite layer and the lack of the excessive dissolving of SiC particles in the matrix of the alloy tested.

References

1. Uzun H.: Friction stir welding of SiC particulate reinforced AA2124 aluminium alloy matrix composite. Materials and Design, 2007, No. 28, pp. 1440-1446.
2. Chidambaram A., Bhole SD.: Metallographic preparation of aluminum–alumina metal matrix composites. Mater Charact, 1997, No. 38 (March), pp. 187–91.
3. Klimpel A., Janicki D., Lisiecki A., Wilk Z.: Laser welding technologies. Examples of application of high power diode lasers. Biuletyn Instytutu Spawalnictwa, 2008, No. 5, pp. 35-45.
4. Burakowski T., Wierzchoń T.: Inżynieria powierzchni metali. Wydawnictwo Naukowo-Techniczne, Warszawa, 1995.
5. Radziszewska A., Kusiński J., Kąc S.: Laserowe stopowanie stali niskowęglowej węglikiem krzemu. HUTNIK – Wiadomości Hutnicze, 2005, nr 4.
6. Klimpel A.: Technologie laserowe. Gliwice, 2012.
7. Klimpel A., Stano S.: Spawanie laserem diodowym cienkich blach ze stopu aluminium z zastosowaniem substancji zwiększających głębokość przetopienia. Przegląd Spawalnictwa, 2002, No. 8-10.
8. Company materials provided by 3Dcax.