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Fretting wear resistance of aluminum alloy specimens manufactured by laser microcladding

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Abstract – This paper reports the results of studies of the fretting wear resistance of specimens manufactured by laser microcladding. The initial materials were powders of Al-Si hypereutectic alloy which contained: (70–74)wt.% Al (26–30)wt.% Si. %. The influence of the laser microcladding parameters on hardness and fretting wear resistance of the cladded materials was investigated. It was found that hardness and wear resistance of the cladded material increased with the decrease of powder mass flow.

Key words: Laser microcladding / aluminum alloy / Al-Si system alloy / fretting wear

1 Introduction

The three-dimensional forming by laser microcladding is a relatively new trend in additive manufacturing [1–4]. This method is based on enhancing capabilities of coaxial laser cladding towards miniaturization of sizes of the grown element. In coaxial laser cladding, the product is grown by melting the powder material and the underlying layer by laser beam and simultaneously feeding the powder, the shielding gas, and supplying radiation into the treatment zone. In laser microcladding, the miniaturization of sizes of the grown element is achieved by series of action consisting of choosing the corresponding technological equipment and treatment conditions. Such technology makes it possible to create small-sized products of complex shape on the basis of three-dimensional computer models in a single process cycle [5]. The use of laser microcladding method may reduce the time of manufacturing and the prime costs of small-sized workpieces of complex shape during single-piece and small-batch production due to reduction of process stages and absence of the special tools creation phase. A wide range of powder materials and flexibility of laser treatment make is possible to synthesize new materials and coatings [6–9].

The laser microcladding of light aluminum alloys, the laser treatment of which is well studied and introduced into production because of exceptional improvement of physical and mechanical properties of these alloys under a high cooling rate, is of a great interest. Miniaturization of the exposure zone is expected to enhance this effect [10]. Small-sized products of complex shape, manufactured by laser microcladding method from powder material on the base of aluminum alloy, may become widely used in aerospace, power, and precision machinery industry. It is necessary to study the physical and mechanical properties of workpieces produced by laser microcladding method, for obtaining guaranteed properties of material, which is a crucial task in modern machine engineering industry.

The paper presents the studies of fretting wear resistance of Al-Si system alloys produced by laser microcladding [11]. The fretting wear is a mechanical wear of bodies contacting under conditions of slight tangential relative displacements. The displacement amplitudes during fretting are 0.025 μm–0.05 mm. Fretting causes damages in rivet, thread, spline, key, pin connections; force-fitted parts.

The objective of this work is to study fretting wear resistance of aluminum alloy specimens manufactured by laser microcladding.

2 Methodology

Al-Si system hypereutectic alloy powder was chosen as the initial material to manufacture test specimens and pieces. It was produced by gas atomization and had the following composition: (70–74)wt.% Al (26–30)wt.% Si. %. The specimens were manufactured using preferential laser microcladding parameters sets (further – set) presented at the Table 1 at a laser microcladding unit the configuration of which was chosen according to the specified recommendations [3] and included: TruDISK

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Table 1. Laser microcladding parameters of AlSi30 alloy for manufacturing of small-sized workpieces.

Laser microcladding parameters sets	Powder feed rate, g/min	Radiation power, *W*	Scanning speed, m/min	Vertical increment Δz, μm	Other parameters
Set 1	0.6	110	12	30	$F_{Z.G.} = 5$ l/min;
Set 2	0.15	110	12	8	$F_{N.G} = 10$ l/min;
				nozzle edge offset to the workplane $a_D = 8$ mm	

1000 continuous-wave disk Yb:YAG-laser with a wavelength of 1.03 μm (the actual diameter of radiation focusing: 62 μm): "10-Twin-systems" powder feeder; "COAX-powerline" coaxial nozzle; Hermle C800U machining center acting as positioning system.

The test specimens produced by laser microcladding were subjected to subsequent heat treatment: two hours in the air at a temperature of 300 °C.

The density of specimens was determined as a ratio of specimen weight to the occupied volume. The weight of specimens was determined using MS403S Precision Balance (USA) precision laboratory balance with scale division of 0.0001 g. The sections for metallographic studies were prepared using standard techniques. The microstructure of the specimens was studied using *Olympus GX51* optical microscope (*Olympus Corporation*, Japan) with maximum magnification of 500×. The microhardness of specimens material was measured using HP Mikromat instrument (*Hegewald&Peschke*, Germany) under loads of 0,5; 0,3; 0,25 N. The loading time was 10 s.

The surface roughness was determined using *HOMMEL TESTER T800* (*Hommelwerke GmbH*, Germany) and *Perthometer M1* (*Mahr GmbH*, Germany) profilographs-profilometers at the baseline lengths of 1.75 mm, 5.6 mm and 17.5 mm.

The fretting wear study experiments were conducted at Tribology Laboratory of Khmelnytskyi National University under supervision of Prof. Yu. I. Shalapko. The tribological properties of material under fretting conditions were studied at a test bench, the general view and layout of which are presented in Figure 1.

The contact operation in a low-mobile plane-sphere scheme connection, where a sphere was a steel ball (HRC 59... 61), and the plane was the studied specimen, was simulated during the test. The specimen fixed in a holder 1 moves along guides 3 in a carriage 2. The reciprocating movement of the carriage 2 is ensured by electromagnet 4 and a spring system 5. The guides 3 are connected with a spigot 7 by plates 6, and the spigot is connected with a shaft 9 by radial thrust bearings 8 taking axial and transverse loads. The shaft 9 is secured on a bed plate 11 by columns 10. The normal forces are created by plummet 12 located on the guides 3 directly above the contact zone. The counter-body secured in a holder 13 is located on a tensobeam 14 installed on the bed plate 15.

The normal load in the contact F_N is created by a lever mechanism formed by the counter-body drive unit and the support of the structure, and was 20 N during all experiments. In all experiments, the tangential displacements amplitude was set at level $\delta = 50$ μm with frequency $f = 100$ Hz.

The method of continuous monitoring of the state of the contact zone was used to study operation of a low-mobile connection [12,13]. Moreover, instantaneous values of friction force in the contact and values of relative displacements of the rubbing bodies were determined, on the basis of which the fretting process hysteresis loops were developed (Ffr – δ). By processing the frictional hysteresis loops, the values of one of key characteristics of the fretting process were obtained, i.e. the apertures ratio criteria Z, according to:

$$Z = \delta_S/\delta \tag{1}$$

where δ_S and δ is the amplitude of reciprocal displacement and the exciting amplitude respectively, μm.

The resultant values of Z-criteria were used to identify a rubbing bodies interaction mechanism and determine association between dynamical characteristics of the contact and destruction of the low-mobile connection. When $Z \to 0$, there are no reciprocal displacements of contacting bodies, and the low-mobile connection is in a no-slip state. The destructive processes arising during operation of the connection cause the occurrence of relative displacements of the rubbing bodies, due to which the contact goes into a partial slipping mode, a combined mode, and then into a full-blown slipping mode. In a full-blown slipping mode, the development of fatigue cracks is not observed, but the wearing out occurs due to a heavy abrasive wear due to wear products being formed during plastic deformation of the material and the peeling thereof as a result of cleavage bridges and oxidation. According to [14], the value of apertures ratio criteria $Z = 0.26$ corresponds to transition from a partial slipping mode to a full-blown slipping mode.

The values of volume losses of the specimen under known number of loading cycles were used as fretting wear resistance criterion.

3 Results and discussion

The influence of laser microcladding parameters and the subsequent heat treatment on the structure of test specimens has been studied (Fig. 2, Tab. 2).

The structure of AlSi30 alloy produced by laser microcladding under low-energy condition (set 1), is represented by colonies of quasi-eutectic mixture of supersaturated α-solid solution of Al(Si) and Si, peripherally to which the Si (Sip) primary crystals, surrounded by a band of α-phase, are located. The structure of specimen material produced under high-energy condition (set 2) has a higher homogeneity, a smaller size of structure components and an increased solubility of Si in the Al-lattice.

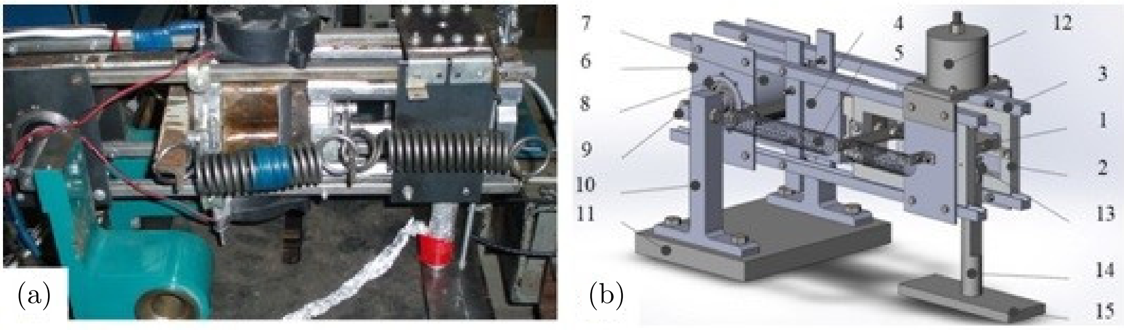

Fig. 1. General view (a) and a layout of the unit (b) for studying the fretting wear.

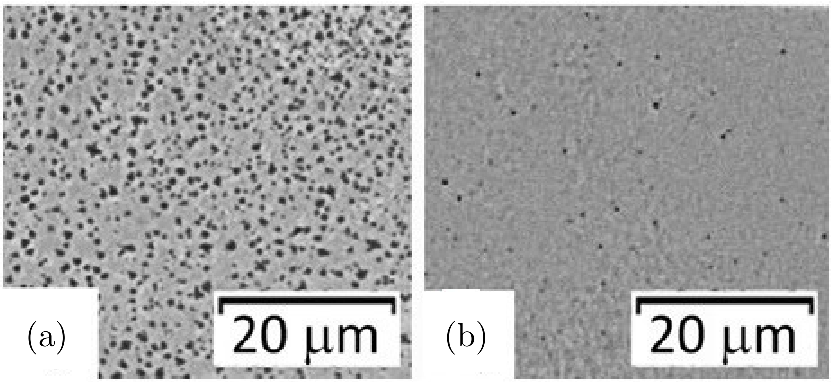

Fig. 2. Microstructure of AlSi30 alloy specimens produced under different laser microcladding sets: (a) low set 1, (b) set 2.

The described structural changes are consistent with the results of electric conductivity measurements, which increases with transition from low - to high-energy condition of laser microcladding from 11.1 ± 0.1 to 12.3 ± 0.2 mS.m^{-1}, and ensure the increase in hardness from 240 to 300 HV$_{0,05}$. Table 2 shows that the 2-hours long in-air annealing to a maximum temperature of 300 °C is accompanied by a partial dissolution of supersaturated α-solid solution and a uniform fallout of disperse silicon phase, which ensures the preservation of material hardness of at least 290 HV$_{0,05}$ for the specimen produced under parameters set 2.

The influence of laser microcladding parameters on the tested specimen surface roughness has been studied: the transition from low-energy condition (set 1) to high-energy condition (set 2) is accompanied by a decrease in surface roughness Ra 4.5 ± 0.5 μm to Ra 1.6 ± 0.2 μm.

The study of the low-mobile friction connection destruction kinetics for AlSi30 alloy produced by laser microcladding method demonstrates the influence of laser microcladding parameters on the behavior of destructive processes in the contact (Fig. 3).

The criterion of apertures ratio of material of the specimens produced under low-energy condition (set 1) increases starting from the first loading cycles. Upon reaching the value of 0.75, the criterion stops increasing and remains constant for 5 040 000 loading cycles. Further on, it begins to increase, but it increases slowly and reaches the value of 1 at 9 720 000 loading cycles. The destruction kinetics of the low-mobile connection for specimens produced under high-energy condition (set 2) are different: the apertures ratio criterion remains unchanged during the first 11 160 000 loading cycles and amounts to $Z \approx 0.7$. Upon further loading of the connection, a certain decrease in the apertures ratio criteria is observed.

The obtained data allow us to conclude that the friction of specimens of AlSi30 alloy produced under preferential laser microcladding parameters set is accompanied by a full-blown relative slipping and the absence of zones of elastic interaction, which makes it possible to eliminate the possibility of fatigue fracture of the rubbing bodies. This is consistent with the results of analysis of worn surfaces of the studied specimens (Fig. 4): the damage spots of AlSi30 alloy specimens produced by laser microcladding are characteristic for abrasive wear. Also, in case with the specimen produced under low-energy condition (set 1), we could say that the wear of the counter-body was heavier compared to the AlSi30 alloy specimen produced under parameters set 2. The analysis of worn surfaces of AlMgSi0.5 aluminum alloy specimen do not allow us to eliminate the possibility of fatigue cracks formation despite the high values of the apertures ratio criterion which increases from the beginning of loading and reaches the value of 1 as soon as at 1 440 000 loading cycles. The look of the worn surface of this group of specimens is characteristic for partial slipping.

It was shown that the volume specific fretting wear decrease with transition from laser microcladding parameters set 1 to set 2 by a factor of 1.4 and amounts to 2.9×10^{-4} μm^3/loading cycle, which is by more than an

Table 2. The results of the study of the structure and electric conductivity of AlSi30 alloy under different laser microcladding parameters sets.

	Results of X-ray diffraction and quantitative phase analysis				
	Phase content ±0.25%		Interplanar distance, ±0.00005 nm		Electrical conductivity, MS/m
	α-Al	Si	α-Al	Si	
Set 1	75.70	24.30	0.40470	0.54378	11.1 ± 0.1
Set 2	76.55	23.45	0.40386	0.54259	12.3 ± 0.4
Set 2 + annealing	76.20	23.80	0.40490	0.54257	15.2 ± 0.4

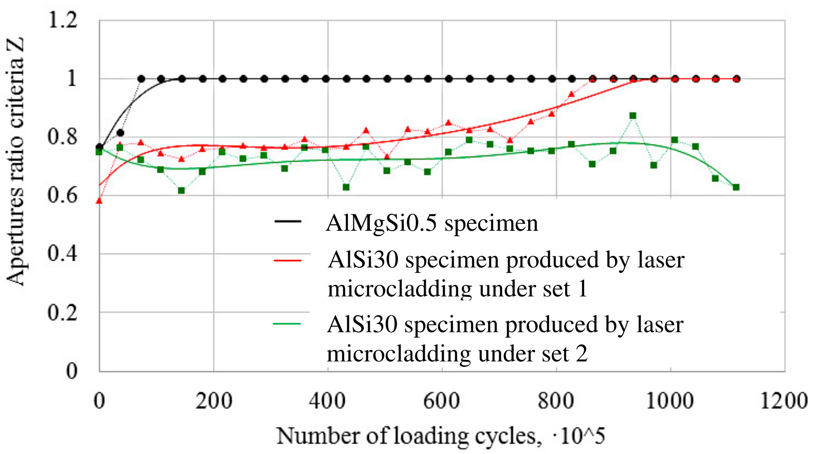

Fig. 3. Apertures ratio criteria values for AlSi30 alloy specimens produced under different laser microcladding parameters, and the AlMgSi0.5 alloy specimen (normal load: 20 N; displacements amplitude: 50 μm; frequency: 100 Hz): the dash line corresponds to values obtained experimentally, and the solid line is the trend line.

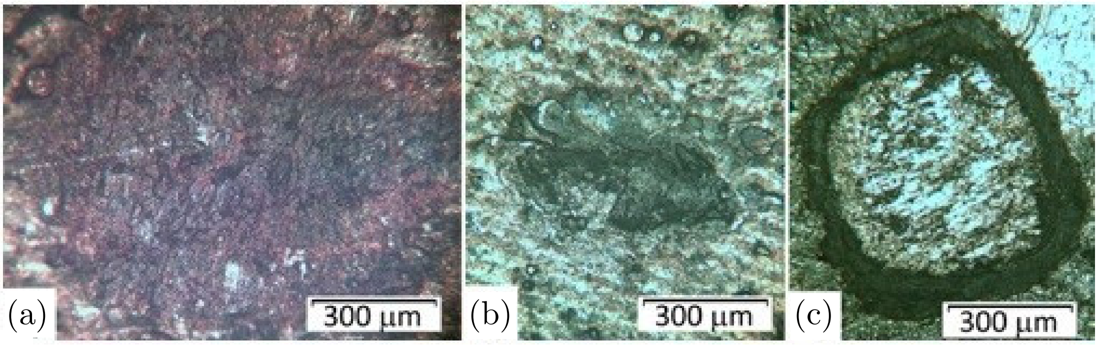

Fig. 4. Images of worn surfaces of the studied specimens: (a) AlSi30 alloy specimen produced by laser microcladding under set 1 (8 640 000 loading cycles); (b) AlSi30 alloy specimen produced by laser microcladding under set 2 (11 160 000 loading cycles); (c) AlMgSi0.5 alloy specimen (360 000 loading cycles).

order lower than the values of volume specific wear for AlMgSi0.5 alloy specimens. The influence of laser microcladding parameters on the wear resistance of AlSi30 alloy specimens is associated with the change of the alloy structure and the accompanying change of physical and mechanical properties of the material: the reduced size of the structural components and the formation of supersaturated α-solid solution lead to an increase in microhardness in case of transition from low-energy condition (set 1) to high-energy condition (set 2), from 240 to 300 $HV_{0,05}$. The structure becomes more uniform and homogeneous. The solid, extremely disperse Al-Si-matrix of Al-Si alloy, produced by laser microcladding under high-energy condition (set 2), holds the hardening particles of Si_P, preventing the erosion of the material and the degradation of the surface.

4 Conclusion

The influence of laser microcladding parameters on AlSi30 alloy structure has been determined. It was shown that the transition from low-energy condition (set 1) to high-energy condition (set 2) of laser microcladding results in a decrease of sizes of structural components, an increase of solubility of silicon in aluminum lattice, and formation of structure comprising uniformly distributed fine primary crystals of silicon, and quasi-eutectic mixture of fine supersaturated α-solid solution Al(Si) and Si particles, which ensures the increase in microhardness of AlSi30 alloy from 240 ± 40 $HV_{0,05}$ to 300 ± 20 $HV_{0,05}$.

The study of fretting wear resistance of AlSi30 alloy specimens produced by laser microcladding shows the influence of laser microcladding parameters on the behavior of destructive processes in the contact of the low-mobile friction connection with a steel counter-body: that the friction of specimens of AlSi30 alloy produced under preferential laser microcladding parameters set is accompanied by a full-blown relative slipping and the absence of zones of elastic interaction, which makes it possible to eliminate any fatigue fracture of the rubbing bodies. The volume specific fretting wear decreases with transition from low-energy laser microcladding condition (set 1) to high-energy condition (set 2) by 1.4 times and amounts to 2.9×10^{-4} μm^3/cycles, which is by more than an order lower than the values of volume specific wear for AlMgSi0.5 alloy specimens. As to the specimen produced under low-energy condition (set 1), we may say that the wear of the counter-body was heavier compared to the AlSi30 alloy specimen produced under high-energy condition (set 2).

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