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Experimental studies of the possibility of laser processing as a cleaner method of achieving a surface with good adhesion

Barbara Ciecińska[1,*]

[1] Rzeszow University of Technology, al. Powstańców Warszawy 12, 35-959 Rzeszów, Poland
*Correspondence: barbara.ciecinska@prz.edu.pl, Tel.: +48 17 865 14 48

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Abstract

In manufacturing processes many technological operations are designed, in which the adhesive properties of the treated surface are very important. These are processes related to application of any coating on the surface, such as gluing, painting, varnishing and others. Durability of coatings depends on proper preparation of the surface to which they are going to be applied. Conventional methods, such as grinding, sandblasting with subsequent washing and degreasing, as well as galvanic treatment applied to e.g. aluminium alloys - require the use of not only specific equipment but also chemical substances. They often lead to a significant burden on the environment due to their harmful properties. In an experimental study, attention was drawn to the significant environmental aspects of such a technological process and work was carried out to demonstrate whether it is possible to eliminate toxic and hazardous substances and to create good adhesion conditions by laser processing. To this purpose, samples were made out of two representative materials: X6Cr17 steel and AW-2024 aluminium alloy, abrasive surface treatment or in a galvanic bath and then washed, degreased and dried. Laser surface treatment without the use of additional chemicals was proposed as an environmentally cleaner technology. Surface roughness and adhesion of the test polymer coating were measured for comparative evaluation of the applied treatment methods. Obtained results were discussed in terms of the possibility of eliminating harmful influences and implementing laser treatment as a cleaner technology in the production of components requiring coating.

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1. Introduction

The need to respect the environment, the necessity for sustainable development, as well as the respect for natural resources and attention to the quality of human life, have been presented in various documents around the world (Ciecińska, 2021).

Numerous studies (Berkel et al., 1997; Hens et al., 2018) have pointed out that many machining processes use toxic substances, negatively affecting the health of workers, but also causing environmental hazards due to residues, which are treated as waste. Used or contaminated fluids and their packaging are the so-called hazardous waste.

Many processes also emit metallic dusts or vapours into the air, polluting it and accelerating the appearance of occupational diseases. The enterprises must respond to disruptive and harmful processes. The incentive to implement changes is the Cleaner Philosophy and its link to the concept of the sustainable development. Cleaner Production (CP) is preventive environmental strategy for its protection, integration and continuous improvement of processes. The CP is aimed at increasing the efficiency of production and services and reducing the risk for people and the environment. It is represented not only by the declaration of reduction of negative impact on the environment, but, above all, by the active management of processes in which less and less water, energy and materials are used, toxic substances are eliminated and waste is reduced (Jabareen, 2008; Parris et al., 2003). CP is based on the principle of waste prevention by planning cost-effective packaging, rational process design and the use of clean technologies. Elimination of waste can be achieved in various ways, through: changes of construction and materials in the product, balancing and control of processes by the input-output method, implementation of good production practices, but first of all by changing the technology, i.e. the substances, machines, measuring methods used, as long as it shows environmentally burdensome features. Only then, through the CP ideas implemented, the postulate of sustainable development becomes a reality (Chichilnisky, 1997; Nowosielski et al., 2007).

The technology of gluing materials is extremely cumbersome in the context presented. In order to properly join elements using an adhesive, it is necessary to create the appropriate conditions of adhesion. This takes place most intensively in the initial stage of bonding, which is the preparation of the surface before the application of the adhesive layer and the curing of the bond. Depending on the type of material, the procedure varies. In general, it can be said that for the so-called inherent adhesion, which is responsible for formation of chemical bonds, surfaces are cleaned of any remaining dirt, grease and fat. In the case of steel components, sandblasting, rubbing with sandpaper to remove physical layers by mechanical treatment, is typical. For degreasing, acetone, naphtha, TRI, etc. are used to wash the surface. In the case of aluminium alloys, galvanic baths requiring the preparation of various solutions from acids and salts are used more frequently and surfaces are rinsed with demineralised water after immersion in subsequent solutions (Ciecińska, 2021; Langer et al., 2012).

The second aspect of creating the right adhesion conditions is the geometric structure of the surface. The so-called mechanical adhesion refers to a rough surface on which there are depressions and bumps, creating specific hooks for the adhesive, improving the strength of the adhesive bond (Radek et al., 2021). The abrasive treatment mentioned for steel also serves to create a surface with a certain roughness and structure in the case of aluminium alloys the purpose of galvanic baths is to create a layer of oxides, porous and strongly bonded to the core layer of the material (Çoban et al., 2019).

However, typical technologies give rise to significant environmental aspects:

- atmospheric pollution by metallic and ceramic dust from abrasive machining,
- emission of toxic vapours from galvanic baths, washing in special liquids, etc,
- solid waste loads in form of used abrasive tools,
- load with liquid waste in form of contaminated chemical solutions for degreasing, washing, after chemical treatment,
- solid waste load in form of residual packaging from used chemical preparations.

The effect of these aspects is degradation of the environment and the negative impact on human health.

An important problem is the issue of minimizing or eliminating the burdensome and harmful technology (Zhu et al., 2019). For this reason it was proposed to change the surface preparation from conventional to laser processing (Montealegre et al., 2010; Ulewicz et al., 2018). This paper presents the results of an experimental study using a readily available and not too expensive low-power fibre laser. It has been estimated that the results of the laser beam may be comparable, or even better, than the methods typically used (Genna et al., 2017; Rotel et al., 2000). An additional reason for choosing laser processing is the intensive development of laser equipment observed in recent years, its greater availability, but, above all, its undoubted advantages (Capello et al., 2003; Landete-Ruiz et al., 2015; Mandolfino et al., 2015; Muna, 2018).

2. Experimental work

2.1. Materials

Two materials, used in a wide range of applications, on which it is useful to apply coatings for various reasons, were selected for the experimental study:

- stainless steel X6Cr17 (1.4016)
- aluminium alloy AW-2024

X6Cr17 steel, with the chemical composition shown in Table 1, is a chromium ferritic stainless steel resistant to many common corrosive agents. The steel is resistant to water, steam, alcohols, nitric acid, acetone, benzene, esters, adhesives, fuel and many other substances. It is not resistant to hydrochloric, hydrofluoric and sulphuric acids. The X6Cr17 steel is not suitable for welding.

Table 1. Chemical composition of steel X6Cr17 (in %) (PN-EN 10088-1)

C	Mn	Si	P	S	Cr	Ni
<0.08	<1.0	<1.0	<0.04	<0.015	16.0-18.0	-

It is used in the production of tanks, cisterns, fittings in the food, textile and automotive industries, pipeline components, as well as household goods. It is characterised by a very smooth, mirror-like surface and a hardness of approximately 200 HB.

Aluminium alloy AW-2024 is an alloy with added copper having the chemical composition shown in Table 2.

Table 2. Chemical composition of the alloy AW-2024 (in %) (PN-EN 573-3)

Mg	Mn	Fe	Si	Cu
1.20-1.80	0.30-0.90	≤0.50	≤0.50	3.80-4.90
Zn	Cr	Ti	other	Al
≤0.25	≤0.10	≤0.15	≤0.15	remainder

The AW-2024 alloy is weldable only by friction welding and has an average machinability. It is used for light products with high strength, especially fatigue strength, e.g. in aircraft production. Surface of this alloy is very smooth and matt. Hardness of the alloy is about 120 HB.

2.2. Experiment concept

In both cases, an 1 mm thick rolled sheet was used to carry out the experimental work. Samples were cut from it in the dimensions necessary for the measurements to be made.

Surface treatment was carried out on steel by grinding, sandblasting and laser processing and on aluminium alloy by grinding, galvanic bath and laser processing. The samples were then washed and dried. The samples prepared in this way were subjected to measurements. Schematic diagram of the experiment is shown in Fig. 1.

Fig. 1. Conceptual plan for the experiment

2.3. Sample treatment

The grinding treatment was carried out with sandpaper of grit: P120 and P240 with a 1280 rpm grinding head with manual feed to achieve a uniformly rough surface.

Sandblasting was carried out in a cabin sandblaster with an operating pressure of 0.6 MPa with an electrocorundum grit size of 45 µm to achieve a similar effect.

The galvanic treatment of aluminium alloy - allodizing - involved immersing the material in an oxidising and then sealing bath without the application of an electric current. The composition of the acid and salt solutions is proprietary and is used in aerospace plants to coat the surface of aluminium alloys with a permanent oxide layer. Steel samples were not allodized.

The laser treatment was carried out using a G3 pulsed fibre laser with a power of 20W, wavelength λ = 1040÷1200 nm, spot size 0.03÷0.05 mm, max pulse energy < 2 mJ and pulse duration >10 ns.

After the abrasive treatment, the steel samples were washed in acetone in an ultrasonic cleaner and then dried in air at an ambient temperature of approximately 20 °C. The aluminium alloy samples were washed in a water jet and dried in a similar procedure. After the laser treatment, the samples were not washed, but cleaned with a compressed air jet to remove possible material particles.

The types of prepared samples are given in Table 3.

Table 3. Marking and making of samples

Sample ID	Treatment	Processing parameters				
		Power W	Speed mm/s	Frequency kHz	Number of repeats	Hatch mm
L1	Laser	20	1000	20	1	0.5
L2					1	0.25
L3					10	0.5
L4					10	0.25
L5					50	0.5
L6					50	0.25
Alod	Chemical	Oxidising and sealing bath				
Sand	Abrasive	Sandblasting with 45 µm electrocorundum, air pressure in nozzle 0.6 MPa				
P120		Sanding with P120 abrasive paper, speed 1280 rpm, manual feed				
P240		Sanding with P240 abrasive paper, speed 1280 rpm, manual feed				

On the surface of L1÷L6 samples, perpendicular transitions were made with 1, 10 and 50 times repetition in order to create specific mechanical adhesion conditions (Fig. 2). Parameter marked as hatch, expresses the distance between individual beam passage paths.

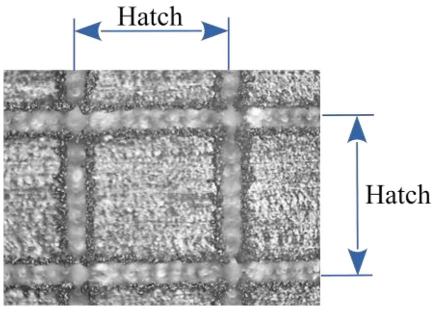


Fig.2. Laser processing

Since the steel samples were covered with a layer of oxides after the laser treatment, one cleaning pass was made with the same laser to remove them, with parameters: power 10W, speed 1000 mm/s, frequency 1000 kHz, hatch 0.1 mm.

2.4. Measurement

In order to determine the surface roughness after different types of machining, measurements were made using a Surtronic S128 contact profilometer with TalyProfile Silver 7.4 software. The measurement results were obtained in form of a surface roughness profile and the numerical values of Ra and Rt parameters expressed in µm.

The adhesion test was performed according to (EN-ISO 4624) using the PosiTest AT-T automatic tester. The dollies with a diameter of 20 mm were used, the test coating was made with Araldite 2012 two-component epoxy adhesive, at 23±2 °C and 50±5 % relative humidity. The test consisted of uniformly applying a tensile force perpendicular to the bonded surface and gradually increasing it at a rate of 1 MP/s until the punch broke.

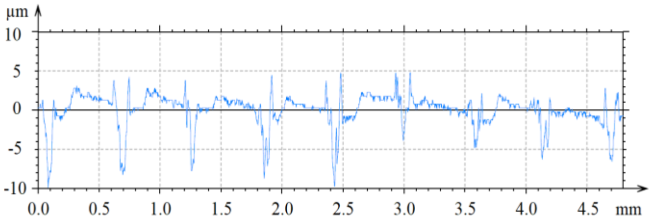
3. Results and discussion

Based on the performed surface roughness measurements, the Ra parameter was determined as the arithmetic mean of the ordinates of the profile (the arithmetic mean of the absolute values of the ordinates inside the elementary section) and the Rt parameter, as the total height of the profile (the sum of the height of the highest elevation of the profile and the greatest depth of the indentation of the profile inside the measuring section) according to (PN-EN ISO 4287). The values of Rmin, Rmax and the arithmetic mean Rme were determined. Results are given in Table 4.

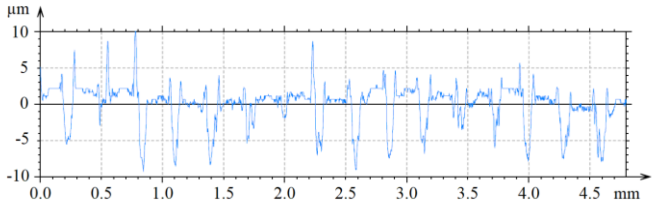
Table 4. Results of surface roughness measurements (in µm)

X6Cr17						
Sample	Ra min	Ra max	Ra me	Rt min	Rt max	Rt me
L1	0.899	1.310	1.105	7.58	7.74	7.66
L2	0.897	0.963	0.930	6.83	9.69	8.26
L3	2.28	2.36	2.320	30.40	34.00	32.20
L4	4.92	5.01	4.965	37.50	34.70	36.10
L5	9.65	10.20	9.925	53.60	55.80	54.70
L6	15.40	15.70	15.55	62.30	67.40	67.85
Sand	1.77	1.97	1.870	15.00	16.00	15.50
P120	0.754	0.797	0.776	6.02	6.65	6.34
P240	0.508	0.569	0.539	3.86	4.67	4.27
AW-2024						
Sample	Ra min	Ra max	Ra me	Rt min	Rt max	Rt me
L1	1.10	1.13	1.12	14.40	15.50	14.95
L2	1.79	1.81	1.80	17.20	19.00	18.10
L3	8.50	8.54	8.52	50.30	56.80	53.55
L4	13.00	13.30	13.15	51.00	57.80	54.40
L5	11.00	13.20	12.10	63.90	69.40	66.65
L6	16.20	17.50	16.85	70.20	84.60	77.40
Alod	0.534	0.646	0.590	4.89	5.80	5.35
Sand	1.81	2.31	2.06	14.10	16.90	15.50
P120	2.34	2.49	2.42	17.30	18.60	17.95
P240	1.02	1.37	1.20	8.06	11.00	9.53

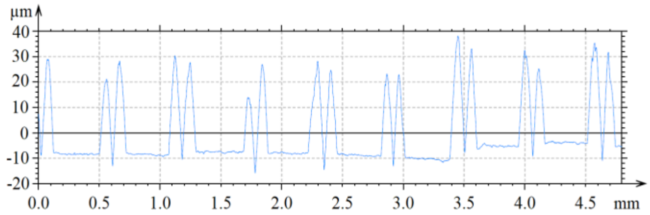
The applied processing methods allowed to obtain surfaces of different roughness and structure. Fig. 3 and 4 show the surface roughness profiles of the tested samples.



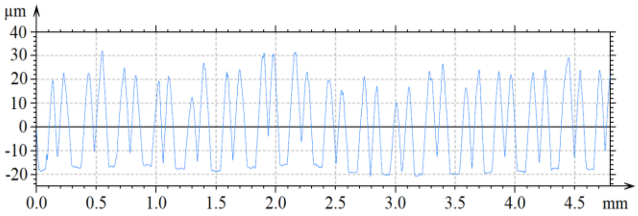
a) L1 (AW-2024, number of repeats - 1, hatch 0.5 mm)



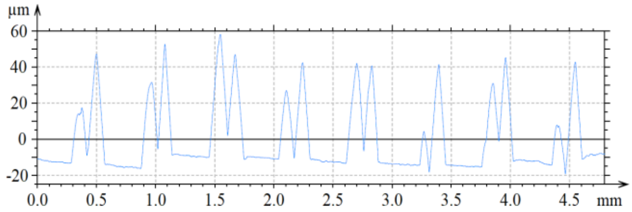
b) L2 (AW-2024, number of repeats - 1, hatch 0.25 mm)



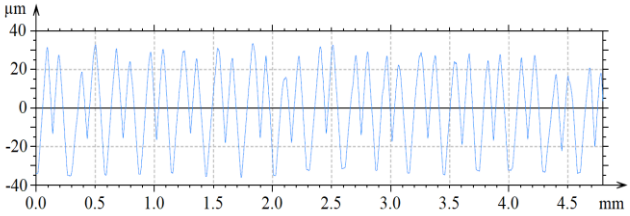
c) L3 (AW-2024, number of repeats - 10, hatch 0.5 mm)



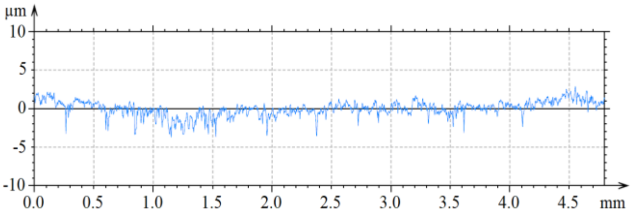
d) L4 (AW-2024, number of repeats -10, hatch 0.25 mm)



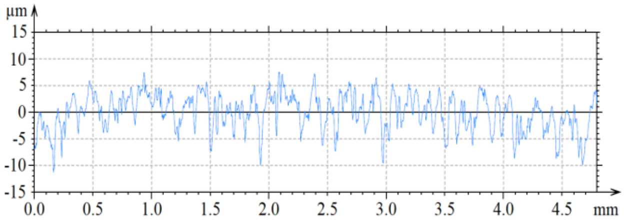
e) L5 (AW-2024, number of repeats - 50, hatch 0.5 mm)



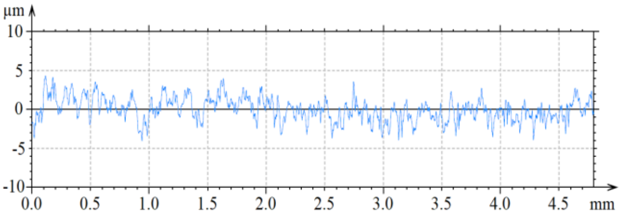
f) L6 (AW-2024, number of repeats - 50, hatch 0.25 mm)



g) allodized (AW-2024)

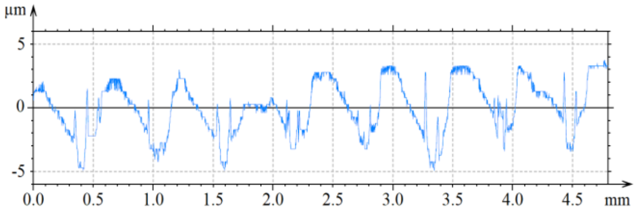


h) P120 (AW-2024)

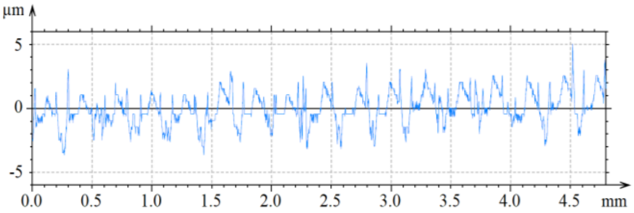


i) P240 (AW-2024)

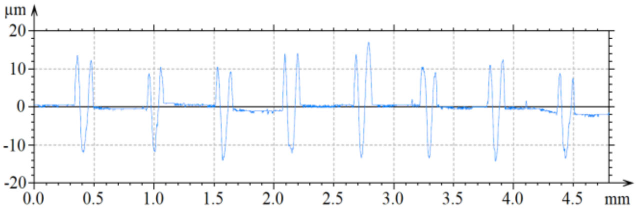
Fig. 3. Surface roughness profiles of AW-2024 samples made by the selected methods



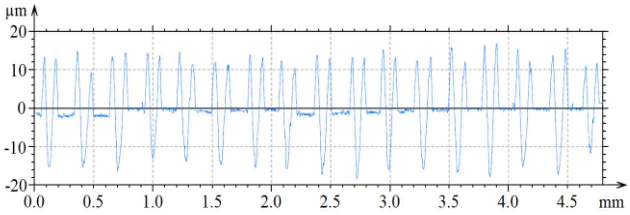
a) L1 (X6Cr17, number of repeats -1, hatch 0.5 mm)



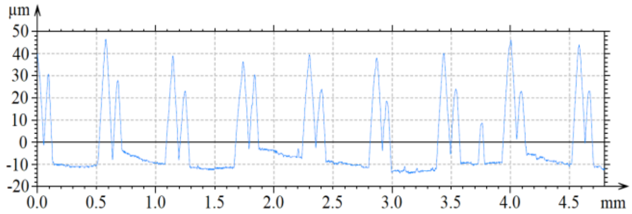
b) L2 (X6Cr17, number of repeats -1, hatch 0.25 mm)



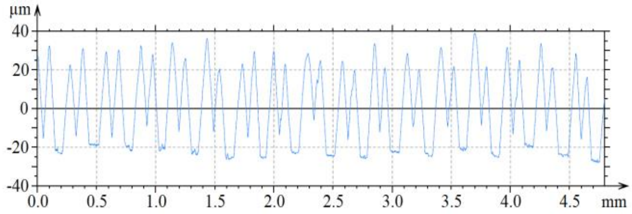
c) L3 (X6Cr17, number of repeats -10, hatch 0.5 mm)



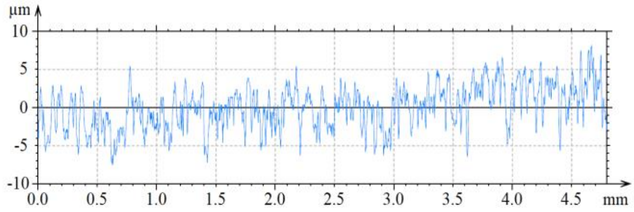
d) L4 (X6Cr17, number of repeats -10, hatch 0.25 mm)



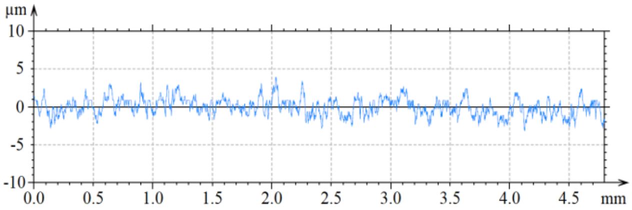
e) L5 (X6Cr17, number of repeats - 50, hatch 0.5 mm)



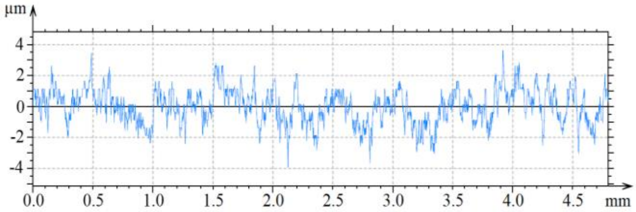
f) L6 (X6Cr17, number of repeats - 50, hatch 0.25 mm)



g) sandblasted (X6Cr17)



h) P120 (X6Cr17)



i) P240 (X6Cr17)

Fig. 4. Surface roughness profiles of X6Cr17 samples made by the selected methods

Comparison of the obtained surface roughness measurement results is shown in Fig. 5.

The test results of the adhesion of the test adhesive coating to the surfaces prepared by the selected method are given in Table 5. The peel strengths σ_{min}, σ_{max} and the arithmetic mean σ_{me}, given in MPa, were taken into account.

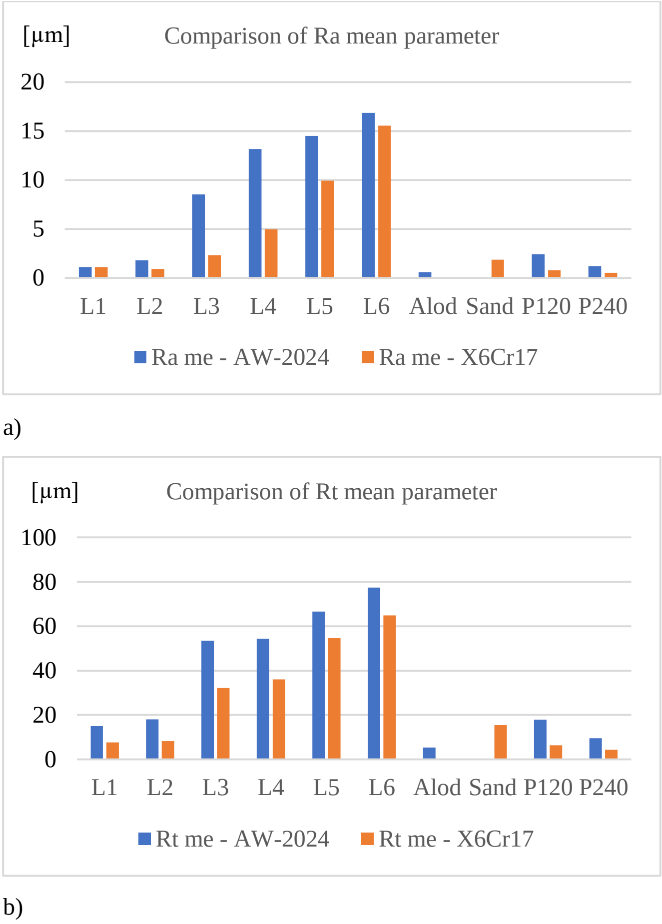


Fig. 5. Surface roughness parameters: a) Ra, b) Rt, in the tested samples

Table 5. Results of adhesion measurements on X6Cr17 steel and AW-2024 alloy samples

Sample	X6Cr17			AW-2024		
	σ_{min}	σ_{max}	σ_{me}	σ_{min}	σ_{max}	σ_{me}
L1	1.10	1.30	1.20	1.04	1.56	1.30
L2	1.24	1.63	1.44	1.74	2.39	2.07
L3	1.91	2.16	2.04	1.73	1.90	1.82
L4	2.02	2.24	2.13	2.34	2.54	2.44
L5	3.47	3.63	3.55	2.55	2.77	2.66
L6	2.28	2.39	2.34	1.86	1.92	1.89
Sand	1.83	2.65	2.24	-	-	-
Alod	-	-	-	0.38	0.72	0.55
P120	0.76	1.10	0.93	1.10	1.41	1.26
P240	0.99	2.15	1.57	0.86	0.89	0.88

Comparison of the results is shown in Fig. 6.

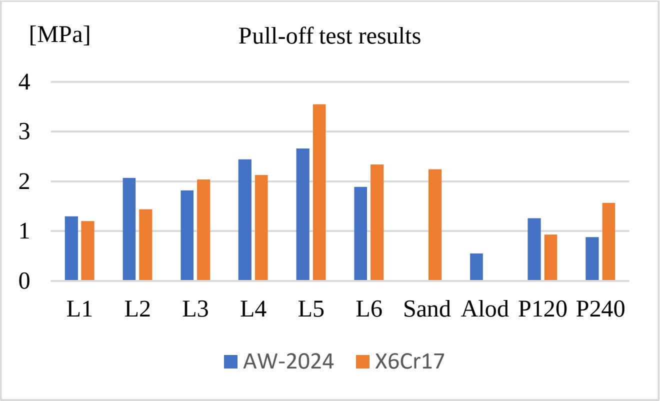


Fig. 6. Comparison of surface adhesion test results

Laser surface preparation gives various results. In the case of aluminium samples L1 and L2, a single pass of the beam makes it possible to obtain roughness comparable to abrasive treatment with P240 paper. This is Ra = 1.12; Ra = 1.80 and Ra = 1.20 µm, correspondingly.

On steel samples, a single beam pass only on sample L2 can be compared to abrasive treatment with P120 and P240 paper. This is Ra = 0.93; Ra = 0.776 and Ra = 0.539 µm correspondingly.

Increasing the number of passes to 10 in both materials resulted in a significant increase in surface roughness. For AW-2024 alloy on L3 and L4 samples, Ra was obtained in range of 8.52÷13.15 µm. For L3 and L4 steel samples, Ra was obtained in range of 2.32÷4.965 µm. This means that the effectiveness of the laser beam on X6Cr17 steel is lower. This is due to the different chemical composition and hardness of the material.

Increasing the number of beam passes to 50 causes a further increase in surface roughness: for AW-2024 on samples L5 and L6 the Ra parameter in range of 12.10÷16.85 µm (about 2x more than for 10 times repetition), for X6Cr17 in range of 9.925÷15.55 µm (this is an increase of about 3 times). Thus, the nature of the change in the Ra parameter is different for both materials.

From the point of view of mechanical adhesion, the parameter Rt may be useful, whose values also increase with an increase in the number of times the laser beam passes. In the case of aluminium samples, Rt increases by about 3÷4 times in the L3 and L4 variants and by 7÷8 times in the L5 and L6 variants. This means the formation of significant depths and heights on the surface, which may improve the adhesion.

By analysing the surface roughness profiles, it can also be concluded that after both chemical and abrasive treatments the surface is rough in different ways, but this is random. After laser treatment, when a predetermined hatch parameter is set as the distance between individual beam paths, the surface has regular depths and highs. However, the character of surface changes varies for the tested materials, due to their properties and susceptibility to the laser beam energy. By setting a technological parameter (hatch), the character of surface roughness profile can be determined.

Increasing surface roughness, however, does not increase adhesion in the same way. The pull-off test shows that there is a limit to the improvement of the adhesive properties. This feature is known from conventional bonding methods and is also confirmed in the case of laser processing. According to (Jakóbczak, 2022), a value from 2 MPa upwards is considered to be satisfactory adhesion. The obtained results show that chemical and abrasive treatments do not give positive results. The results obtained for X6Cr17 steel after the treatment with P120 and P240 paper, where the peel strength is 0.93 MPa and 1.57 MPa, respectively, are highly unsatisfactory. Only sandblasting can be considered effective for mechanical adhesion when σ_{me} = 2.24 MPa. In the case of AW-2024 alloy, the situation is worse - both abrasive and chemical treatments did not give good results. For both materials, laser treatment gives much better results. When paying attention to the surface roughness, it can be concluded that a single pass of the beam is the least effective (the least rough surface). Better results were obtained after treatment with 10 times repetition - values above 2 MPa. In the case of X6Cr17 steel, further increasing the roughness after 50 beam passes is associated with an improvement in adhesion (for specimen L5 σ_{me} = 3.55 MPa), but for AW-2024 alloy the adhesion deteriorates. Adhesion properties are also affected by the degree of mesh compaction. For both steel and AW-2024 alloy in variants L2 and L4, denser mesh (hatch = 0.25 mm) improves adhesion, but in variant L6 it worsens.

4. Summary and conclusion

Based on the results of research presented in the article, it can be concluded that the use of a commercially available low-power laser can be an effective way to prepare surfaces with good adhesion properties. Therefore, the laser processing can be recommended as a substitute for classical methods, often burdensome for the environment.

Experimental tests give knowledge of the specific application of the chosen device and it is reasonable to perform them in order to determine the correct and optimal machining parameters. From the shown example, it can be concluded that extending the machining process by increasing the number of beam passes, thus producing a surface with considerable roughness, makes no sense from the adhesion point of view.

Need for further research is also justified by the observations of the difference in the effects of a beam with the same parameters on different materials. Without the knowledge of treatment results, it is impossible or difficult to design technological processes. In general, it can be suggested that similar results should appear for materials with surface hardness and roughness similar to the properties of the materials presented in the paper.

Experimental studies allow the conclusion that laser processing can be considered as a cleaner technology for surface preparation for adhesion of chosen materials.

Acknowledgements

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激光加工作为获得具有良好粘附性表面的清洁方法的可能性的实验研究

關鍵詞
激光
表面
粗糙度
附着力
清洁技术

摘要

在制造过程中设计了许多技术操作，其中处理过的表面的粘合性能非常重要。这些是与在表面上应用任何涂层相关的过程，例如胶合、涂漆、上漆等。涂层的耐久性取决于将要应用的表面的适当准备。常规方法，例如研磨、喷砂以及随后的清洗和脱脂，以及应用于例如的电镀处理铝合金——不仅需要使用特定的设备，还需要使用化学物质。由于它们的有害特性，它们通常会给环境带来巨大的负担。在一项实验研究中，人们注意到这种技术过程的重要环境方面，并开展了工作以证明是否有可能消除有毒和有害物质并通过激光加工创造良好的粘合条件。为此，样品由两种代表性材料制成：X6Cr17 钢和 AW-2024 铝合金，经过研磨表面处理或在电镀槽中，然后清洗、脱脂和干燥。提出了不使用额外化学品的激光表面处理作为一种环境清洁技术。测量了测试聚合物涂层的表面粗糙度和附着力，用于比较评估所应用的处理方法。就消除有害影响的可能性以及在需要涂层的部件生产中将激光处理作为清洁技术实施的可能性进行了讨论