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Properties modification of Al-10Si alloy under the influence of low-energy high-current electron beam

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Abstract. In this study, we investigated the effects of low-energy high-current electron beam (LEHCEB) treatment on an Al-10Si alloy (silumin), specifically focusing on property modification and relief of the surface. The final outcome of the processing process depends on several factors, including the density of the energy applied, the duration of the processing, the energy level of electrons in the beam, the specific properties of the material, and the initial condition of the surface. Therefore, research aimed at understanding how to modify the properties of materials and surfaces is always relevant and contributes to our understanding of these phenomena. Our objective is to analyze how different irradiation parameters, such as beam energy and the number of pulses, affect crater characteristics. The novelty of this work lies in our detailed examination of crater formation, which provides deeper insights into the impact of LEHCEB on the surface morphology of Al-10Si alloy. By understanding the effects of irradiation parameters on the size and shape of craters, we can optimize the surface properties of these alloys and contribute to advancements in material engineering.
Keywords: Al-10Si alloy, electron beam treatment, silumin, surface, microhardness.

1. Introduction

In today's applications, Al-Si alloys have become prominent due to their cost-effectiveness and exceptional casting characteristics. They have elevated mechanical properties and resistance to corrosion and wear, as well as high-temperature environments. Furthermore, they have a low coefficient of thermal expansion, making them an ideal choice for various components. Al-Si alloys are widely used in products ranging from household appliances to intricate assemblies in the automotive, shipbuilding and aerospace industries. Although these alloys have many advantages, their inherent structural characteristics can lead to suboptimal strength and plasticity in some applications [1–5].

In recent years, innovative tools such as concentrated energy sources such as intense pulsed electron beams, plasma flows and laser beams have emerged as powerful tools for significantly transforming the elemental and phase composition, structure and properties of the surface layer of a material [6–9]. The exceptionally rapid heating and cooling rates in the thin surface layer allow for the formation of a uniform structure on the submicro and nanoscale, thus positively impacting the properties of the final product [10–12]. Over the past few decades, significant efforts have been made towards the study of rapid solidification, which can produce high-performance alloys with a refined microstructure and increased structural and chemical homogeneity. Rapid solidification also extends solid solubility and allows for the production of alloys that would not be possible using conventional techniques [13–14].

In this paper, we present the results of surface treatment of an Al-10Si alloy using low-energy high-current electron beams (LEHCEBs). LEHCEBs are known for their ability to generate electron beams with high power density and short pulse durations. These beams induce superfast heating and melting of the top surface of the sample, followed by rapid solidification.

2. Material and methodology

2.1. Material

The material used in this study is an Al-10Si alloy, known for its versatile properties and wide range of industrial applications. The composition of the Al-10Si alloy consists of 10% silicon and the remaining 90% is aluminum. The samples of the alloy were prepared in the form of flat specimens using waterjet cutting. After cutting into the desired shapes (see Fig. 1), the specimens were not polished. Additionally, there was only one requirement for the samples: they should fit into the working chamber of the apparatus. The specimen shape is due to the original shape of the ingot from which they were cut.

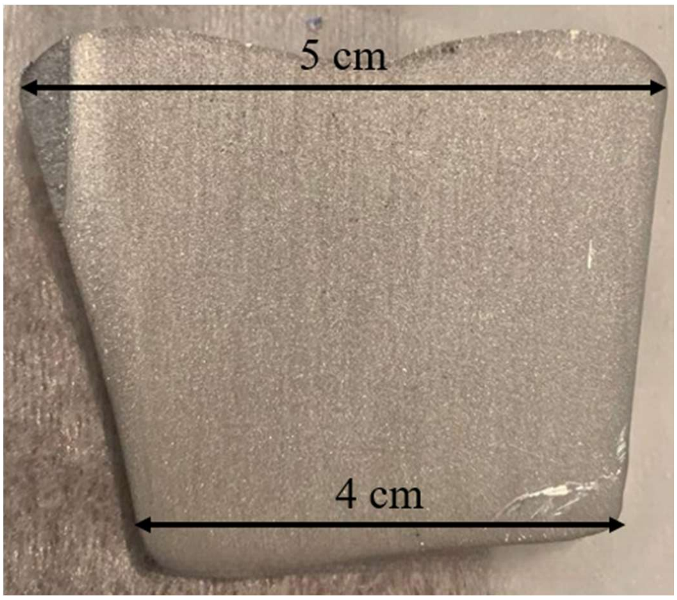

Fig.1. The shape and size of the Al-10Si samples

2.2. Methodology

The experiment was conducted using the RITM-SP setup [15], a specialized apparatus designed for electron beam surface treatment. The parameters for the electron beam irradiation are demonstrated in Table 1.

Table 1. The parameters for the electron irradiation.

	Number of pulses, №	Electron energy, keV	Pulse duration, μs
Sample 1	5	15	2÷3
Sample 2	5	20	2÷3
Sample 3	5	25	2÷3
Sample 4	5	30	2÷3
Sample 5	20	20	2÷3

After treatment, the surface roughness of the samples was measured using the Profilometer 130. The roughness parameters R_a (average roughness) and R_z (maximum height of the profile) were recorded for each sample, ensuring reliable results by measuring the surface roughness 15 times per sample. The measurement error is 3%.

The surface microhardness was evaluated using the tester FM-800 under the pressure of 100 g. The hardness values were measured at multiple points on the sample surface to ensure statistical accuracy, with 5 measurements taken per sample. The measurement error is 1.5%.

Crater dimensions, including height, diameter, and depth, were analyzed to understand the correlation between irradiation energy and surface modifications. These parameters were obtained using the microscope Olympus BX51. The acceptable range for values during the measurements is 2 μm. To ensure accuracy, the crater formation was measured 20 to 25 times for each sample.

3. Results

The average values for peak height, crater depth, and diameter were successfully identified for the Al-10Si alloy samples subjected to low-energy high-current electron beam treatment (Table 2). These parameters were found to vary significantly with the energy density of the beam, indicating a correlation between the input energy and the resulting surface modifications. Figures 2–5 also show images of the surface structure of the treated silumin samples under various irradiation conditions.

Table 2. The average crater parameters of the treated samples

	Sample 2	Sample 3	Sample 4	Sample 5
Average peak height, µm	17.73	27.22	33.53	27.53
Average crater depth, µm	14.85	19.69	39.77	35.07
Average crater diameter, µm	132	178	198.59	218.79

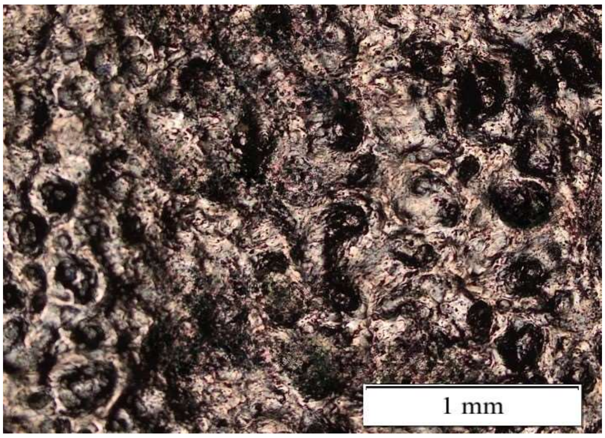

Fig.2. The surface structure of the Sample 2 (20 keV, 5 pulses) irradiated by a pulsed electron beam

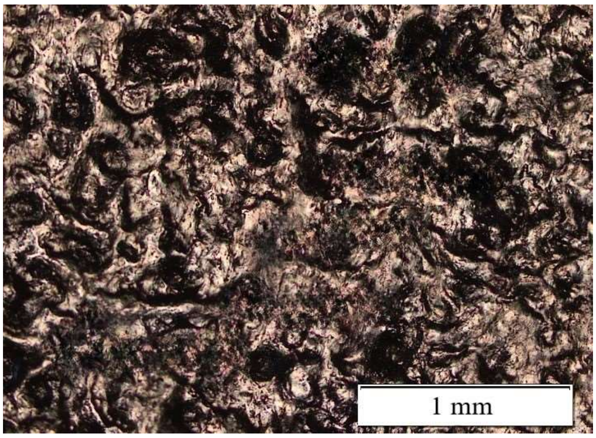

Fig.3. The surface structure of the Sample 3 (25 keV, 5 pulses) irradiated by a pulsed electron beam

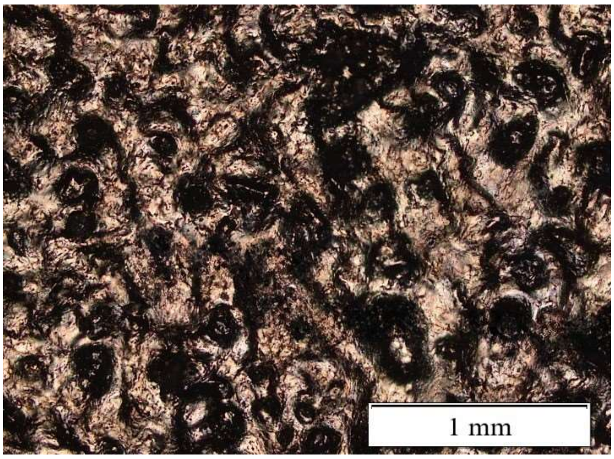

Fig.4. The surface structure of the Sample 4 (30 keV, 5 pulses) irradiated by a pulsed electron beam

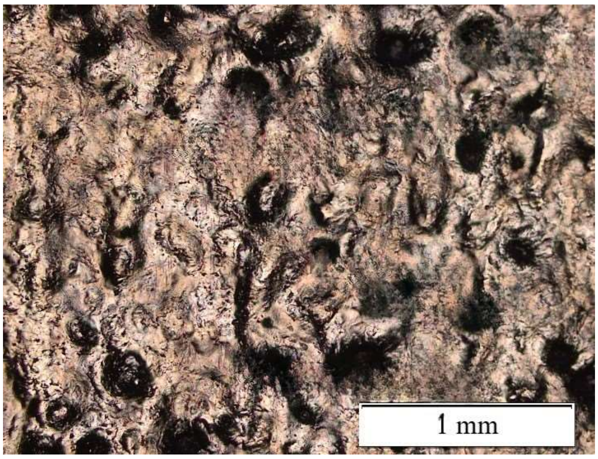

Fig.5. The surface structure of the Sample 5 (20 keV, 20 pulses) irradiated by a pulsed electron beam

The surface roughness parameters, R_a (average roughness) and R_z (maximum height of the profile), were measured for the treated samples. The results are summarized in Table 3.

The analysis of the surface roughness results indicates that the LEHCEB treatment generally increased the roughness of the samples. Sample 4 (30 keV, 5 pulses) exhibited the highest roughness values (R_a = 6.11 µm, R_z = 29.21 µm), suggesting more pronounced surface modifications. In contrast, Sample 5 (20 keV, 20 pulses) had the lowest roughness values (R_a = 4.83 µm, R_z = 23.1 µm), which could be due to specific treatment parameters resulting in less surface disruption. This variation in roughness highlights the significant influence of energy levels and the number of pulses on the surface characteristics of the treated samples.

Table 3. The surface roughness parameters for the electron irradiation.

	Number of pulses, №	Electron energy, keV	Average R_a, µm	Average R_z, µm
Untreated Sample	-	-	3.53	19.8
Sample 1	5	15	5.36	26.29
Sample 2	5	20	5.43	25.46
Sample 3	5	25	5.34	25.3
Sample 4	5	30	6.11	29.21
Sample 5	20	20	4.83	23.1

The surface temperature, when exposed to LEHCEB, exceeded the melting point of the material, leading to the formation of craters and significant surface changes.

The microhardness of the samples was measured to evaluate the impact of LEHCEB treatment on the mechanical properties of the Al-10Si alloy. The microhardness values for untreated and treated samples are shown in Table 4:

Table 4. The microhardness values for untreated and treated samples.

	Number of pulses, №	Electron energy, keV	$HV, \frac{kgf}{mm^2}$
Untreated Sample	-	-	95.67
Sample 1	5	15	144
Sample 2	5	20	167
Sample 3	5	25	148.33
Sample 4	5	30	123.33
Sample 5	20	20	101.83

The microhardness measurements demonstrate an increase in hardness in the treated samples compared to the untreated sample. Sample 2 (20 keV, 5 pulses) exhibited the highest average hardness value, indicating a significant improvement in mechanical properties due to the LEHCEB treatment. This increase in microhardness by about 1.5 times can be explained by the formation of a more refined microstructure and, potentially, the formation of additional solid phases within the alloy as a result of the electron beam processing. The hardness decreased slightly in Sample 5 (20 keV, 20 pulses), reflecting the surface's return to a state similar to the untreated material, possibly due to overexposure or changes in the beam parameters.

4. Conclusion

The study on the properties modification of Al-10Si alloy under the influence of a low-energy high-current electron beam demonstrates significant improvements in surface characteristics. The experimental irradiation of Al-10Si samples using the RITM-SP setup, with parameters ranging from 15 to 30 keV and pulse durations of 2-3 µs, resulted in a consistent decrease in surface roughness parameters R_a and R_z by 10-15%. Additionally, surface microhardness increased approximately by a factor of 1.5, indicating enhanced wear resistance and mechanical properties.

Our experiments reveal that higher beam energies generally lead to larger and more numerous craters, with a peak in crater dimensions observed at 25 keV. Notably, at 30 keV, the average peak height decreased. The results obtained are in complete agreement with the existing physical model of surface relief modification under intense energy flow conditions [16, 17]. These theoretical studies note the threshold nature of crater formation and show that the size and shape of craters are primarily determined by the irradiation conditions and the material type. The density of craters on the surface is dependent on the initial surface relief conditions.

Overall, the application of a pulsed electron beam under the specific conditions has proven effective in enhancing the surface properties of the Al-10Si alloy. These modifications potentially extend the alloy's application range by addressing its inherent limitations, thus making it more suitable for industrial uses requiring higher wear resistance and improved mechanical performance. This research highlights the potential of electron beam treatment as a viable method for the surface engineering of Al-Si alloys.

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