Improving of Surface Quality of Metal Reflector Mirrors Machined by Single Point Diamond Turning

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Abstract

Improving the technology of diamond turning of aluminum alloys is of great importance for expanding the application areas of metal-optical products based on aluminum in aerospace technology. The aim of this work was to study the effect of surface inhomogeneities of the initial aluminum alloy substrates on their optical and mechanical characteristics and to determine ways of improving the quality of aluminum reflector mirrors manufactured using nanoscale single point diamond turning.

The investigated reflector mirrors were made from AMg2 aluminum alloy. The optical surface treatment was carried out on a precision turning lathe with an air bearing spindle using a special diamond cutter with a blade radius of ≤ 0.05 µm. The analysis of the surface structure of the AMg2 alloy substrates was carried out by scanning electron microscopy/electron microprobe. The quality control of the surface treatment of the manufactured reflector mirrors was carried out by atomic force microscopy. The reflectivity and radiation resistance of these samples were also investigated.

It is shown that an important problem in the manufacture of optical elements from aluminum alloys is the inhomogeneity of the structure of the initial material, associated with the presence of intermetallic inclusions. Heat treatment of the AMg2 alloy substrates at T ≥ 380 °C makes it possible to improve the quality of surface and the radiation resistance of aluminum mirrors both by removing mechanical stresses and by partially homogenizing the starting material. The optimum is heat treatment at the maximum allowable temperature for the AMg2 alloy T = 540 ºC, as a result of which there is a complete disappearance of intermetallic inclusions with an increased magnesium content. The use of high-temperature heat treatment of AMg2 alloy substrates allows, in comparison with unannealed samples, to reduce the surface roughness from 1.5 to 0.55 nm, to increase the reflectivity of mirrors at a wavelength of 1064 nm from 0.89 to 0.92, and to increase the laser damage threshold from 3.5 to 5 J/cm^2.

Keywords: aluminum alloys, single point diamond turning, reflecting mirrors, laser damage threshold.

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Повышение качества поверхности металлических зеркал-отражателей при наноразмерной алмазной лезвийной обработке

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Совершенствование технологии алмазного точения алюминиевых сплавов имеет важное значение для расширения областей применения металлооптических изделий на основе алюминия в авиационно-космической технике. Целью настоящей работы являлось исследование влияния неоднородностей структуры поверхности исходных подложек из алюминиевого сплава на их оптические и механические характеристики и определение путей повышения качества алюминиевых зеркал-отражателей, изготавливаемых с использованием наноразмерной алмазной лезвийной обработки.

Исследованные зеркала-отражатели изготавливались из алюминиевого сплава АМг2. Оптическая обработка поверхности производилась на прецизионном токарном станке со шпинделем на воздушном подшипнике с использованием специального алмазного резца с радиусом закругления лезвия менее 0,05 мкм. Анализ структуры поверхности подложек из сплава АМг2 проводился методами растровой электронной микроскопии/электронного микрозонда. Контроль качества обработки поверхности изготовленных зеркал-отражателей осуществлялся методом атомно-силовой микроскопии. Исследовались также отражательная способность и лучевая прочность данных образцов.

Показано, что важной проблемой при изготовлении оптических элементов из алюминиевых сплавов является неоднородность структуры исходного материала, связанная с наличием интерметаллидных включений. Термообработка подложек из сплава АМг2 при $T \geq 380$ °C позволяет улучшить качество обработки поверхности и лучевую прочность алюминиевых зеркал как за счёт снятия механических напряжений, так и за счёт частичной гомогенизации исходного материала. Оптимальной является термообработка при максимально допустимой для сплава АМг2 температуре $T = 540$ ºC, в результате которой происходит полное исчезновение интерметаллидных включений с повышенным содержанием магния. Применение высокотемпературной термообработки подложек позволяет, по сравнению с неотожжёнными образцами, снизить шероховатость поверхности с 1,5 до 0,55 нм, повысить отражательную способность зеркал на длине волны 1064 нм с 0,89 до 0,92 и повысить лучевую прочность с 3,5 до 5 Дж/см^2.

Ключевые слова: алюминиевые сплавы, алмазное наноточение, зеркала-отражатели, лучевая прочность.

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Introduction

Analysis of the technical state of various industries associated with the use of modern structural composite materials, ceramics, non-ferrous metals and alloys for the manufacture of super-precision products shows that the most effective processing method is diamond turning technology, when deviations in the shape and roughness of the processed surface should be within the nanometer range (≤ 5 nm) [1−3].

At present, the technology of single point diamond turning with nanoscale roughness is widely used in the manufacture of metal-optical products, primarily, reflector mirrors for transporting powerful laser energy flows [4–6]. Strict requirements are imposed on metals in the manufacture of reflector-mirrors with high radiation resistance: minimum values of physical, chemical and induced inhomogeneities; low-level of internal stress; good polishability; high reflectivity; high thermal conductivity and minimum coefficient of linear expansion. Due to good machinability, aluminum alloys of the AMg2 and AMg6 types are often used for the manufacture of reflector mirrors [5–10]. These alloys are the preferred material for mirrors in aerospace engineering [5−7].

In the manufacture of metal-optical products, the main attention is paid to the issues of ensuring the accuracy of the shape and reducing the surface roughness [5–10]. At the same time, inhomogeneities of the surface structure and residual internal stresses inherent in aluminum alloys [6, 10] can significantly affect the optical and working characteristics of reflector mirrors, especially in the case of high-power laser radiation. However, these problems are covered to a much lesser extent [11–13].

The aim of this work was to study the effect of surface heterogeneities of the AMg2 aluminum alloy substrates on their optical and mechanical characteristics and to determine a ways to improve the quality of aluminum reflector mirrors manufactured using single point diamond turning.

Research methods

The investigated reflector mirrors were made from AMg2 aluminum alloy. The original billets were discs 100 mm in diameter and 8 mm thick. Preliminary machining of the surface was carried out with a carbide cutter. In order to remove residual mechanical stresses and homogenizing of the substrates surface they were heat treated in air in the temperature range from 200 to 540 °C. The duration of annealing was 10 h, followed by cooling in an oven. The maximum annealing temperature was limited by the melting of the AMg2 alloy. The final optical surface treatment was carried out on a precision lathe MK 6501 (Belarus) with an air bearing spindle using a special diamond cutter with a blade radius less than 0.05 µm.

The analysis of the surface condition of the initial billets from the AMg2 alloy and the billets subjected to mechanical-thermal treatment was carried out by scanning electron microscopy (SEM) / electron microprobe using a LEO 1455 VP electron microscope (Carl Zeiss, Germany) with an Aztec Energy Advanced X-Max 80 attachment. (Oxford Instruments, UK). In addition, the microhardness of the samples was measured using a PMT3 microhardness tester. The quality control of the surface treatment of the manufactured reflector mirrors was carried out by atomic force microscopy (AFM) on a Solver P47 Pro scanning microscope (NT-MDT, Russia). The reflectivity of the mirrors in the spectral range 200 ... 2500 nm was monitored on a precision spectrometer Lambda1050 (Perkin Elmer, USA). The study of the reflector mirrors laser damage threshold was carried out using pulsed radiation (λ = 1.064 µm, τ = 20 ns) of the YAG:Nd^{3+} laser model LS-2137 (Lotis-TII, Belarus). The laser pulse energy was recorded using an IMO-3 energy meter (Etalon, Russia). Sony ICX415AL CCD image sensor was used to control the spatial distribution of energy in the laser spot. The measurements were carried out in the single-pulse mode. The average energy density of laser radiation on the sample surface varied in the range from 0.5 to 15 J/cm^2.

Results and discussion

According to the data of the electron microprobe, the averaged chemical composition of the initial alloy corresponds to the AMg2 grade. However, it is characterized by the presence of intermetallic inclusions, the size of which reaches 10 microns (Figure 1, sample No. 1). The first type of inclusions (light areas in Figure 1) has the composition $Al_{4.5}FeMn_{0.2}$. The second type (dark areas) has the composition Al_3MgSi. The hardness of these inclusions differs significantly from the hardness of the aluminum matrix, which negatively affects the quality of the surface treatment. In addition, the presence of intermetallic inclusions

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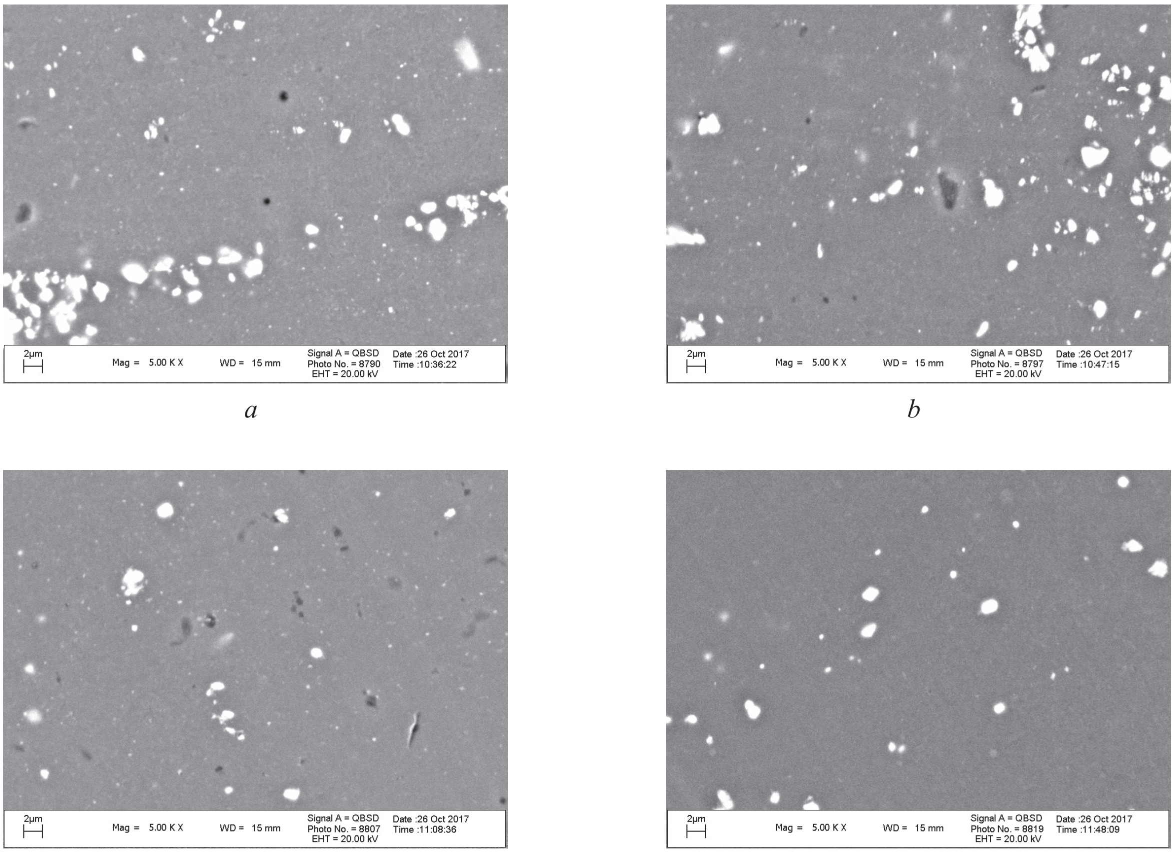
on the surface of the substrates can reduce their radiation resistance. Hence, it is necessary to carry out preliminary homogenizing annealing of the aluminum alloy billets in order to reduce the inhomogeneity of the impurities distribution. For the AMg2 alloy, the recommended homogenizing annealing temperatures are in the range of 510 ... 540 °C. In addition, in the machining of AMg2 alloy intermediate recrystallization anneals are usually used to partially or completely soften the material and increase its plasticity. Recommended temperature ranges of annealing are 150… 200 and 350… 420 °C. Based on the above, for the experiments, we have chosen the following temperatures for preliminary heat treatment of the AMg2 alloy billets: 200, 380 and 540 °C.



a *b* *c* *d*

Figure 1 – Microphotographs of the surface of the initial sample of aluminum alloy AMg2 (*a*) and samples after annealing at various temperatures: *b* – 200 ºC; *c* – 380 ºC; *d* – 540 ºC

The effect of preliminary heat treatment on the size and composition of intermetallic inclusions in the AMg2 alloy is shown in Figure 1. It can be seen that annealing at T = 200 ºC does not affect the size and composition of intermetallic inclusions (Figure 1, sample No. 2). At T = 380 ºC, a decrease the size of inclusions with an high magnesium content is observed. For inclusions with a high iron content, no changes are observed (Figure 1, sample No. 3). As a result of annealing at T = 540 ºC, inclusions with a high magnesium content disappear completely. Inclusions with a high iron content are preserved, but they are somewhat reduced in size (Figure 1, sample No. 4).

Figure 2 shows the effect of preliminary heat treatment on the microhardness of aluminum alloy substrates. The initial alloy is in a cold-worked state, therefore, for it a noticeable decrease in microhardness with an increase in the load is observed (sample No. 1). Homogenizing annealing at T ≥ 200 ºC leads to softening of the surface of the initial alloy (sample No. 2). The microhardness of the samples decreases with an increase in the annealing temperature up to 380 ºC (sample No. 3). A further increase in the annealing temperature does not lead to a noticeable change in the microhardness (sample No. 4).

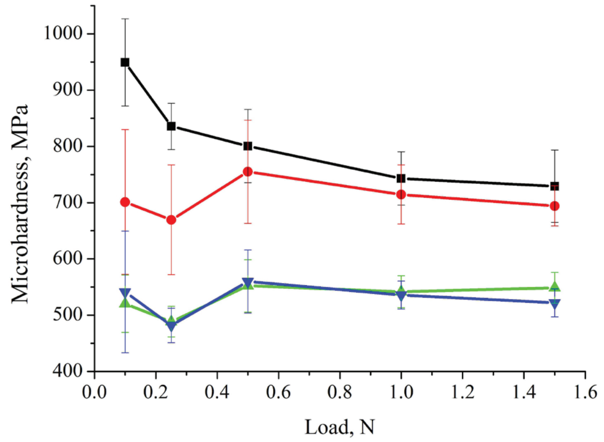


Figure 2 – Microhardness versus load for the investigated samples of substrates made of aluminum alloy AMg2, heat-treated at various temperatures: (■) – initial sample; (●) – T = 200 °C; (▲) – T = 380 °C; (▼) – T = 540 °C

After homogenizing annealing, all substrate samples underwent superfinishing treatment using nanoscale single point diamond turning to obtain optical surface clarity. The surface roughness of the manufactured reflector mirrors was studied using an atomic force microscopy. The measurement results are shown in the table and in Figure 3. It is clear that homogenizing annealing has a positive effect on the surface finish of the AMg2 alloy with a diamond turning. So for the original sample No. 1, not subjected to annealing, after finishing, the measured value of the surface roughness R_a is 1.5 nm. For a sample annealed at T = 200 ºC, R_a = 1.1 nm. For samples No. 3 and No. 4, annealed at T ≥ 380 ºC, the surface roughness R_a is less than 1 nm.

Table

Values of the surface roughness of the experimental samples depending on the heat treatment modes

№	R_a, nm	R_q, nm
1(initial)	1.5	2.0
2(200 ºC, 10 h.)	1.1	1.7
3(380 ºC, 10 h.)	0.65	0.84
4(540 ºC, 10 h.)	0.55	0.75

A decrease in surface roughness naturally leads to an increase in the reflectivity of the manufactured mirrors. So for a sample annealed at T = 540 °C, the reflection coefficient at a wavelength of 1064 nm increases compared to the original sample from 0.89 to 0.92, and at a wavelength of 532 nm – from 0.86 to 0.89.

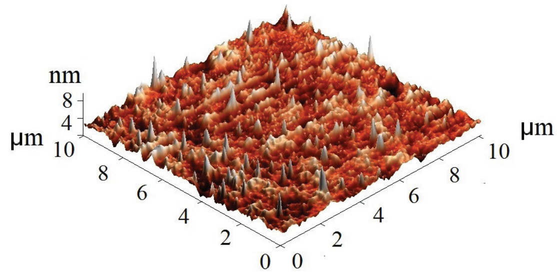
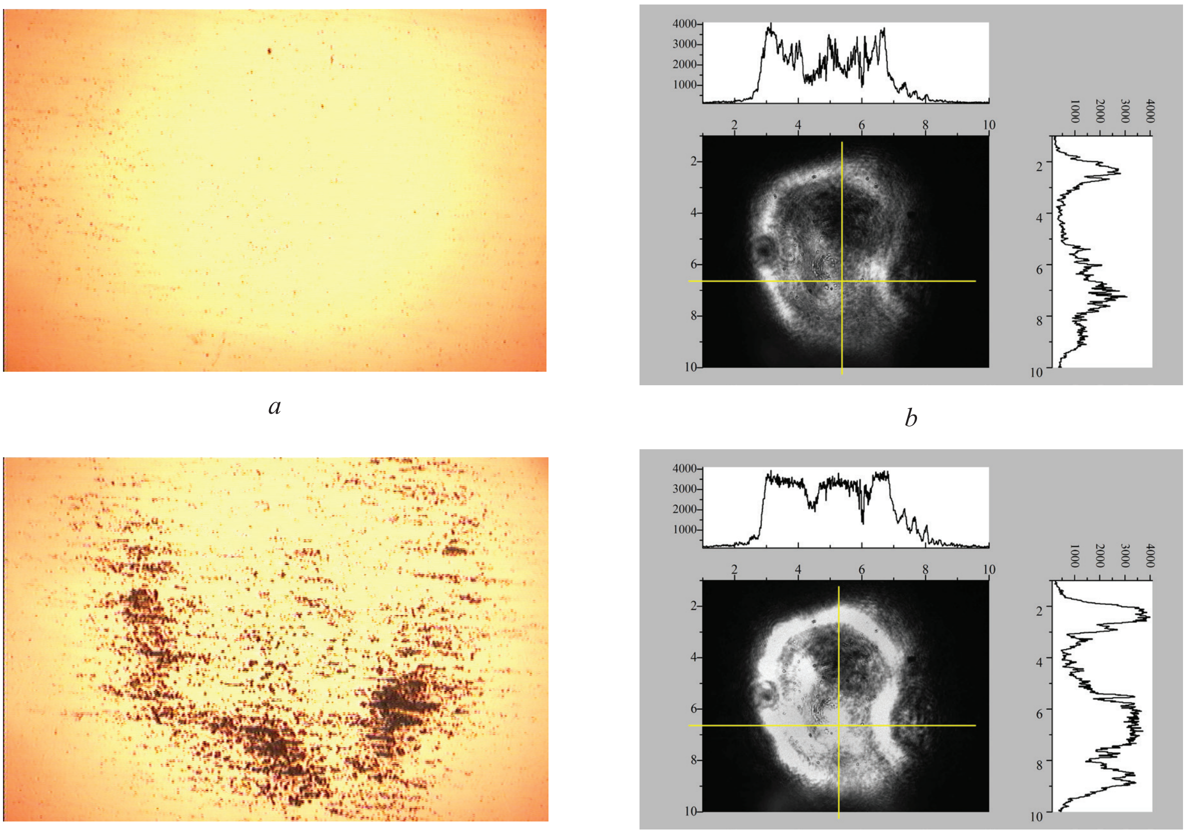


Figure 3 – Atomic force microscopy image of the surface relief of specimen of mirror No. 4 with R_a = 0.55 nm

For the manufactured reflector mirrors, tests for laser-induced damage threshold were carried out. The measurements were carried out in the mode of single laser pulses with a duration of 20 ns. The diameter of the laser spot on the mirror surface was 2.2 mm. The pulse energy was varied in the range from 70 to 300 mJ. Taking into account the real spatial distribution of energy in the laser spot, the energy density on the mirror surface varied in the range from 0.5 to 15 J/cm^2. An example of determining of the mirror surface damage threshold under the action of laser radiation is shown in Figure 4. It can be seen that the laser we used has a substantially nonuniform energy distribution over the cross section of the laser spot. This pattern is typical for commercial solid-state lasers. For a pulse with an energy of 100 mJ (Figure 4*b*), the power density of laser radiation varies over the spot cross section in the range of 0.5...8.0 J/cm^2. The average energy density W_a is 2.4 J/cm^2. For a pulse with an energy of 270 mJ (Figure 4*d*), the power density varies within the range of 1.25… 13.00 J/cm^2, and W_a = 6.5 J/cm^2. Analysis of the distribution of damage on the mirror surface (Figures 4*a* and 4*c*) for several laser pulses with different energies allows to determined the threshold energy of laser radiation with high accuracy.

According to the test results, it was found that for the initial aluminum alloy (sample No. 1), the threshold energy density of laser radiation is 3.5 J/cm^2. This value significantly exceeds the damage threshold of ≈ 1 J/cm^2 recorded for aluminum substrates subjected to abrasive or electrochemical polishing [13–14]. It is obvious that an increase in the radiation resistance of aluminum reflector mirrors is provided by a decrease in the surface roughness and an increase in its reflectivity. Thus, the promising nature of single-point diamond turning as a highly efficient method of forming optical surfaces on aluminum alloys has been confirmed.

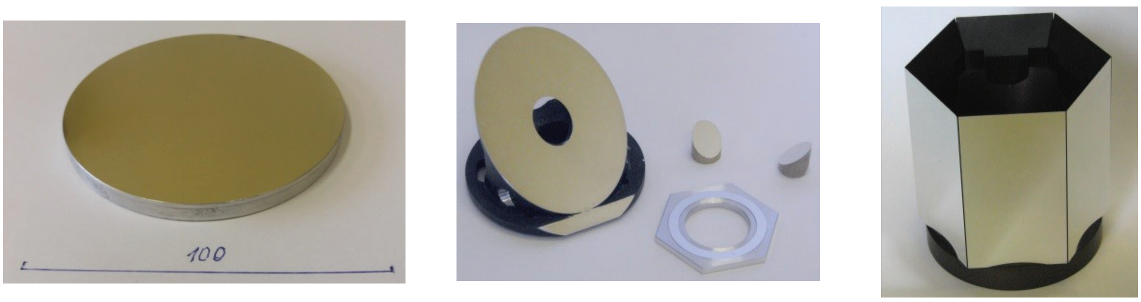


a *b* *c* *d*

Figure 4 – Image of the surface of mirror No. 4 after exposure to a laser pulse with an energy of 100 (*a*) and 270 mJ (*c*), the spatial distribution of energy in the laser spot at a pulse energy of 100 (*b*) and 270 mJ (*d*)

Heat treatment of substrates in the temperature range from 200 to 380 °C does not lead to a noticeable change of the reflector mirrors damage threshold. So for samples No. 2 and No. 3, threshold energy densities are in the range of 3.5...4.0 J/cm^2. For a sample annealed at T = 540 °C, the threshold energy density is about 5 J/cm^2, which is ≈ 30 % higher than for the original sample. Detailed studies of the nature of the high-power laser pulses destruction of the mirrors surface manufactured using the single-point diamond turning technology from initial AMg2 aluminum alloy show that degradation begins in the areas of localization of intermetallic inclusions. Thus, the increase the laser damage threshold of the sample annealed at T = 540 °C compared to the initial alloy can be associated with its partial homogenization.

The obtained results were used in the manufacture of various metal-optical products from aluminum alloys with increased radiation resistance (Figure 5).



a *b* *c*

Figure 5 – Optical products from aluminum alloys manufactured at Research Institute of Applied Physical Problems: *a* – laser mirrors with high radiation resistance; *b* – corner reflectors and scanners; *c* – multifaceted prism mirrors for video surveillance systems

Experimental operation of these products shows that the combination of technologies for preliminary heat treatment of aluminum alloy billets and single-point diamond turning makes it possible to increase the competitiveness of manufactured optical elements and expand their application areas.

Conclusion

Investigations of the influence of inhomogeneities of the surface structure of AMg2 aluminum alloy substrates on their optical and mechanical characteristics have been carried out and the ways of improving the quality of aluminum reflector mirrors manufactured using the single-point diamond turning have been determined.

It is shown that an important problem in the manufacture of optical elements from aluminum alloys is the inhomogeneity of the structure of the initial material, associated with the presence of intermetallic inclusions. Preliminary annealing of billets from AMg2 alloy at $T \geq 380$ °C makes it possible to improve the surface treatment quality and the laser damage threshold of aluminum mirrors both by removing mechanical stresses and by partially homogenizing the initial material. The optimum is heat treatment at the maximum allowable temperature for the AMg2 alloy T = 540 ºC, as a result of which there is a complete disappearance of intermetallic inclusions with an increased magnesium content.

Experimental studies have shown the possibility of obtaining mirror roughness $R_a = 0.55$ nm and the laser damage threshold of about 5 J/cm^2. Based on the obtained results a technology of aluminum alloys single-point diamond turning for the manufacture of metal-optical products with high radiation resistance has been developed.

References

1. Gorokhov V., Zakharevich E., Skvortsova M. *Povyshenie tochnosti detaley metallooptiki pri almaznom tochenii na ul'trapretsizionnom oborudovanii* [Accurancy improvement of metal-optical parts during diamond turning on ultra-precision equipment]. *Fotonika* [Photonics], 2014, no. 1, pp. 118–123 (in Russian).

2. Davim J.P., Jackson J.M. Nano and Micromachining. London: ISTE,Wiley, 2009, 312 p.

3. Kumar K., Zindani D., Kumari N., Davim J.P. Micro- and Nano-Machining of Engineering Materials: Recent Developments. *Springer*, 2018, 150 p.

4. Guregian J.J., Pepi J.W., Schwalm M., Azad F. Material trades for reflective optics from a systems engineering perspective. *Proc. SPIE*, 2003, vol. 5179, pp. 85–96. **DOI:** 10.1117/12.511537

5. Vukobratovich D., Schaefer J.P. Large stable aluminum optics for aerospace applications. *Proc. SPIE*, 2011, vol. 8125, p. 81250T. **DOI:** 10.1117/12.892039

6. Zhang J., Zhang X., Tan S., Xie X. Design and Manufacture of an Off-axis Aluminum Mirror for Visible-light Imaging. *Current Optics and Photonics*, 2017, vol. 1, no. 4, pp. 364–371.
DOI: 10.3807/COPP.2017.1.4.364

7. Schaefer J.P. Advanced metal mirror processing for tactical ISR systems. *Proc. of SPIE*, 2013, vol. 8713, pp. 871306-1-871306-10. **DOI:** 10.1117/12.2015496

8. Li L.H., Yu N.H., Chan C.Y., Lee W.B. Al6061 surface roughness and optical reflectance when machined by single point diamond turning at a low feed rate. *PLoS ONE*, 2018, vol. 13, no. 4, p. e0195083.
DOI: 10.1371/journal.pone.0195083

9. Otieno T., Abou-El-Hossein K. Molecular dynamics analysis of nanomachining of rapidly solidified aluminium. *Int. J. Adv. Manuf. Technol*., 2017, vol. 94, pp. 121–131. **DOI:** 10.1007/s00170-017-0853-5

10. Steinkopf R., Gebhardt A., Scheiding S., Rohde M., Stenzel O., Gliech S., Giggel V., Löscher H., Ullrich G., Rucks P., Duparre A., Risse S., Eberhardt R., Tünnermann A. Metal mirrors with excellent figure and roughness. *Proc. SPIE*, 2008, vol. 7102, p. 71020C.
DOI: 10.1117/12.797702

11. Tillack M.S., Pulsifer J.E. Development of Damage-Resistant Metal Mirrors for Laser-IFE. IEEE 22nd Symposium on Fusion Engineering, 2007.
DOI: 10.1109/fusion.2007.4337952

12. Revela P., Khanfira H., Fillit R.-Y. Surface characterization of aluminum alloys after diamond turning. *J. of Materials Processing Technology*, 2006, vol. 178, pp. 154–161. **DOI:** 10.1016/j.jmatprotec.2006.03.169

13. Liu W., Sun M., Guo Y., Jiao Z., Wu R., Pan X. Ablation characteristics of aluminium alloy and stainless steel induced by picoseconds laser pulses. *Proc. SPIE*, 2019, vol. 11063, p. 110631B. **DOI:** 10.1117/12.2539907

14. Zaghloul M., Tillack M., Mau T.K. Laser-induced damage of metal mirrors under long-term exposure at shallow angle of incidence. IEEE 19th Symposium on Fusion Engineering, 2002, pp. 272–275.
DOI: 10.1109/FUSION.2002.1027693