

Study on a two-step polishing method using pulsed fiber laser for SKD11 tool steel components

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ABSTRACT

In this study, the authors propose and experimentally investigate a two-step polishing technique using a medium power pulsed fiber laser for cold work die components made of SKD11 tool steel. The objective is to improve the surface finish after milling by applying a high-precision laser polishing process that enables efficient and scalable automation. The experiments employed a pulsed fiber laser source with a maximum power of 35 W and a wavelength of 1064 nm, combined with a galvo scanning head and a digital control system. The polishing was performed under argon shielding gas with various scanning parameters. The study focused on evaluating the effects of laser power and the number of scanning passes on surface morphology, roughness, and near-surface microstructure. Results showed that the two-step polishing strategy, starting with high power laser passes (35 W) to remove major surface peaks, followed by low power passes (21 W) to smooth finer irregularities, effectively reduced surface roughness R_a from $\sim 4.5 \mu\text{m}$ to $\sim 1.2 \mu\text{m}$ ($\sim 73\%$ reduction). Microstructural observations revealed phase transformations in the surface layer, with the formation of austenitic structures induced by the high-energy laser pulses. This study highlights the effectiveness of two-step pulsed laser polishing for difficult-to-machine materials like SKD11 and opens promising prospects for its application in precision mold manufacturing and automated surface finishing processes.

Keywords: Laser polishing; Pulsed laser; SKD11 tool steel; Two-step polishing.

1. INTRODUCTION

SKD11 tool steel is primarily used in the manufacturing of cold stamping dies, where metal deformation occurs at room temperature. These dies require not only high hardness and excellent wear resistance but also a superior surface finish with low roughness. SKD11 is an alloy tool steel belonging to the Cr-Mo (Chromium-Molybdenum) group, offering outstanding wear resistance, high strength, and thermal stability [1]. In both general and cold stamping die applications, surface roughness is a critical quality indicator, directly influencing dimensional accuracy, surface friction, and product aesthetics [2]. However, maintaining low surface roughness is particularly challenging due to the steel's intrinsic hardness and wear resistance [3].

Polishing is one of the most essential steps in mold fabrication, typically accounting for approximately 20% of the total machining time [4]. To improve polishing efficiency and enable process automation, several polishing technologies have been developed, including electrochemical polishing [5], plasma beam polishing [6], and ultrasonic-assisted polishing [7]. Recently, laser polishing has emerged as one of the most promising technologies. Fundamentally, laser polishing is a complex thermodynamic process wherein highly concentrated laser beams

interact with the material, inducing localized melting, vaporization, and resolidification of a thin surface layer. This process involves material removal, lowering the peak's height, and redistribution of material in adjacent areas under the influence of multi-directional surface tension forces [8]. Figure 1 illustrates the principle of laser polishing. Compared to traditional polishing techniques such as grinding, laser polishing offers higher accuracy and efficiency [9]. Additionally, it can be applied at both macro and micro scales [10, 11], to advanced materials such as ceramics and glass [12, 13], and does not require chemical agents or mechanical contact, thereby avoiding tool wear and chip formation.

Recently, laser polishing has attracted significant research attention due to its technical advantages and the rising demand for cold stamping dies, particularly in addressing process-related challenges associated with mold materials. In a study by Ukar E. et al. [4], CO₂ and high-power diode lasers were used to polish DIN 1.2379 steel after milling and electrical discharge machining (EDM). By identifying and optimizing process parameters, surface roughness was reduced by up to 90%, achieving Ra < 0.5 μm. In another investigation by the same research group, the influence of laser energy density on roughness reduction was explored [14]. An interesting observation was that surfaces with randomly distributed peaks and valleys resulted in the lowest roughness after laser polishing. The research team led by D.A. Lesyk combined laser and ultrasonic treatment for AISI D2 cold work tool steel, achieving a 90% reduction in roughness, more than a 10% increase in hardness, and the introduction of beneficial compressive residual stresses near the surface [15]. Ross and colleagues used both continuous and pulsed laser modes to polish AISI D2 steel, examining surface morphology and chemical composition near the surface layer [11]. Their results indicated that using both laser modes with optimized parameters reduced grain size and improved uniformity in chromium carbide distribution.

In this study, we propose a two-step polishing technique using a medium power pulsed fiber laser with Ar shielding gas for polishing SKD11 tool steel parts after milling. By employing the two-step laser polishing method, the surface roughness Ra was reduced from approximately 4.5 μm to 1.2 μm, a reduction of ~73%, while the areal roughness S_a decreased from ~4.3 μm to ~1.2 μm. The effects of laser power and the number of scanning passes were also investigated. Surface morphology and subsurface microstructure analysis revealed that laser interaction not only altered the surface geometry but also transformed martensitic structure into austenite. The findings provide valuable insights into the application of medium-power pulsed fiber laser technology for surface polishing of SKD11 cold stamping die materials.

2. EXPERIMENTS

2.1. Equipment and materials

The laser polishing system used in this study is illustrated in figure 1. The setup consists of a pulsed fiber laser source with a maximum average power of 35 W, a wavelength of $\lambda = 1064$ nm, pulse width ranging from 25 - 300 ns, and a repetition frequency between 70 - 500 kHz. The laser beam, with an initial 1/e² diameter of 10 mm, is directed through a galvanometer scanner head (RC1001, Sino-Galvo) equipped with two mirrors for X and Y axis scanning, enabling a maximum scanning speed of 2000 mm/s. The beam is then focused by an f-theta lens (160D10, CS) with a focal length of 160 mm. The resulting spot diameter at the focal plane is approximately ~50 μm. The scanning head has a repeatability of 8 μrad, which corresponds to a calculated deviation on the sample surface of approximately 1.28 μm (for a focal length of 160 mm). This deviation is negligible compared to the laser beam diameter (~ 50 μm). The laser system and scanning head are connected to a computer and controlled via dedicated scanning software.

The specimens were made of SKD11 tool steel and were prepared by milling (using a 20 mm diameter HSS end mill at 800 rpm and a feed rate of 200 mm/min). Each sample measured 100

mm × 50 mm × 22 mm. After milling, the specimens were cleaned using acetone to remove oil residues and contaminants. The chemical composition of SKD11 steel is listed in table 1 [16].

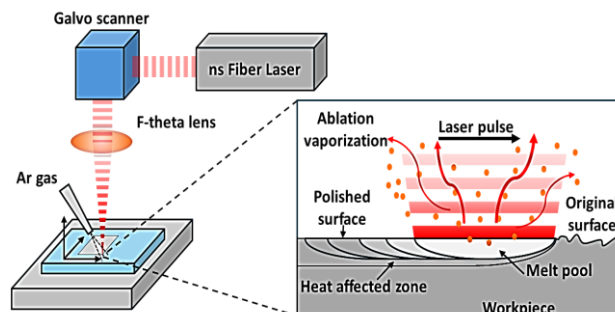


Figure 1. Schematic diagram of the experimental setup and the principle of pulsed laser polishing.

Table 1. Chemical composition of SKD11 steel (wt%).

C	Si	Mn	Cr	Mo	V	Fe
1.4–1.6	≤0.4	≤0.6	11–13	0.8–1.2	0.2–0.5	Bal.

2.2. Experimental procedure

Laser polishing experiments were conducted under ambient conditions at room temperature, with the polishing zone protected by argon shielding gas (purity 99.99%). The argon gas was supplied from a pressurized tank and delivered directly to the processing area through a 6 mm diameter nozzle. A constant flow rate of 10 L/min was maintained using a flow regulator. The nozzle was positioned at a 70° angle relative to the horizontal plane and at a distance of approximately 20 mm from the polishing zone to avoid obstructing the laser beam. Each polished area measured 5 mm × 5 mm and corresponded to a distinct set of process parameters.

The basic process parameters for laser polishing were as follows: scanning speed $v_{scan} = 550$ mm/s, repetition frequency $f = 30$ kHz, and pulse width $P_w = 250$ ns. The effective laser power was varied among 21 W, 28 W and 35 W. The distance between adjacent scan lines was set to 15 μ m, corresponding to a 70% overlap. The process parameters for polishing SKD11 steel are summarized in table 2. The specimen and scanning pattern are illustrated in figure 2.

Table 2. Laser polishing process parameters for SKD11 steel.

Laser power (W)	Scanning speed (mm/s)	Frequency (kHz)	Pulse width (ns)	Overlap %
21, 28, 35	550	30	250	70

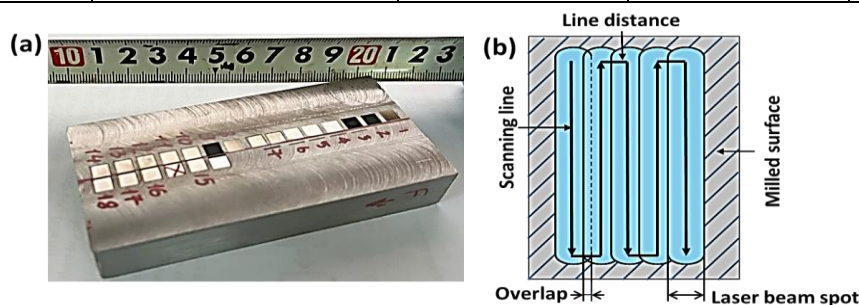


Figure 2. (a) Photograph of the experimental specimen and (b) scanning pattern geometry.

After laser polishing, the specimens were examined using an optical microscope (Axioskop 2 Mat, Zeiss) to assess surface characteristics. Surface roughness and three-dimensional surface structure were measured using a white light interferometry profilometer (Zegage Pro HR 3D,

Zygo). The accompanying software, with its default settings, uses fixed display units that cannot be altered; consequently, the output images from the software present roughness values in nanometers (nm) and sample dimensions and measurement area sizes in micrometers (μm). Although laser polishing significantly improved the surface smoothness, the measurement instrument is capable of operating at a precision range several orders of magnitude higher. Therefore, for ease of comparison with other published works, the authors present all roughness values in micrometers (μm) in this study.

3. RESULTS AND DISCUSSION

3.1. Effect of laser power on surface tracks

The laser scanning process on the sample surface essentially involves the continuous overlapping of multiple single-pass laser tracks. Therefore, examining the characteristics of individual laser tracks provides valuable insights into the surface polishing strategy. Figure 3 presents the 3D surface structure of samples scanned by a single laser track at powers of 21 W, 28 W, and 35 W, respectively.

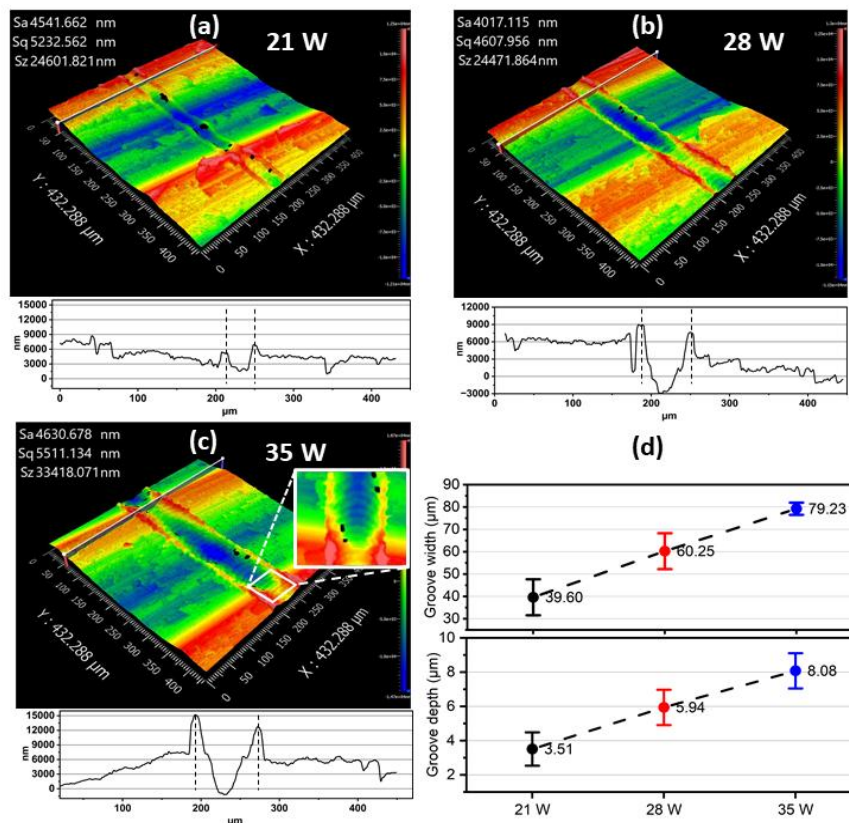


Figure 3. Single laser scan tracks on the sample surface corresponding to laser powers of (a) 21 W, (b) 28 W, and (c) 35 W, along with the measured width and depth of the laser-induced grooves on the sample surface at the respective laser powers.

The average measured surface roughness S_a ranges from approximately 4.0 - 4.6 μm . The residual milling marks are visible as alternating red (elevated) and blue (depressed) regions on the surface. A single laser scan forms a pronounced groove traversing both the high and low regions of the milled surface. Given that the overall height difference is less than 6 μm ($S_z < 6 \mu\text{m}$) and the calculated Rayleigh length is approximately 1.54 mm, both elevated and depressed regions remain within the focal depth of the laser beam.

It is evident that laser power has a significant effect on the morphology of the laser groove. The groove width was measured at three random positions perpendicular to the scanning direction. The measurements show a linear increase in groove width with increasing laser power. The average groove widths were 39.60 μm , 60.25 μm , and 79.23 μm for laser powers of 21 W, 28 W, and 35 W, respectively. Similarly, the groove depths increased from 3.51 μm to 5.94 μm and 8.08 μm as the laser power increased.

At the highest laser power of 35 W, a two-dimensional view reveals that consecutive laser pulses form a distinct fish scale pattern (see 2D inset in figure 3c). This pattern results from the combination of pulse energy, repetition rate, and scanning speed used in the experiment.

3.2. Two-step laser polishing technique

After examining the influence of laser power on single scan tracks, surface scanning using a sequential zigzag strategy (figure 2), with varying laser powers and conditions, was applied to the samples. For ease of identification, the samples were labeled using the notation M-X-Y, where X represents the number of scans at 35 W, and Y represents the number of scans at 21 W. The laser power of 35 W represents the maximum output achievable by the system, whereas the lower power setting of 21 W is sufficient to induce a clear and measurable effect on the sample surface. The milled sample without laser treatment is denoted as M-0-0. Figure 4a shows the 3D surface structure of the initial milled sample (M-0-0). The milling marks are clearly visible as progressive curved lines along the main feed direction. From the surface roughness profile perpendicular to the surface pattern, a periodic texture can be observed. The initial surface roughness values of sample M-0-0 were $S_a = 4.27 \mu\text{m}$ and $R_a = 4.65 \mu\text{m}$.

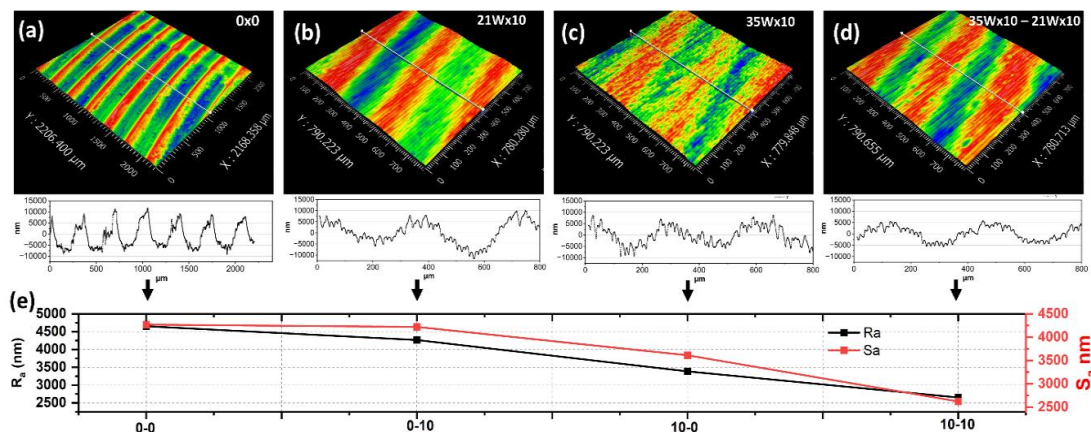


Figure 4. Surface structures of: (a) initial sample M-0-0, (b) M-0-10, (c) M-10-0, (d) M-10-10, and (e) corresponding S_a and R_a values.

Sample M-0-10, which was scanned 10 times with a laser power of 21 W (figure 4b), exhibited only a slight decrease in surface roughness compared to the milled surface. This can be explained by the single scan results at 21 W, which showed an average groove depth of only 3.51 μm (figure 2d) - insufficient to remove surface irregularities from the milling process. As a result, high (red) and low (blue) regions remained visible, with minimal roughness reduction. In contrast, sample M-10-0, which underwent 10 scans at 35 W (figure 4c), exhibited a significant reduction in roughness. At 35 W, the single scan depth reached up to 8 μm , enough to eliminate the prominent surface peaks. Additionally, the laser track width increased to 79.23 μm , while the hatch spacing remained 15 μm , effectively raising the actual overlap from a theoretical 70% to approximately 81%. These two factors contribute significantly to the enhanced roughness reduction at 35 W.

To further reduce surface roughness, a two-step laser polishing approach was applied, combining high and low power laser treatments. Figure 4d shows the surface structure of sample M-10-10,

which was first scanned 10 times at 35 W, followed by 10 scans at 21 W. This method leverages the deep and wide groove-forming ability of high-power laser pulses to remove large asperities, then uses low-power scanning to refine smaller irregularities. The resulting roughness values were reduced to $S_a = 2.62 \mu\text{m}$ and $R_a = 2.65 \mu\text{m}$. Notably, in sample M-20-50 (figure 5), where 20 high-power (35 W) scans were followed by 50 low-power (21 W) scans, the surface roughness decreased further to $S_a \approx 1.18 \mu\text{m}$ and $R_a \approx 1.09 \mu\text{m}$. Optical microscopy (figure 5a) and 3D topography (figure 5b) revealed a uniform surface with most of the original peaks and valleys from the milled sample removed. The roughness profile in figure 5c shows that large peaks were virtually eliminated. However, small peaks remained, likely induced by the laser interaction itself during the second polishing step. Moreover, increasing the number of scans beyond this point led to significantly longer processing times without substantial improvement in surface quality, suggesting that further roughness reduction would require a different scanning strategy or parameter set.

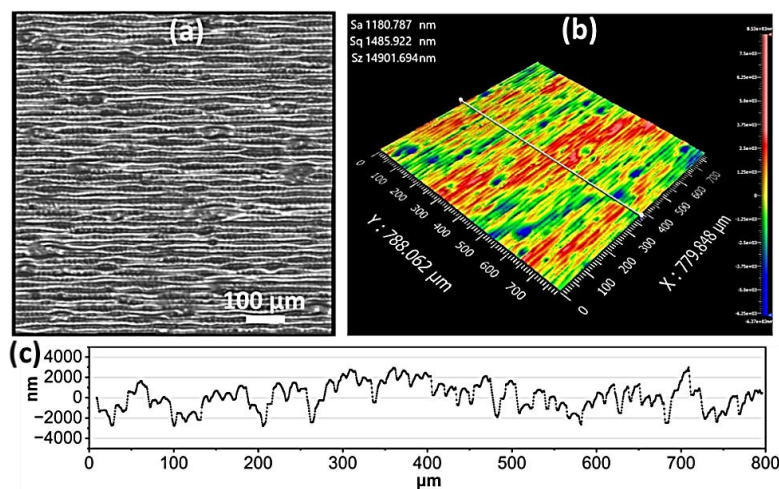


Figure 5. Sample M-20-50: (a) optical micrograph, (b) 3D surface image, and (c) roughness profile.

3.3. Microstructural transformations

To investigate the microstructure of the base material and its transformations under the effect of laser polishing, sample M-20-50 was sectioned, embedded in epoxy, ground, polished, and etched using a Nital solution (10 seconds) for observation under an optical microscope (figure 6). The results show that after laser polishing, the surface roughness of sample M-20-50 was significantly reduced; major surface asperities were flattened. Notably, after etching, the microstructure of both the substrate and the laser-polished surface layer could be clearly observed. In the original SKD11 steel material, dark regions correspond to martensitic structures, while the bright regions are primarily chromium carbides or retained austenite. This microstructural distribution in SKD11 steel is due to its high carbon and chromium content. During the manufacturing process, which includes casting, hot rolling, and heat treatment, incomplete martensitic transformation leads to the formation of retained austenite and chromium carbides. In addition, the elongated orientation of carbide particles parallel to the polished surface indicates the rolling direction of the original material sheet [17]. However, the thin laser-polished surface layer exhibits a bright appearance, clearly distinct from the underlying martensitic and carbide regions. When exposed to high-energy pulsed laser radiation ($> 7 \text{ kW}$) over a very short duration, the SKD11 surface is rapidly heated and subsequently cooled, resulting in the transformation of the original martensitic matrix into austenite [2, 18]. This transformation can also lead to the complete dissolution of chromium carbide particles [11, 19]. These findings are consistent with previous studies on the use of nanosecond pulsed lasers for polishing high-chromium alloy steels.

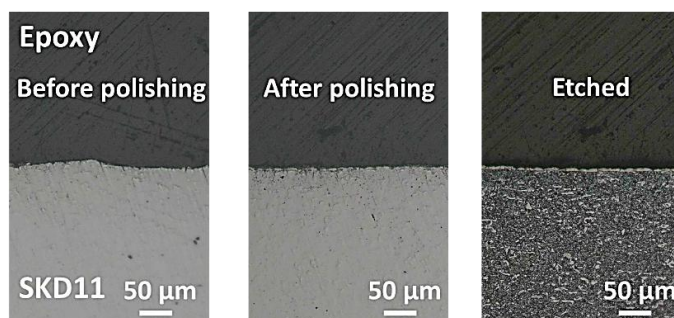


Figure 6. Cross-sectional images of M-20-50 sample: (a) Before polishing; (b) After polishing; (c) After etching.

4. CONCLUSIONS

The study has demonstrated the feasibility and effectiveness of a two-step pulsed laser polishing strategy for machined SKD11, a high-hardness, wear-resistant tool steel that is traditionally difficult to process using conventional methods. The application of high-power laser irradiation in the initial step plays a critical role in eliminating large surface asperities, thereby facilitating the subsequent low-power polishing step for surface finishing. The correlation among laser power, number of passes, and actual overlap ratio highlights the significant influence of process parameters on final surface roughness and uniformity. In addition to the mechanical effects on roughness reduction, the study also revealed notable microstructural transformations on the polished surface - a factor that must be considered in practical applications where hardness, wear resistance, and thermal stability are key performance criteria for cold stamping dies. Nevertheless, the limitations of the method were also identified: further increasing the number of laser passes does not yield proportional improvements in surface quality, while significantly prolonging processing time. Overall, the two-step pulsed laser polishing method presents a promising approach for high-precision and automated surface finishing of SKD11 tool steel molds.

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TÓM TẮT

Nghiên cứu phương pháp đánh bóng hai bước bằng laser xung sợi quang cho chi tiết thép dụng cụ SKD11

Trong nghiên cứu này, nhóm tác giả đề xuất và áp dụng một kỹ thuật đánh bóng hai bước bằng laser xung sợi quang công suất trung bình cho vật liệu khuôn dập nguội bằng thép SKD11. Mục tiêu nhằm cải thiện độ bóng bề mặt sau phay thông qua phương pháp đánh bóng bằng laser có tính chính xác và tiềm năng tự động hóa cao. Các thí nghiệm được tiến hành bằng việc sử dụng nguồn laser xung sợi quang công suất tối đa 35 W, bước sóng 1064 nm, kết hợp với đầu quét galvo và hệ thống điều khiển số. Các mẫu được đánh bóng dưới khí bảo vệ argon với nhiều thông số quét khác nhau. Nghiên cứu tập trung khảo sát ảnh hưởng của công suất laser và số lần quét đến cấu trúc bề mặt, độ nhám và tổ chức tế vi gần bề mặt. Kết quả cho thấy, khi áp dụng kỹ thuật đánh bóng hai bước – bước đầu dùng laser công suất cao (35 W) để loại bỏ các đỉnh nhấp nhô lớn, bước tiếp theo dùng laser công suất thấp hơn (21 W) để làm mịn các vùng lồi lõm nhỏ – độ nhám bề mặt R_a giảm từ ~ 4.5 μm xuống còn ~ 1.2 μm (~ 73%). Tổ chức tế vi sau đánh bóng có sự thay đổi pha tại lớp bề mặt, thể hiện qua sự hình thành vùng tổ chức austenite do ảnh hưởng của xung laser năng lượng cao. Nghiên cứu góp phần làm rõ hiệu quả của kỹ thuật đánh bóng hai bước bằng laser xung đối với vật liệu khó gia công như SKD11, mở ra triển vọng ứng dụng công nghệ này trong chế tạo khuôn chính xác và tự động hóa gia công.

Từ khóa: Đánh bóng; Laser xung; Thép dụng cụ SKD11; Đánh bóng hai bước.