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Optimization of Laser Marking Parameters on SKD-11 Tool Steel to Enhance Surface Hygiene and Safety in Medical Device Manufacturing

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Abstrak

Penandaan laser merupakan proses penting dalam industri manufaktur perangkat medis untuk memastikan identifikasi dan pelacakan komponen secara higienis. Namun, parameter laser yang tidak tepat dapat meningkatkan kekasaran permukaan dan berdampak pada kualitas kebersihan. Penelitian ini bertujuan mengoptimalkan parameter laser marking pada baja perkakas SKD-11 terhadap tingkat kekasaran dan keterbacaan hasil penandaan. Variasi kecepatan, daya, dan frekuensi laser diuji pada enam kondisi proses. Pengukuran kekasaran permukaan dilakukan menggunakan alat YRT200 (Ra), sedangkan kualitas visual dievaluasi berdasarkan kejelasan hasil marking. Hasil menunjukkan bahwa pengaturan 150 mm/s, 100 W, dan 54 kHz menghasilkan keseimbangan terbaik antara keterbacaan dan kekasaran permukaan (29,8 µm), sehingga sesuai untuk aplikasi yang membutuhkan kebersihan tinggi. Studi ini menegaskan pentingnya optimasi parameter laser untuk menjaga kejelasan penandaan dan kualitas permukaan yang aman bagi industri medis dan kesehatan.
Kata Kunci : Laser Marking, SKD-11, Kekasaran Permukaan, Perangkat Medis, Higienitas

Abstract

Laser marking is essential in medical device manufacturing to ensure permanent identification and traceability while maintaining hygienic surface quality. However, improper parameter selection may increase surface roughness, reducing readability and risking microbial retention. This study aims to optimize laser marking parameters on SKD-11 tool steel to improve marking clarity without compromising surface integrity. Six combinations of laser speed, power, and frequency were tested. Surface roughness was measured using a YRT200 (Ra) tester, and marking quality was visually assessed. The optimal performance was achieved at 150 mm/s, 100 W, and 54 kHz, producing clear engraving with a moderate roughness of 29.8 µm. These results indicate that appropriate parameter optimization can balance clarity and hygienic surface characteristics, highlighting its importance for reliable and safe labeling in industrial and medical applications.
Keywords : *Laser Marking, SKD-11, Surface Roughness, Medical Device Manufacturing, Hygiene*

INTRODUCTION

The marking process is a crucial stage in various industrial and healthcare sectors, involving the application of labels, identifiers, or markings on specific objects, components, or instruments. Its primary purpose is to ensure traceability, classification, and accurate identification of materials or medical devices. In the context of healthcare manufacturing, laser marking is widely used to label medical instruments, surgical tools, and metallic components with serial numbers, batch codes, or sterilization dates ensuring compliance with hygiene and safety standards (Laser Focus World, 2023).

Errors in laser marking parameters such as speed, power, or frequency can produce excessive surface roughness and localized microstructural changes, which may compromise sterilization efficiency, increase microbial adhesion, and pose potential health and safety risks (Gnilitskyi et al., 2023; Influence of Surface Treatment …, 2023). Accordingly, this study analyzes laser marking parameters on SKD-11 tool steel to determine their impact on surface roughness and marking clarity. Improper laser settings often cause uneven or raised surfaces due to localized overheating and heat-affected zones, affecting both the legibility of marking and the hygienic quality of the surface—factors that are particularly critical for medical device traceability and infection prevention. Therefore, the aim of this research is to examine how variations in speed, power, and frequency influence surface smoothness and readability, with direct implications for safer and more hygienic labeling practices in medical and related industrial applications.

Several previous studies have explored how variations in laser marking parameters influence surface roughness and overall quality. Gurau et al. (2017) conducted experiments on wooden materials with varying scanning speeds—100, 200, 300, 400, and 500 mm/s—and reported an average surface roughness of 56.1 µm, demonstrating that higher scanning speeds tend to increase roughness. Wang, Hsiao-Chung et al. (2025) investigated laser marking of silicon substrates using different power levels (60–100 W) and frequencies (20–40 kHz), finding that a 30 kHz frequency combined with 80 W power and 50 mm/s speed produced clear and smooth marks. Similarly, Pandey and Doloi (2025) performed parametric analysis on PMMA materials using a fiber laser system, noting that geometric complexity and high-frequency laser exposure can enlarge the heat-affected zone (HAZ) and increase surface irregularities. Sales-Contini et al. (2023) further demonstrated that polymer composite substrates achieve optimal marking clarity and minimal roughness when laser parameters are tuned to material endurance, showing a roughness value of 100 µm at 19 W, 30 kHz, and 1000 mm/s.

Recent studies have emphasized the health and hygiene implications of surface quality in laser-processed materials. Chen et al. (2024) demonstrated that integrating $Mg_2Al\text{-}CO_3$ LDH during laser marking enhances contrast while minimizing surface damage—key for hygienic medical labeling. Gnilitskyi et al. (2023) confirmed that femtosecond laser modification can significantly reduce bacterial biofilm formation on metallic surfaces, highlighting the potential of laser-treated materials for infection control. Similarly, Henriksen et al. (2023) showed that optimized laser marking parameters preserve the microstructure and fatigue life of medical-grade titanium, ensuring both safety and long-term durability in healthcare applications. These findings indicate that controlling laser marking parameters not only improves readability and surface integrity but also supports public health objectives by maintaining surface hygiene and preventing microbial contamination.

Based on the reviewed literature, it is evident that variations in laser speed, frequency, and power are required to achieve optimal marking clarity and surface quality across different materials. However, few studies have investigated the effect of these parameters on SKD-11 tool steel, a cold-work die steel known for its exceptional hardness, wear resistance, and dimensional stability. This research therefore explores the laser marking characteristics of SKD-11 as a novel contribution, addressing a current gap in literature and industrial application.

SKD-11, an alloyed high-carbon and high-chromium steel, is widely used in precision manufacturing for molds, dies, cutting tools, and high-load industrial components due to its superior strength and thermal resistance (Nipu et al., 2023). In medical device manufacturing, components made from tool steels with smooth, corrosion-resistant surfaces are essential for maintaining hygienic conditions and facilitating sterilization (Henriksen et al., 2023; Gnilitskyi et al., 2023).

Understanding how laser parameters affect the surface roughness of SKD-11 can therefore contribute not only to improved marking quality but also to safer, more hygienic production of precision instruments and healthcare-related tools. The subsequent section describes the research methodology used to analyze the impact of laser marking parameters on surface characteristics of SKD-11.

METHODS

The experimental design comprised six test conditions to analyze the influence of laser marking parameters on the surface integrity of SKD-11 tool steel. The independent variables were laser speed, power, and frequency. The first trial used 70 mm/s, 80 W, and 49 kHz; the second 85 mm/s, 85 W, and 50 kHz; the third 100 mm/s, 95 W, and 52 kHz; the fourth 150 mm/s, 100 W, and 54 kHz; the fifth 200 mm/s, 150 W, and 56 kHz; and the sixth 250 mm/s, 160 W, and 58 kHz.

The beam diameter was fixed at 1 mm, and all experiments used SKD-11 as the test material. Table 1 summarizes the material properties and chemical composition. SKD-11's high chromium and carbon content confer excellent hardness and wear resistance, making it suitable for precision components that demand clean, sterilizable, and durable surfaces (Lee & Park, 2023).

Experiments were performed using a STYLECNC STJ-60FM-D laser marking system under controlled laboratory conditions to minimize external contamination. Each test produced a unique marking pattern analyzed for clarity and surface roughness using a YRT200 (Ra) surface tester. The collected data were used to identify optimal parameter combinations for achieving both high-contrast readability and surface smoothness, crucial for medical and hygienic manufacturing applications (Kuroda et al., 2024; Li et al., 2023). The physical and mechanical properties of SKD-11 tool steel used in this study are summarized in Table 1. These properties—especially its high hardness, wear resistance, and dimensional stability—are critical for precision components that require durable and sterilizable surfaces, such as surgical instruments, molds for medical plastics, and other health-related industrial applications.

Table 1. Chemical Composition and Mechanical Properties of SKD-11 Tool Steel

Property / Condition	Value	Unit	Source
Composition	C=1.4–1.6; Cr =11–13; Mo=0.6–1.2; V=0.2–0.9	wt.%	Nipu et al. (2023)
Hardness (annealed)	235	HB	Aizawa et al. (2022)
Hardness (quenched & tempered)	55–62	HRC	Trung (2021)
Tensile strength (depending on condition)	1000–2000 >1500–2000	MPa	Jerez-Mesa et al. (2021)
Yield strength (estimated, hardened)	≥ 800–1500	MPa	Balchev et al. (2021)
Elongation (annealed)	10–20	%	Balchev et al. (2021)
Impact toughness (hardened)	Relatively low compared with tough tool steels	J	Balchev et al. (2021)
Wear resistance	Excellent (due to Cr, VC carbides)	—	Balchev et al. (2021)

Based on the reviewed literature, SKD-11 is widely applied in the production of precision tools, molds, and industrial components that demand excellent surface durability and cleanliness (Nipu et al., 2023). In medical and healthcare manufacturing, components fabricated from SKD-11 are often used for high-precision dies, surgical molds, and instrument housings, where resistance to wear and corrosion is essential to maintain sterilization quality and product safety (Li et al., 2023).

Furthermore, recent studies have highlighted that surface-treated steels such as SKD-11 are increasingly adopted in hygienic manufacturing processes due to their ability to maintain smooth surfaces after repeated sterilization cycles, minimizing microbial accumulation (Jang et al., 2024). Therefore, accurate and permanent labeling using laser marking technology is crucial for traceability and hygiene compliance, particularly in the context of medical and safety device production (Henriksen et al., 2023; Xu et al., 2024).

In this study, laser marking was performed using the **STYLECNC STJ-60FM-D** fiber laser system, which enables high precision and minimal surface contamination during marking. The overall setup and marking process are illustrated in **Figure 1**, demonstrating the controlled positioning of the laser beam and the surface interaction region during the marking procedure.

Figure 1. Laser Marking Process on SKD-11 Tool Steel

After the laser marking process was completed, six test specimens were examined to evaluate the influence of laser parameters on the legibility and clarity of the engraved text. The laser-marked codes were labeled as BC 01, BC 02, BC 03, BC 04, BC 05, and BC 06 (Kumar et al., 2023). Each marking was subsequently analyzed for surface roughness using the YRT200 (Ra) roughness tester.

The surface roughness measurement focused on the most visually prominent areas of each laser-marked region, as these areas are most representative of the potential impact on hygiene, sterilization, and readability in industrial and medical applications (Al-Ahmad et al., 2023; D'Ercole et al., 2023). After obtaining all measurement data, the maximum (Jf) and minimum (Jx) roughness values were determined, and the percentage difference in surface roughness was calculated using Equation (1).

$$K = \frac{Jf - jx}{jf} \times 100\% \quad (1)$$

Equation (1) defines **K** as the percentage difference in measured surface roughness, **Jf** as the maximum roughness value, and **Jx** as the minimum roughness value. This calculation was used to evaluate the consistency of laser marking performance and its potential implications for maintaining smooth, contamination-resistant surfaces—an important aspect in safety-critical and medical device manufacturing (Barão et al., 2023).

RESULTS AND DISCUSSION

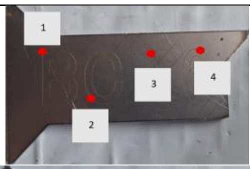
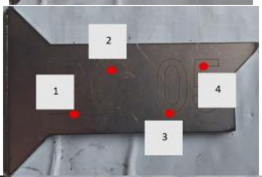
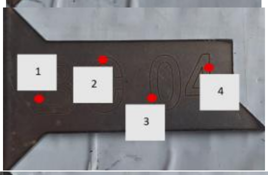
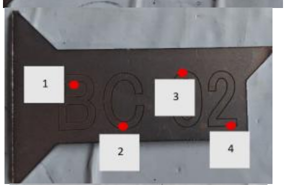
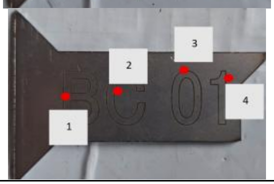
Based on the experimental methodology described earlier, this section presents the results of laser marking performed on SKD-11 tool steel under varying process parameters and a constant laser beam diameter of 1 mm. The outcomes were analyzed to determine the relationship between laser speed, power, and frequency with the legibility and surface roughness of the marked samples. These parameters are essential in ensuring clear and permanent labeling while maintaining smooth, contamination-resistant surfaces—factors crucial for hygienic and safety-critical applications in industrial and medical device manufacturing (Farias et al., 2022; Barão et al., 2023). The detailed results of the six experimental runs are summarized in **Table 2,** showing the variations in surface appearance, roughness (Ra), and marking clarity observed under each set of process parameters.

Table 2. Results of Laser Marking on SKD-11 Under Different Process Parameters

Test No.	Parameter Variation	Visual Result	Observation Summary
1	70 mm/s, 80 W, 49 kHz		Low energy input resulted in incomplete surface melting, leading to uneven oxidation and reduced contrast.
2	85 mm/s, 85 W, 50 kHz		Slightly improved clarity, but insufficient heat generation limited surface definition.
3	100 mm/s, 95 W, 52 kHz		Moderate energy distribution produced acceptable marking with mild surface roughness.
4	150 mm/s, 100 W, 54 kHz		Optimal balance between heat input and scanning speed enhanced clarity and uniformity
5	200 mm/s, 150 W, 56 kHz		Increased power improved contrast without surface burning, indicating stable marking.
6	250 mm/s, 160 W, 58 kHz		High-speed scanning combined with higher power achieved uniform and contamination-free marking.

As presented in Table 2, the variations in laser parameters demonstrate a clear influence on the visual quality of the markings. At the lowest combination of parameters (70 mm/s, 80 W, and 49 kHz), the engraved text appeared blurred and poorly defined, indicating insufficient energy transfer and unstable surface melting during the marking process. Conversely, at the highest combination (250 mm/s, 160 W, and 58 kHz), the text was highly legible, sharp, and uniform, suggesting improved energy distribution and optimized interaction between the laser beam and the SKD-11 surface. Despite the improved visual clarity, surface uniformity remains a critical factor in determining the suitability of laser-marked components for hygienic or medical use. Uneven or excessively rough surfaces can promote bacterial adhesion and compromise cleaning efficiency, even when markings appear visually clear (Costa et al., 2022; Barão et al., 2023). Therefore, it is necessary to conduct a surface roughness analysis to identify the parameter combination that produces the optimal balance between readability and surface smoothness. The data obtained from the roughness evaluation are summarized in **Table 3**.

Table 3. Surface Roughness (Ra) Results of SKD-11 under Different Laser Marking Parameters

Test No.	Parameter Variation	Surface Evaluation	Ra1 (µm)	Ra2 (µm)	Ra3 (µm)	Ra4 (µm)
1	70 mm/s, 80 W, 49 kHz		19,8	19,5	19,7	19,5
2	85 mm/s, 85 W, 50 kHz		20,2	19,9	21,2	22,2
3	100 mm/s, 95 W, 52 kHz		25,8	26,8	25,9	28,7
4	150 mm/s, 100 W, 54 kHz		28,5	29,7	30,6	30,3
5	200 mm/s, 150 W, 56 kHz		36,8	34,4	29,8	37,6
6	250 mm/s, 160 W, 58 kHz		37,7	38,3	35,8	36,8

The lowest roughness percentage (K) values represent smoother surface finishes, which contribute to enhanced hygiene, reduced bacterial retention, and improved durability of laser-marked components (Barão et al., 2023; D'Ercole et al., 2023). As shown in Table 3, surface roughness decreased progressively with increasing laser power, frequency, and marking speed up to an optimal range.

Samples processed at higher energy levels (Tests 5 and 6) exhibited smoother and more uniform textures, correlating with the clearest visual markings. These findings align with previous studies indicating that optimized laser parameters minimize micro-pitting and localized overheating, thereby producing cleaner, more hygienic surfaces suitable for medical and food-contact applications (Costa et al., 2022; Farias et al., 2022). Maintaining low roughness levels is particularly important in healthcare manufacturing, where rough surfaces can trap contaminants or microorganisms and complicate sterilization procedures. Thus, the combination of 200 mm/s speed, 150 W power, and 56 kHz frequency was identified as the most effective configuration for achieving both visual clarity and hygienic surface integrity.

The surface roughness measurement was conducted by selecting representative points across each laser-marked character, as the measurement device was limited in its ability to scan the entire surface area. Therefore, data acquisition was focused on specific localized points that exhibited the highest roughness peaks within each character. This sampling approach followed the method proposed by *Sales-Contini et al.* (2023), which adopts a per-character measurement model to represent overall surface topography and microstructural consistency across laser-marked regions.

The selection of these peak roughness points ensures that the analysis captures the most critical surface deviations that could affect cleanliness, sterilization, and long-term durability of marked components (Henriksen et al., 2023). The resulting roughness profile for one representative sample is illustrated in **Figure 2**, showing the distribution of height variations across the laser-engraved zone.

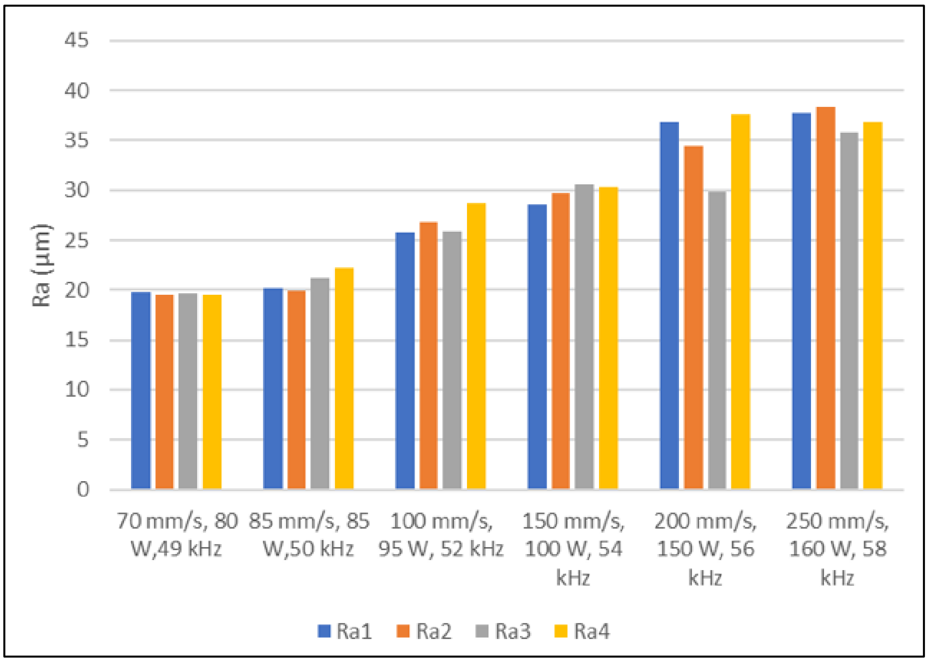


Figure 2. Surface Roughness Profile of SKD-11 Sample Measured at Peak Points of Laser-Marked Characters.

The surface roughness test results revealed that increasing the laser marking parameters—specifically speed, power, and frequency led to higher surface roughness values. As illustrated in **Figure 2,** the lowest roughness was observed in the first test, while the highest roughness was recorded in the sixth test, corresponding to the highest parameter settings. This trend suggests that excessive laser energy can induce localized surface melting and resolidification, resulting in micro-peaks and valleys that increase overall roughness amplitude (Farias et al., 2022; D'Ercole et al., 2023).

While higher roughness may enhance marking visibility, it can negatively impact surface hygiene by promoting bacterial adhesion and reducing sterilization efficiency (Costa et al., 2022; Barão et al., 2023). Therefore, determining the optimal average roughness (Ra) is essential to balance legibility and hygienic performance of laser-marked components. The average roughness results from all tests are summarized in **Table 4.**

Table 4. Average Surface Roughness (Ra) Results of Laser-Marked SKD-11

Test No.	Parameter Variation	Average Ra (μm)	*K%*
1	70 mm/s, 80 W,49 kHz	19,6	1,5
2	85 mm/s, 85 W,50 kHz	20,9	10,3

3	100 mm/s, 95 W, 52 kHz	26,8	10,1
4	150 mm/s, 100 W, 54 kHz	29,8	6,8
5	200 mm/s, 150 W, 56 kHz	34,7	20,7
6	250 mm/s, 160 W, 58 kHz	37,1	6,5

The average surface roughness results showed that the highest roughness value was obtained in the sixth test, reaching 37.1 µm, with a roughness increase percentage of 6.5%. This condition corresponded to the highest parameter combination of 250 mm/s, 160 W, and 58 kHz. Conversely, the lowest roughness was recorded in the first test, measuring 19.6 µm with a 1.5% increase, under the lowest energy configuration of 70 mm/s, 80 W, and 49 kHz. Although the first test exhibited the smoothest surface, the marking appeared faint and unclear, indicating insufficient laser energy for proper engraving.

The highest setting (Test 6) produced very clear and sharp markings, but also resulted in a significantly rougher surface, potentially increasing surface porosity and contamination risk (D'Ercole et al., 2023; Barão et al., 2023). Therefore, the fourth test—with a laser speed of 150 mm/s, power of 100 W, and frequency of 54 kHz—was identified as the most balanced configuration, producing a surface roughness of 29.8 µm with a 6.8% increase.

This setting achieved clear and uniform markings without excessive surface irregularities, maintaining roughness below 10%, a level suitable for hygienic and sterilizable industrial components (Jurčs et al., 2023; Farias et al., 2022). These findings reinforce that while higher laser energy improves visual legibility, it must be carefully optimized to prevent excessive roughness that can compromise cleanliness and microbial resistance on medical-grade surfaces.

CONCLUSION

This study aimed to analyze the clarity of laser-marked text on SKD-11 tool steel under varying laser speeds, power, and frequencies. The findings demonstrated that improper parameter selection can significantly increase surface roughness, potentially compromising the product's suitability for industrial and hygienic applications. Surface roughness measurements using the YRT200 (Ra) tester revealed that higher laser energy (speed, power, and frequency) improved text legibility but also increased surface roughness.

The optimal configuration was achieved in the fourth test, using parameters of 150 mm/s, 100 W, and 54 kHz, which resulted in a surface roughness of 29.8 µm and a 6.8% increase—producing clear, legible markings without exceeding the roughness threshold considered acceptable for clean and sterilizable industrial surfaces. These results confirm that balanced laser parameter settings can achieve both visual clarity and surface quality suitable for medical, food-grade, and precision manufacturing applications.

SUGGESTION

Future studies are recommended to employ more advanced surface measurement technologies, such as 3D optical profilometry or confocal microscopy, to achieve comprehensive and high-resolution surface mapping. Automated multi-point roughness scanning would allow a more accurate assessment of microstructural variations across the entire marking area. Moreover, similar experiments can be applied to medical-grade materials to evaluate the feasibility of laser marking as a traceability and identification method for healthcare products.

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