Investigation of Influencing Factors on Surface Quality during Low-Speed Cutting of Steels with a Hardness exceeding 50 HRC for forging Dies

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ABSTRACT

This study investigates the factors that affect surface quality in low-speed milling of steel with a hardness greater than 50 HRC, specifically for forming molds. The material used in the experiment was SKT4 mold steel with a hardness of 50 HRC, which is commonly employed to form molds, with dimensions of 100×100×50 mm. The cutting tools put into service were carbide ball end mills of the HARD Series 5R×10×60L. This study examines changes in the surface roughness values of the milled workpiece material based on the feed rate and cutting depth. The constant spindle speed deployed was 1,200 rpm, and heat dissipation was achieved by air cooling. The results revealed that the feed rate and the interaction between the feed rate and the cutting depth had a p-value of 0.000. This considerably influences the average surface roughness (R_a) value at the 0.05 significance level. However, the cutting depth had a p-value of 0.061, which is greater than the significance level of 0.05 and thus does not substantially affect the average surface roughness.

Keywords-factors affecting surface quality; low-speed cutting; steels; hardness greater than 50 HRC; die forging

I. INTRODUCTION

JIS SKT4 is a highly utilized steel in the fabrication of hot work forging dies. It is well-regarded for its outstanding attributes, including exceptional strength, toughness, high hardness, resistance to elevated temperatures, and efficient hardening capabilities. It also exhibits excellent resistance to impact and compression forces. The utilization of precision milling and grinding techniques is indispensable to achieve minimal surface roughness, guaranteeing a finished product of superior quality. High-quality surfaces are a key sign of high-performance machining in the production process [1-2]. Ongoing research in the machining of hardened materials, such as JIS SKT4, plays a pivotal role in enhancing the efficiency of mold and die production. This, in turn, contributes to advances in the automotive industry by fostering improved manufacturing processes and ameliorating product quality.

The study of factors that influence surface quality in low-speed milling processes for steel with a hardness exceeding 50 HRC in the manufacturing of forged dies is a significant research endeavor. This is crucial because steel with a hardness greater than 50 HRC is highly rigid, making high-speed milling challenging and resulting in potential cracks and surface defects [3-4]. Therefore, it is necessary to employ low-speed milling to achieve the desired smooth and high-quality surface. The surface roughness in the milling process depends on various factors, including material properties, cutting tools, cutting parameters, and machine settings. This applies to the SKT 4 steel milling process using ball-nose carbide end mills and cooling with air, as several factors can affect the surface roughness. The cooling fluid plays a pivotal role in the milling of hardened steel or other challenging-to-machine materials, especially when operating at high speeds. The utilization of coolant in milling is primarily intended to reduce cutting temperatures and friction, thereby extending the useful life of the cutting tool effectively. Furthermore, it improves machining efficiency and plays a vital part in achieving superior surface quality [5-8]. Since dry machining is widely recognized as a sustainable solution to reduce negative impacts on human health and the environment, dry or near-dry machining has been widely accepted [9]. Dry machining reduces pollution, has less harmful effects on health [10], and is a more cost-effective alternative to wet machining, as it does not require a coolant [11-12]. Dry milling is a versatile process that can be deployed to machine a wide range of materials [13-14]. However, during dry milling, the absence of coolant creates significant friction between the tool and the workpiece, leading to elevated cutting temperatures. This thermal stress accelerates tool wear and promotes the adhesion of workpiece material to the cutting edge (built-up edge), further exacerbating frictional forces and compromising machining accuracy [10].

This study evaluates selected factors that affect the surface quality of steel with a hardness greater than 50 HRC in the process of die formation. A low rotational speed of 1200 rpm was employed with variable feed rates and cutting depths to improve cutting efficiency and enhance the surface roughness (R_a) of SKT4 steel. Previous studies have shown that cutting speed, feed rate, and cutting depth affect surface roughness [15-19]. In [20-23], surface roughness was examined as a function of cutter axis inclination angle, tool diameter, spindle speed, feed rate, and cutting depth. In [24], the optimal conditions for the final milling pass were defined by the quality of the surface finish and the tactile feedback from the cutting tool. The selection process considered a cutting speed (V_c) of 204 m per minute, a feed rate (f_z) between 0.1 and 0.2 mm per tooth, a cut width (a_e) of 0.2 mm, and a cutting depth (a_p) of 0.2 mm [24]. Optimizing cutting parameters, including axial cutting depth, spindle speed, and feed rate, is crucial to achieve superior surface quality. Monitoring the resulting surface finish to ensure that it remains within the desired range is essential and requires further investigation [1].

As milling plays an essential role in the machining of dies and molds, it is a necessary to pinpoint the influential factors that contribute to the surface roughness of the resulting dies crafted from SKT4 steel. This study engaged ball-end mill cutters on a CNC milling machine. The radius of the ball end mill determines the curvature of its cutting surface. A smaller radius yields a finer surface finish by accessing tighter spaces. Conversely, a larger radius leads to a coarser finish as it covers more area per pass. The radial depth of the cut determines how deeply the tool cuts into the material perpendicular to its axis. A smaller radial depth typically produces a finer finish by reducing material removal per pass, minimizing chatter, and smoothing surfaces. This study investigates the selection of appropriate cutoff factors that affect the machining competence and surface quality of steel with a hardness exceeding 50 HRC, with particular emphasis on low speeds, feed rates, and cutting depth.

II. EXPERIMENTAL PROCESS

The experimental process aimed to analyze how machining parameters affect surface roughness (R_a) in forging dies made of JIS SKT4 tool steel. This study implemented a Chevalier QP 2026-L (3-axis) CNC milling machine with a ball nose carbide end mill, as depicted in Figure 1. SKT4 steel samples, sized 100×100×50 mm with a hardness range of HRC 50 were prepared, as observed in Figure 2. Surface roughness was measured utilizing a Mitutoyo Surftest SJ-301, portrayed in Figure 4. The results were exploited to optimize the machining parameters for better surface roughness and quality in forging die manufacturing.

Fig. 1. The CNC milling machine (3axis).

Fig. 2. SKT4 workpiece used in the experiment.

TABLE I. SKT4 TOOL STEEL PROPERTIES

Chemical	**C** (%)	**Si** (%)	**Mn** (%)	**Cr** (%)	**Ni** (%)	**Mo** (%)	**V** (%)
Composition	0.55	0.30	0.80	1.20	1.6	0.50	0.10

Fig. 3. Cutting tool used in the experiment (ball-nose carbide end mill).

Fig. 4. Calibrated Mitutoyo surface roughness tester model SJ-310.

The identification of factors and responses involved collecting variables that were anticipated to influence the production process and quality of the forging dies. Drawing on previous studies and mold milling specialists from a forging mold factory, this study pinpointed the primary factors influencing the mold milling process, as outlined in Table II. This study chose surface roughness (R_a) as the measurement criterion to determine responses. Two key factors, feed rate with a maximum spindle speed of 1200 rpm and cutting depth, were identified as significantly affecting surface roughness (R_a). Using Analysis of Variance (ANOVA), the results were analyzed to identify factors with a significant impact on the response [25]. The surface roughness measurement parameters were derived from the analysis of the experimental results employing Minitab 16, with a selected significance level of 0.05 [26-27].

The current study specifically explored the surface roughness produced with a ball nose carbide end mill in SKT4 steel mold materials. A workpiece of the desired size and shape was prepared and placed in the automatic milling machine with selected parameters. At first, rough milling was performed, followed by clamping the workpiece and air cooling. Then, the experimental parameters were entered into the milling machine for surface roughness milling with air assistance, as exhibited in Figure 5. Surface roughness (R_a) measurements were carried out applying the Mitutoyo Surf Test 3D, taking 8 measurements per surface, totaling 128 measurements, as observed in Figure 6.

III. RESULTS AND DISCUSSION

ANOVA was used to assess the direct and indirect effects of feed rate and cutting depth on surface roughness. The experimental workpiece, customized to the desired size and shape, was milled on an automatic milling machine, following the experimental design parameters. The workpiece was milled and grooved with a size of 10 mm as per the experimental design, incorporating feed rates of 300, 500, 600, and 800 mm/min, and depths of 0.1, 0.2, 0.4, and 0.6 mm. Table III illustrates the results, highlighting the impact of these machining parameters on the surface roughness of the SKT4 steel, utilizing 2-flute carbide ball-nose end mills with a diameter of 10 mm.

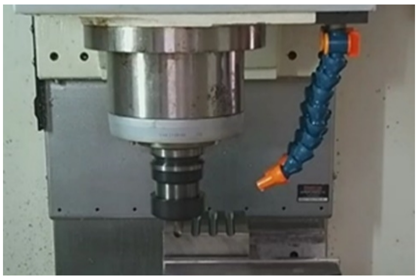

Fig. 5. Milling of the experimental workpiece.

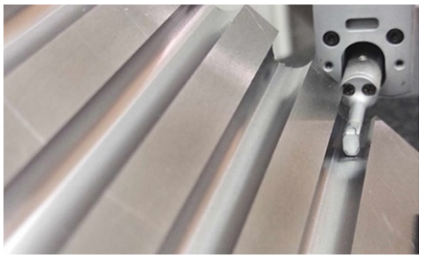

Fig. 6. Using tools to check the surface roughness of workpieces.

TABLE II. EXPERIMENTAL FACTORS AND LEVELS USED

Parameter	Level				Unit
Spindle speed	1200				rpm
Feed rate	300	500	600	800	mm/min
Depth of cut	0.1	0.2	0.4	0.6	mm

The results of the ANOVA at the 5% significance level ($p<0.05$) were utilized to identify the statistically significant impact of the milling parameters on surface roughness. The predictive model was tested at the 5% significance level, and the cutting performance or cutting efficiency was evaluated based on surface roughness. Statistical comparisons were made between feed rates and depths to find the most appropriate relationship. The ANOVA results at feed rates of 300, 500, 600, and 800 mm/min and depths of 0.1, 0.2, 0.4, and 0.6 mm demonstrated that the feed rate and the interaction between the feed rate and the cutting depth had a p-value of 0.000, which is less than the significance level of 0.05. Table IV indicates that feed rate substantially affects surface roughness, as evidenced by the p-value associated with this variable being considerably lower than the chosen significance level [26]. However, the cutting depth has a p-value of 0.061, which is higher than the significance level of 0.05, and therefore it does not considerably affect the average surface roughness. Surface roughness increases with an increase in the feed rate. On the contrary, cutting depth does not exhibit an importal influence on surface roughness [28].

TABLE III. EXPERIMENTAL DESIGN MATRIX WITH SURFACE ROUGHNESS RESULTS IN THE MACHINING OF JIS SKT4 TOOL STEEL AT A SPINDLE SPEED OF 1200 RPM.

Runs	Factors			R_a1 (µm)	R_a2 (µm)	R_a3 (µm)	R_a4 (µm)	R_a5 (µm)	R_a6 (µm)	R_a7 (µm)	R_a8 (µm)	R_a (avg) (µm)
	Spindle speed (rpm)	Feed rate (mm/min)	Cutting depth (mm)									
1	1200	300	0.1	0.355	0.403	0.452	0.427	0.304	1.317	0.345	0.504	0.513
2			0.2	0.385	0.479	0.655	1.146	0.857	0.547	0.428	0.456	0.619
3			0.4	0.618	0.414	0.769	0.995	0.301	0.430	0.416	0.416	0.545
4			0.6	0.543	0.995	0.797	0.550	0.927	0.557	0.605	0.577	0.694
5		500	0.1	0.821	0.921	0.961	0.758	1.109	1.096	1.124	1.198	0.999
6			0.2	0.434	0.339	0.362	0.338	0.293	0.457	0.514	0.515	0.407
7			0.4	0.478	0.396	0.466	1.092	0.393	0.471	0.512	0.526	0.542
8			0.6	0.606	0.737	0.741	0.522	1.372	1.351	1.251	1.318	0.987
9		600	0.1	0.456	0.393	0.657	0.700	0.804	1.022	0.700	0.599	0.666
10			0.2	0.664	0.850	0.362	0.345	1.037	1.496	1.465	1.527	0.968
11			0.4	0.502	0.447	0.341	0.614	1.078	1.039	0.893	1.049	0.745
12			0.6	0.732	0.951	0.365	0.451	0.628	0.693	0.677	0.667	0.646
13		800	0.1	0.801	0.713	0.869	0.922	0.760	0.816	0.953	0.842	0.835
14			0.2	0.971	0.906	0.988	0.899	0.921	0.549	0.616	0.611	0.808
15			0.4	0.994	0.978	1.033	0.975	0.700	0.921	0.522	0.766	0.861
16			0.6	1.079	1.142	1.390	1.308	0.454	0.719	0.966	1.176	1.029

TABLE IV. ANOVA FOR SURFACE ROUGHNESS TO FEED RATE, CUTTING DEPTH, AND FEED×CUTTING DEPTH

Analysis of Variance					
Source	**DF**	**Adj SS**	**Adj MS**	**F-value**	**p-value**
Feed rate	3	1.3398	0.44660	6.73	0.000
Cutting depth	3	0.5029	0.16764	2.53	0.061
Feed rate × Cutting depth	3	2.6365	0.29294	4.42	0.000
Error	112	7.4269	0.06631		
Total	127	11.906			

The statistical equation used to calculate surface roughness (R_a) is given by:

$$R_a = 0.557 + 0.000563 \times Feed$$
$$-1.290 \times Depth\ of\ cut + 2.069 \times Depth\ of\ cut^2 \quad (1)$$

Figure 7 shows the error analysis. The normal probability plot displays the relationship between the surface roughness (R_a) and the normal distribution. The R_a should be normally distributed. If R_a is normally distributed, the graph line will pass through the center of the graph. The histogram demonstrates the distribution of R_a, which is mostly in the range of -0.5 to 0.5. The versus fit presents the relationship between the actual R_a and the predicted. The actual R_a values are close to the predicted R_a constants. The versus order reveals the relationship between the actual R_a and the measurement order. The actual R_a values are consistent in each measurement order. The examination of residuals indicates that the model is well-suited for predicting surface roughness during the hard milling process of JIS SKD61 steel, as all residuals consistently remain within the defined control limits [29-30].

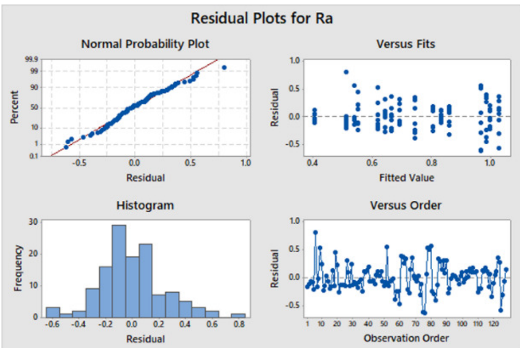

Fig. 7. Plot of residuals for surface roughness.

Figures 8 depicts the comparison of 95% confidence intervals of R_a versus cutting depth and feed rate. Specifically, Figure 8 (a) compares the 95% confidence intervals for the depth levels of milling (0.1, 0.2, 0.4, and 0.6 mm), disclosing that there is no statistically significant difference. Figure 8 (b) illustrates the comparison of the 95% confidence interval for the feed rates of 800 and 300 mm/min. This has a considerable impact on surface quality, with the feed rate of 800 mm/min providing a better surface quality than the feed rate of 300 mm/min. For feed rates between 500 and 300, 600 and 300, 600 and 500, 800 and 500, and 800 and 600 mm/min, there is no statistically substantial difference.

(a)

(b)

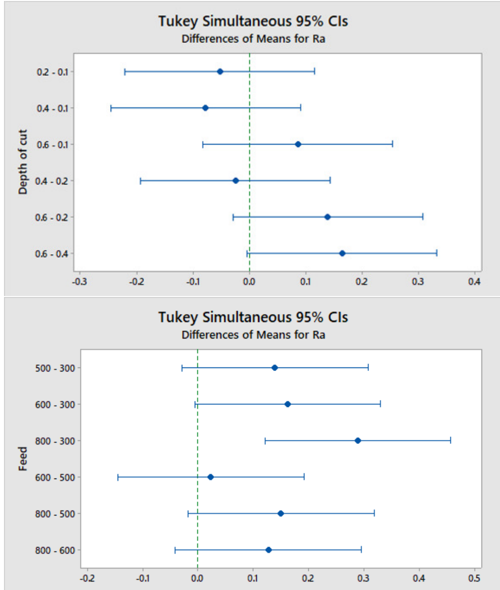

Fig. 8. Tukey's comparison plots indicating the 95% differences for the depth and feed rate values.

The impact analysis in Figure 9 manifests that the feed rate has a positive correlation with the R_a value. As the feed rate increases, the R_a value also increases, resulting in a rougher surface texture. Similarly, the graph for cutting depth indicates a positive relationship with the R_a value. As the cutting depth rises, the R_a value also increases, leading to a rougher surface texture. Furthermore, the graph for the feed rate × cutting depth demonstrates a positive correlation with the R_a value. When both the feed rate and the cutting depth increase, the R_a value increases, causing the surface texture to become rougher. In summary, these results showcase that feed rate and feed rate × cutting depth have a positive relationship with the R_a value.

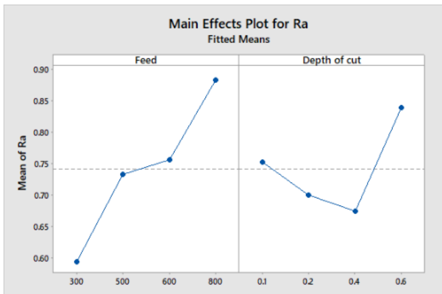

Fig. 9. Main influence graph illustrating the average values of each factor.

The impact analysis spotted in Figure 10 discloses that the feed rate has a positive relationship with the R_a value. The R_a value increases as the feed rate increases, resulting in a rougher surface texture. This is evident from the steep incline of the graph when the feed rate increases from 300 to 500 mm/min. However, the graph's slope gradually decreases as the feed rate increases from 500 to 800 mm/min. Similarly, the cutting depth graph indicates a positive relationship with the R_a value. The R_a value increases as the cutting depth increases, leading to a rougher surface texture. This is apparent from the steep incline of the graph when the cutting depth raises from 0.1 to 0.2 mm. However, the graph's slope gradually decreases when the cutting depth increases from 0.2 to 0.4 mm. Furthermore, the feed rate × cutting depth graph demonstrates a positive correlation with the R_a value. The R_a value increases as feed rate × cutting depth increases, resulting in a rougher surface texture. This is visible from the steep incline of the graph when the feed rate × cutting depth increases from 300 at 0.1 mm to 500 mm/min at 0.2 mm. However, the graph's slope gradually decreases when the feed rate × cutting depth increases from 500 mm/min at 0.2 mm to 800 mm/min at 0.4 mm.

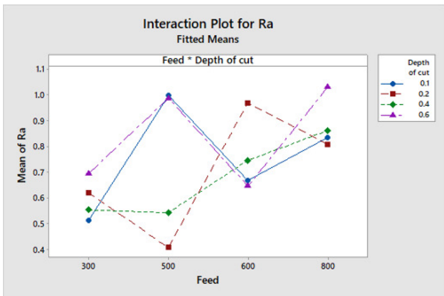

Fig. 10. The combined influence of feed rate and cutting depth.

IV. CONCLUSIONS

This study aimed to optimize the cutting parameters to minimize surface roughness (R_a) during the milling of JIS SKT4 tool steel (HRC 50) using carbide ball nose endmills. The ANOVA results showed that the factors, namely constant speed at 1200 rpm, feed rate, and cutting depth, were systematically controlled based on the experiment's predetermined parameters. Feed rate has the greatest influence, followed by cutting depth. Analyzing response factors that are significantly correlated at a 95% confidence level and considering the surface roughness (R_a) conditions of JIS SKT4 tool steel in hard milling are crucial for its application. The results displayed that the factors that influence surface quality in low-speed milling (1200 rpm) of high-hardness steels (> 50 HRC) forging are crucial, as evidenced by the significant challenge in achieving a desired surface roughness (R_a) finish. This is highlighted by the experimental results, which reveal an average surface roughness ranging from 0.407 to 1.029 μm. The optimized cutting parameters for a material with a hardness of 50 HRC to achieve desirable surface roughness include feed rates of 300, 500, 600, and 800 mm/min and a cutting depth ranging from 0.1 to 0.6 mm. The predicted surface roughness falls within the range of 12.5 to 3.2μm under these specified conditions [31]. This study provides valuable insights into the relationship between cutting parameters and surface roughness [32]. The results exhibited that feed rate and cutting depth affect surface roughness, which is consistent with previous studies. A low spindle speed (1200 rpm) was chosen, finding that the surface roughness values resulting from the experiments were of high quality and suitable for use in the final machining process. Future research will investigate how parameters such as feed rate, cutting depth, and low cutting speeds influence both tool wear and surface quality.

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