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Interaction Effects of Cutting Parameters on Surface Roughness in Hard Milling of AISI D2 Tool Steel

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ABSTRACT: This paper investigates the effects of cutting speed, feed rate, and depth of cut on the surface roughness (R_a) in the dry hard milling of AISI D2 steel (60–62 HRC) using carbide inserts. A Box–Behnken experimental design was applied to evaluate the interaction effects among the machining parameters. The experimental results clearly reveal the influence trends and interaction relationships of cutting conditions on surface roughness. At a depth of cut of 0.15 mm, lower surface roughness values were obtained when the cutting speed ranged from 105 to 120 m/min and the feed rate was maintained between 0.10 and 0.11 mm/tooth. For a feed rate of 0.15 mm/tooth, improved surface quality was achieved with cutting speeds of 108–120 m/min and depths of cut of 0.10–0.15 mm. Furthermore, when the cutting speed was fixed at 100 m/min, feed rates of 0.10–0.11 mm/tooth combined with all investigated depths of cut produced lower Ra values. These findings provide useful technical guidelines for future studies and practical applications in hard milling processes.

KEYWORDS: Hard Milling; Cutting Parameter; Cutting Speed; Feed Rate; Depth Of Cut; Surface Roughness

1. INTRODUCTION

In the last few decades, machining of difficult-to-cut materials has been gaining much attention and widely applied in production practice, in which hard machining is typically an advanced manufacturing process used to machine materials with hardness typically above 45 HRC after heat treatment [1]. Up to now, this technology has been commonly used in modern industries such as aerospace, automotive, die and mold, and precision engineering due to its ability to replace conventional grinding operations [2]. Hard machining processes mainly include hard turning, hard milling, and hard drilling, which are commonly performed using cutting tools made from cubic boron nitride (CBN), ceramics, or coated carbides [3]. Compared with traditional grinding, hard machining offers several advantages, including reduced production time, lower manufacturing cost, higher flexibility, and the ability to achieve complex geometries with acceptable surface quality and dimensional accuracy [4]. However, machining hardened materials also presents challenges such as high cutting forces, rapid tool wear, elevated cutting temperatures, and difficulties in maintaining surface integrity [5]. Therefore, understanding the effects of cutting parameters, tool materials, lubrication conditions, and machining environments is essential for improving machining performance and product quality. As a result, hard machining has become an important research area in advanced manufacturing and sustainable machining technologies.

AISI D2 steel is a high-carbon, high-chromium cold-work tool steel widely used in manufacturing industries because of its excellent wear resistance, high hardness, and good dimensional stability after heat treatment. It typically contains a high amount of carbon and chromium, along with alloying elements such as molybdenum and vanadium, which contribute to its superior mechanical and metallurgical properties [6]. After hardening and tempering, AISI D2 steel can achieve a hardness range of approximately 55–62 HRC, making it highly suitable for hard machining applications. One of the most important properties of AISI D2 steel is its outstanding wear resistance, which results from the presence of large volumes of chromium-rich carbides in its microstructure. This property allows the material to maintain tool life and resist abrasion during severe working conditions. In addition, AISI D2 steel possesses high compressive strength and good resistance to deformation, enabling it to perform effectively in die and mold applications. The steel also exhibits moderate toughness and good dimensional stability during heat treatment, reducing distortion and maintaining precision in finished components. However, due to its high hardness and abrasive carbides, AISI D2 steel is considered difficult to machine using conventional cutting tools. Machining this material often generates high cutting temperatures, increased tool wear, and large cutting forces [5]. Therefore, advanced cutting tools such as cubic boron nitride (CBN), ceramic, and coated carbide tools are commonly used for machining AISI D2 steel. Because of its excellent combination of hardness, wear resistance, and strength, AISI D2 steel is extensively applied in punches, dies, shear blades, rolling tools, and precision forming components [7]. Hence, the selection of cutting parameters plays a key role in improving the machining performance of this type of tool steel. Besides, from the obtained results, the technological guidelines are provided for further studies and manufacturing practice.

2. METHODOLOGY

MCV-410 milling machine (Japan) was used for hard milling experiments (Figure 1). The cutting trials were carried out under dry condition. AISI D2 steel samples were heat-treated to achieve hardness values between 60 and 62 HRC and subsequently utilized in the hard milling experiments. Tables 1, 2 show the chemical composition and mechanical properties of AISI D2 tool steel. The values of surface roughness R_a were measured three times after each cut and the average value was taken. The Box-Behnken experimental design was used to form the experimental matrix shown in Table 3. The cutting trials were implemented by following the run order to investigate the effects of surveyed variables including cutting speed, feed rate, and depth of cut on the surface roughness R_a.

Table 1. Chemical composition of AISI D2 tool steel (ASTM A681 standard specification)

Element	C		Mn		P	S	Si		Cr		V		Mo	
Weight (%)	1.4	1.6	0.1	0.6	0.03	0.03	0.1	0.6	11	13	0.5	1.1	0.7	1.2

Table 2. Mechanical Properties of AISI D2 tool steel

Mechanical Properties	Metric	Imperial
Hardness, Knoop (converted from Rockwell C hardness)	769	769
Hardness, Rockwell C	62	62
Hardness, Vickers	748	748
Izod impact unnotched	77.0 J	56.8 ft-lb
Poisson’s ratio	0.27-0.30	0.27-0.30
Elastic modulus	190-210 GPa	27557-30457 ksi

Figure 1. MCV-410 milling machine used for experiments

Table 3. The experimental matrix based on Box-Behnken experimental design

Std Order	Run Order	PtType	Blocks	v (m/min)	f (mm/tooth)	d (mm)
14	1	0	1	100	0.15	0.15
15	2	0	1	100	0.15	0.15
12	3	2	1	100	0.2	0.2
8	4	2	1	120	0.15	0.2
10	5	2	1	100	0.2	0.1
6	6	2	1	120	0.15	0.1

Std Order	Run Order	PtType	Blocks	v (m/min)	f (mm/tooth)	d (mm)
1	7	2	1	80	0.1	0.15
11	8	2	1	100	0.1	0.2
2	9	2	1	120	0.1	0.15
13	10	0	1	100	0.15	0.15
5	11	2	1	80	0.15	0.1
3	12	2	1	80	0.2	0.15
4	13	2	1	120	0.2	0.15
7	14	2	1	80	0.15	0.2
9	15	2	1	100	0.1	0.1

3. RESULTS AND DISCUSSION

The hard-milling experiments were carried out by following the run order based on the Box-Behnken experimental design. A contour plot is used to represent the relationship between two input variables and a response variable on a two-dimensional plane. This plot helps observe the change in output values when two input factors change simultaneously. Contour lines are lines connecting points with the same response value, similar to contour lines on a topographic map. When contour lines are close together, it indicates that the response value changes rapidly and that the area is sensitive to changes in the variables. Conversely, if the lines are far apart, the change is slower and more stable. The shape of the contours also helps identify the interactions between variables; curves or bends often indicate non-linear interactions or relationships between factors. Contour plots are commonly used in design experiments (DOE), response surface methods (RSM), and process optimization to determine the optimal operating conditions or desired output values. The contour plots below illustrate the interaction effects of input variables on output variables when one variable is kept at a fixed value. Specifically, when the cutting depth is kept fixed at 0.15 mm, the cutting speed is between 105-120 m/min and the feed rate is 0.1-0.11 mm/tooth, resulting in a smaller surface roughness value R_a (R_a <0.15 µm) (Figure 2).

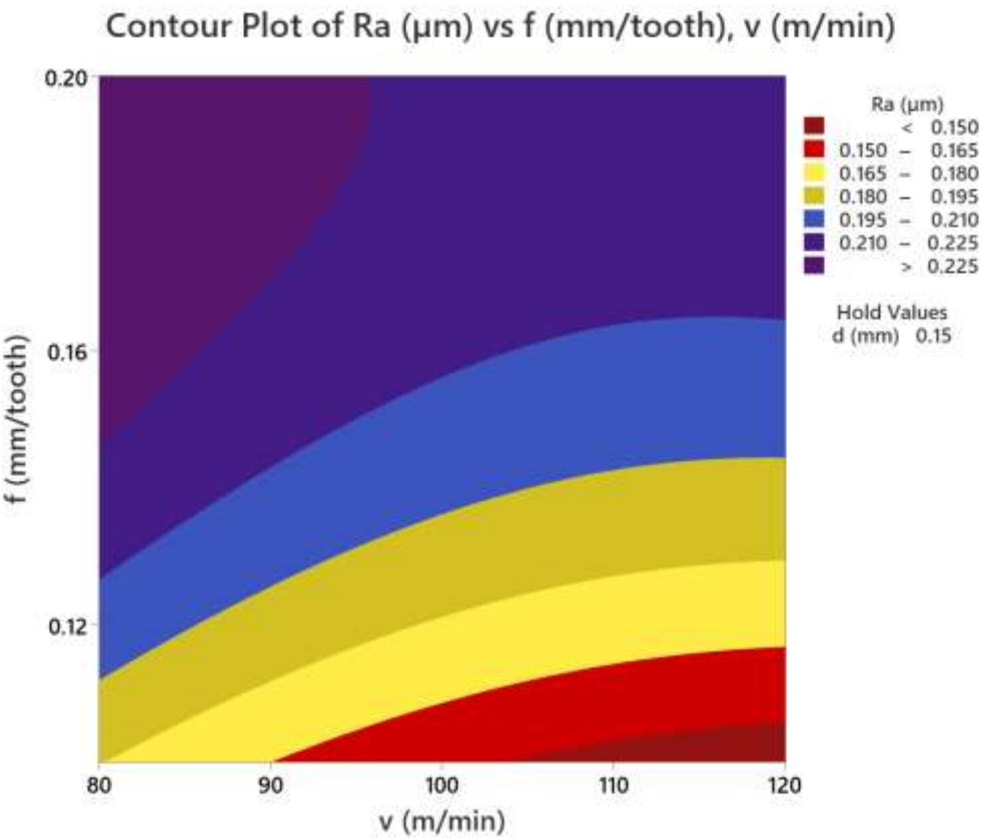

Figure 2. Contour plot of the effects of feed rate and cutting speed on surface roughness R_a

In the case of a feed rate f=0.15 mm/tooth, a cutting speed in the range of 108-120 m/min and a cutting depth in the range of 0.1-0.15 mm will result in a smaller surface roughness value R_a (R_a<0.2 µm) (Figure 3). When the cutting speed is kept fixed v=100 m/min, the feed rate in the range of 0.1-0.11 mm/tooth and the cutting depth can be selected within the entire range of values investigated, which will result in smaller surface roughness R_a values with R_a<0.165 µm (Figure 4). Thus, for each specific cutting condition, a suitable range of cutting parameter values can be selected to achieve better surface quality when milling hardened AISI D2 steel. This is of significant importance in providing reasonable technological guidelines and serves as a foundation for further research.

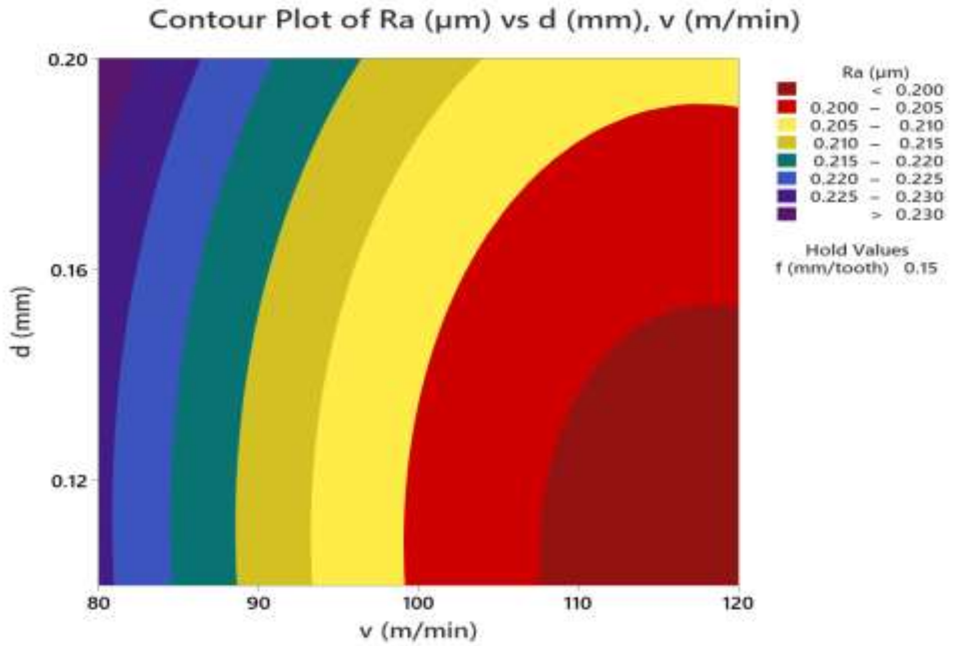

Figure 3. Contour plot of the effects of depth of cut and cutting speed on surface roughness R_a

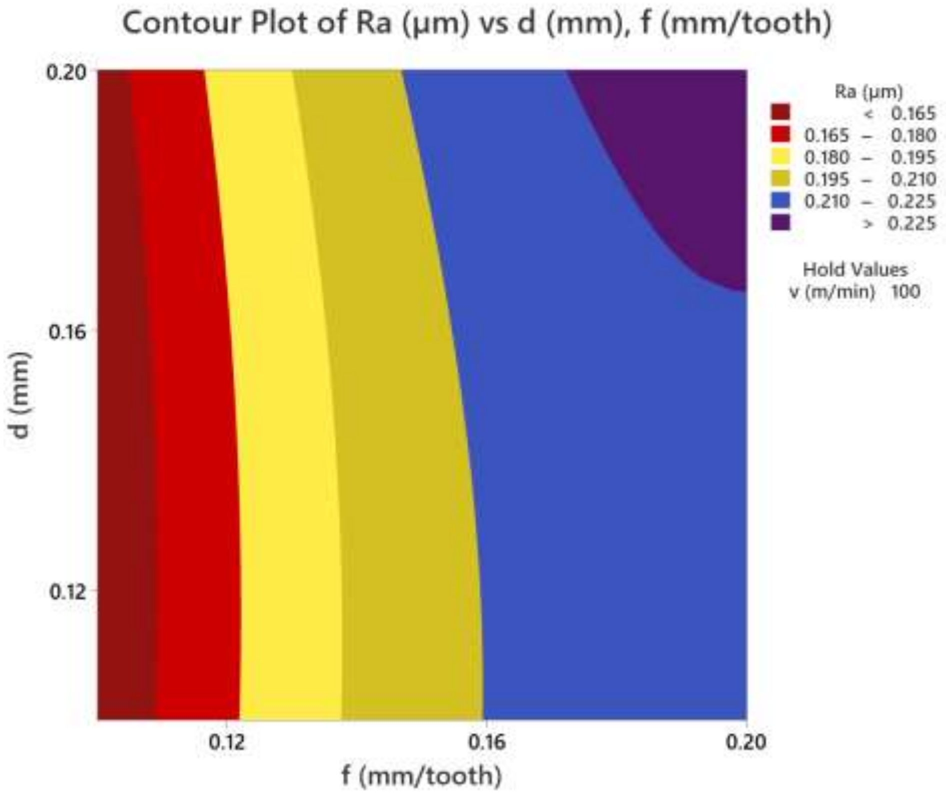

Figure 4. Contour plot of the effects of depth of cut and feed rate on surface roughness R_a

4. CONCLUSION

This article experimentally investigates the effects of machining parameters on the surface roughness value (R_a) during the hard milling of AISI D2 steel (60–62 HRC) using coated carbide inserts under dry cutting conditions. A Box–Behnken experimental design was employed to analyze the interaction effects of cutting speed, feed rate, and depth of cut. The results clearly demonstrate the influence trends and interaction relationships among these parameters on surface roughness. When the depth of cut was maintained at 0.15 mm, a cutting speed ranging from 105 to 120 m/min combined with a feed rate of 0.10–0.11 mm/tooth produced lower surface roughness values ($R_a < 0.15$ µm). For a feed rate of 0.15 mm/tooth, selecting a cutting speed between 108 and 120 m/min and a depth of cut between 0.10 and 0.15 mm resulted in reduced surface roughness values ($R_a < 0.20$ µm). In addition, when the cutting speed was fixed at 100 m/min, feed rates in the range of 0.10–0.11 mm/tooth together with any investigated depth of cut generated lower surface roughness values ($R_a < 0.165$ µm). The study provides practical technological guidelines that can serve as a basis for future research and manufacturing practice.

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