Optimization of Process Parameters for Machining of Steel Molds used for Aluminum Casting in Wheel Industry

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Abstract. The wheel industry, employing low-pressure casting techniques for producing lightweight alloy wheels, operates within a highly competitive manufacturing environment with significant production volumes. To fabricate essential mold core components for the aluminum wheel casting process, hot work tool steel alloys are selected for their exceptional durability and resistance to wear, fatigue, distortion, and high-temperature plastic deformation. Efficient machining operations for these steel molds require identifying optimal parameter combinations to minimize tool wear, surface roughness, and energy consumption while maximizing material removal rates. This study focuses on determining such parameters, utilizing DIN 1.2367 steel, to enhance manufacturing efficiency and meet industry requirements. The effects of machining parameters such as cutting speed, depth of cut, and number of inserts were investigated using the design of experiments. Depth of cut was determined as the most influential factor on tool wear, revealing the optimum parameter as 0.4 mm, followed by cutting speed. Notably, the number of inserts exhibits minimal direct impact but interacts significantly with the depth of cut, influencing wear patterns. This research contributes to sustainable machining practices by enhancing mold core manufacturing efficiency, prolonging tool life, and reducing tool wear. Such advancements are vital for the long-term competitiveness and environmental stewardship of the wheel industry.

1 Introduction

The wheel industry of Türkiye, whose foundation dates back to the 50s, has over ten major and mid-scale enterprises with a significant production volume and scope [1]. The wheel industry commonly incorporates low-pressure casting, which involves filling the casting cavity against gravity, for the fabrication of light alloy wheels [2]. Due to their low density, ease of machinability, high strength, and resistance to corrosion, aluminum alloys have been a common material of choice in the light wheels as well as many other components used in automotive industry [3]. The molds needed for low pressure casting of aluminum alloys for the manufacturing of light wheels are composed of a variety of assembly pieces besides the

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core parts. Side, top, and bottom mold cores are main parts of wheel molds where the bottom core provides the contour to the wheel's style surface. Molten aluminum alloy, usually at a temperature of 680-720°C fills the casting cavity whose boundaries are defined by the core parts of the molds [4]. Because of those elevated temperature values during the casting process, hot work tool steel alloys which are durable, wear-, fatigue-, and distortion-resistant, as well as resistant to plastic deformation at high temperatures are employed for the fabrication of the mold core parts to be used in the aluminum casting process [5].

Steels used in hot work tools are categorized based on their chemical composition. One material cannot be expected to possess every one of the beneficial qualities of hot work tool steels. For this reason, it is crucial to select the right material for the intended use when selecting steel [6]. DIN 1.2367 steel, which is also known as X38CrMoV5-3 and composed of vanadium, molybdenum, and chromium, is commonly used in punches, die cores, injection molds, extrusion dies, etc. It is suitable for heat intervention and can readily achieve high hardness values. Later in the hardening phase, it reaches its peak toughness and provides improved resistance to thermal shock and fatigue, resulting in longer tool life and less maintenance needs. In addition, its machinability and weldability add to its extensive application in a variety of manufacturing industries [7].

Determination of appropriate combination of machining parameters for specific material and experimental setup to minimize tool wear, surface roughness of workpiece, energy consumption of the machining operation etc. with maximized material removal rate has been an important task to improve the efficiency of machining operations [8]. To achieve this, design of experiment (DoE) tools which provides a statistical formal methodology that enables us to establish a statistical association between an array of input parameters and a selected output of the system or process under examination are commonly employed [9]. Taguchi technique is a widely used approach for DoE to optimize machining parameters in manufacturing industry since it enables a prediction of a maximum number of primary outcomes in an unbiased (orthogonal) manner with a minimal number of experimental runs [10]. Hence, many different research groups benefited from the advantages of Taguchi method to seek the optimum machining conditions for minimized surface roughness after milling of Hardox 600 steel [11], for minimized surface roughness and tool wear after end milling of hardened steel [12], for maximized tool life after milling of titanium alloy [13], and so on. However, the literature on the determination of optimum machining process parameters for minimized tool wear after machining of DIN 1.2367 steel is limited.

This work aims to determine the optimized machining parameters for the fabrication of bottom core component of a casting mold to be utilized in the aluminum alloy wheel industry. Based on the listed advantages above and requirements of the industry and casting process, DIN 1.2367 steel is selected as the working material. With this study, we aim to minimize the tool wear during the milling operation as a part of our efforts to decrease the number of operations and time required for total manufacturing of mold cores that are used for casting of light aluminum alloys in wheel industry.

2 Materials and Methods

The material of the workpiece that was used during the milling processes utilized in this study was a DIN1.2367 steel obtained from Birleşik Metal & Special Alloys Co. (İzmir, Türkiye). The chemical composition of the material is provided in Table 1. To avoid hard machining conditions, the hardness of the DIN 1.2367 steel was kept at 32 HRC by adjusting the tempering process. Machining was carried out using a 3 -Axis vertical CNC milling machine (DMU 85 Monoblock, DMG MORI, Heidenhain ITNC 530). Sandvik R210-025T12-09M Ø25R1.5 tool holder and Sandvik R210-0904 14E-PM S30T inserts were selected for performing the cutting operation.

Table 1. Chemical composition of DIN 1.2367 steel

% C	% Mn	% Mo	% Si	% Cr	% P	% S	% V
0.38	0.41	2.70	0.37	4.85	0.018	0.005	0.41

Table 2. Machining parameters and their levels

Levels	Number of inserts	Depth of cut (mm)	Cutting speed (mm/min)
Level 1	2	0.25	150
Level 2	3	0.4	175
Level 3	-	0.5	200

Table 3. Design matrix used for Taguchi L18 array.

Exp. No	Number of Inserts	Depth of Cut (mm)	Cutting Speed ($mm \cdot min^{-1}$)	Tool Wear (mm)
1	2	0.25	150	0.016
2	2	0.25	175	0.018
3	2	0.25	200	0.018
4	2	0.4	150	0.002
5	2	0.4	175	0.003
6	2	0.4	200	0.003
7	2	0.5	150	0.006
8	2	0.5	175	0.006
9	2	0.5	200	0.007
10	3	0.25	150	0.011
11	3	0.25	175	0.013
12	3	0.25	200	0.014
13	3	0.4	150	0.004
14	3	0.4	175	0.004
15	3	0.4	200	0.005
16	3	0.5	150	0.008
17	3	0.5	175	0.008
18	3	0.5	200	0.008

Three factors (cutting speed, depth of cut, and number of inserts) with varying levels were examined as shown in Table 2. The wear of the tool, which was measured using a HAIMER Presetter Vio Linear 20 50 measurement system was the output parameter for the experiments. Our objective is to seek for the variable parameters' optimal values for the minimum tool wear. Considering the three variables with different levels, Taguchi L18 array was used to investigate the effect of the variables on the output. There are 18 experimental points, and these points correspond to combinations of various factor levels. The purpose of these experiments is to ascertain the interactions and effects of various elements. Table 3 presents the design matrix layout used in this study for the 18 experimental runs and the tool wear resulting from each experiment. Machining parameters are varied and their effect on tool wear is analyzed using ANOVA.

3 Results and Discussion

The Taguchi design was analyzed using Minitab 18 to understand the optimal parameter settings. Table 4 presents the ANOVA results, indicating the depth of cut as the most influential factor with the lowest p-value (1E-06) and substantial contribution of 89%. Notably, a depth of cut of 0.4 mm exhibited minimal tool wear as it can be seen from the main effect plots in Figure 1a. The trend shows that higher or lower depth of cut value will lead to an increase in tool wear. It can be understood that the range of parameter levels for depth of cut was chosen effectively to reveal the optimum value in this experimental design. Cutting speed follows the depth of cut with 1.17% contribution level as a parameter that impacts the tool wear. The first level, which is 150 mm/min of cutting speed was determined as the optimum parameter level to minimize the tool wear as shown in Figure 1a. As the cutting of speed increases from 150 to 200 mm/min, the tool wear escalates. There appears to be a potential for mitigating tool wear by operating at speeds below 150 mm/min since the trend in the main effect plot shows a decrease with the lower speeds. Number of inserts has a slight impact on tool wear when it is increased from 2 to 3. Even though results show that there is a minor effect of the number of inserts, it was observed that tool failures are more common when the insert number is increased to 3 due to chip entanglement between the workpiece and cutting tool. Since further increasing the number of inserts would cause further chip entanglement and tool failures, we only used 2 and 3 inserts attached to the cutting tool. Even though the p-value of the parameters, depth of cut and number of inserts, are higher than 0.05, the trends must be considered for future experiments.

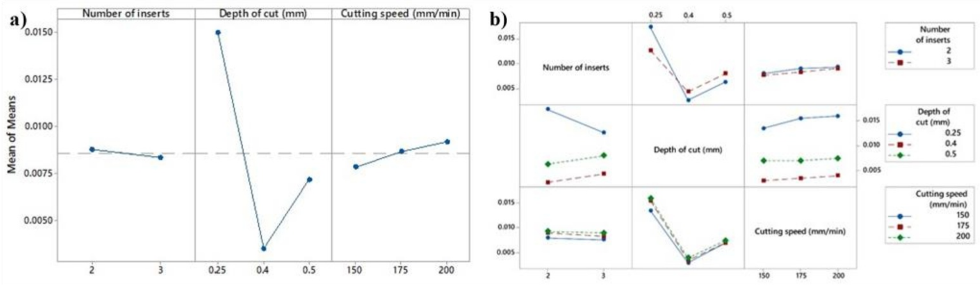

Fig. 1. a) Main effect plots for tool wear. b) Interaction plot of different parameters.

Figure 1.b shows the full interactions plot matrix of the process parameters. There is no interaction observed between number of inserts and cutting speed as the lines are approximately parallel to each other in the panels at top right and bottom left corners. However, a clear interaction between the depth of cut and the number of inserts is observed. When the number of inserts is switched from 2 to 3, the blue line representing 0.25 mm of depth of cut shows a descending trend. Similarly, if the 0.25 mm depth of cut is used, higher number of inserts is associated with the lower tool wear, whereas with the 0.4 mm depth of cut the lower number of inserts, which is 2, will give better results in terms of tool wear. The interaction between the depth of cut and cutting speed is negligible as the lines are almost

parallel to each other, except 0.25 mm depth of cut showing a slight increase as the cutting speed increases.

Table 4. ANOVA results for machining parameters

Factors	DF	Seq SS	Contribution	Adj SS	Adj MS	F-Value	P-Value
Number of inserts	1	1E-06	0.19%	1E-06	1E-06	0.24	0.63135
Depth of cut (mm)	2	0.00041	89.16%	0.00041	0.00021	56.47	1E-06
Cutting speed (mm/min)	2	5E-06	1.17%	5E-06	3E-06	0.74	0.49661
Error	12	4.4E-05	9.47%	4.4E-05	4E-06		
Total	17	0.00046	100.00%				

Table 5 shows the summary of the model properties. The low S value and the high percentage of variation in the response (R-sq) indicate that the model fits the data well. Small PRESS (The prediction error sum of squares) suggests that the model has good predictive ability.

Table 5. The model summary

S	R-sq	R-sq (adj)	PRESS	R-sq (pred)
0.001915	90.53%	86.58%	0.000099	78.68%

4 Conclusion

In this study, we have investigated the impact of the machining parameters of depth of cut, number of inserts and cutting speed on the wear of cutting tool. Our experiments showed that cutting speed is directly related to tool wear where an increase in cutting speed has a negative effect on tool wear. Moreover, while the depth of cut has a major effect on tool wear, a linear effect was not observed. The primary effect plots showed that tool wear was low at a cut depth of 0.4 mm. The trend indicates that increasing or decreasing the depth of cut value will result in more tool wear. Tool failures were observed more frequently when the number of inserts was set to three, even though the results indicate that the number of inserts has only a little impact. When interactions of factors are investigated, the number of inserts and cutting speed do not appear to be interacting. Nonetheless, a distinct relationship is seen between the number of inserts and the depth of cut. When 0.25 mm depth of cut is employed, a higher number of inserts is linked to reduced tool wear; conversely, when a 0.4 mm depth of cut is used a lesser number of inserts will produce better tool wear outcomes.

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