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Investigation of surface roughness in laser-assisted hard turning of AISI 4340

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ABSTRACT

In recent years, new materials such as titanium, nickel alloys, and high-strength steels have been widely used in medical, nuclear, and other industries. Since the manufacturing of different components from these materials has always been associated with the machining process, the use of hard machining in their production is unavoidable. The short life of the cutting tool, the poor quality of the machined surfaces, and the long machining time are some of the challenging issues involved in the traditional machining of these materials. Therefore, researchers have investigated new machining techniques to increase the efficiency and quality of produced parts. Thermal-assisted machining, especially laser-assisted machining is one of the promising methods of machining difficult-to-machine materials. However, this process faces some challenges in terms of the achievable surface integrity of the machined surfaces. This research studies the effect of cutting and thermal parameters on the surface roughness in the laser-assisted turning (LAT) process of AISI 4340 hard steel with a hardness of 560 HV. The results illustrated that by selecting a proper combination of process parameters, the damage caused by the heat penetration into the workpiece can be minimized and the advantages of LAT can be benefited from.

1. Introduction

Grinding based technologies have been attracted much attention for the fabrication of various components including gears, bearing rings, and crankshafts, owing to the achievable high surface quality of this process [1]. On the other hand, low material removal rates during the grinding process together with the inherent limitation of the process for the manufacturing of complex geometries significantly raise the cost of the operations [2,3]. To tackle these limitations, the present paper analyzes the potential of using laser-assisted turning (LAT), a hybrid machining process, as an alternative to the grinding operations.

Unlike the traditional methods, it is possible to produce a desirable shape, at a low cost, using hybrid technologies. One important process performed in the form of hybrid machining is thermal-assisted machining where a heat source is integrated into the machining process. At high temperatures, the yield strength of a brittle material is reduced to less than its fracture resistance, changing the brittle-to-ductile transition behavior of the material. For ductile materials, the high temperatures decrease the yield strength of the material while increasing ductility. This results in a substantial reduction in tool wear and machining forces, whereas surface quality is enhanced [4,5]. With the increasing demand for machining hard and brittle materials, thermal assisted machining has evolved over the past years. Various heat sources can be integrated into the machining process, the most important of which are electric current [6], magnetic induction [7], gas flame [8], plasma [9], and laser. Among the available heat sources, the laser has advantages such as ease of control, large heat production, and a higher degree of heat concentration compared to other heat sources [10].

In this research, the laser, as a heat source, was used for machining. One of the most important challenges of using heat-assisted machining of hard materials is the proper selection of a combination of process parameters which can result in the desired

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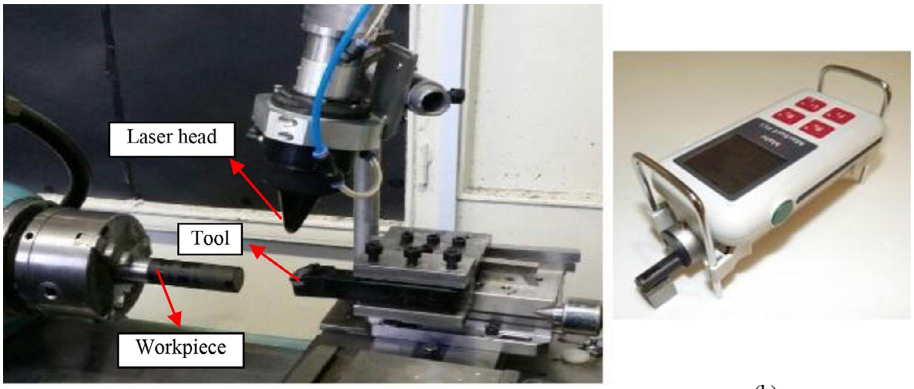
outputs. In most engineering applications, the failure of the material such as wear, corrosion, creep, and fatigue is related to some surface phenomena. Therefore, the surface quality of the workpiece is used as a criterion for the acceptance or rejection of the machined components.

A machined surface is defined as the boundary between the machined workpiece and the environmental conditions of the machining process. In the current research, the turning process of AISI 4340 hardened steel was studied from the perspective of surface roughness. These steels are a subclass of high-tensile strength alloy steels (strength higher than 1400 MPa) in which desirable physical and mechanical properties can be generated with heat treatment. Many researchers have studied thermal-assisted machining. In 2010, Shine et al. [11] examined the surface quality of the hard materials in laser-machining, comparing the hard machining process with laser-machining. Their results showed that the material removal rate and surface quality in laser machining process were significantly improved compared with hard machining. Also investigated is the effect of machining process parameters on the surface residual stress, with the results illustrating that machining with laser creates compressive stress around 150 MPa on the surface. Rahman Rashid et al. [12] investigated the impact of laser characteristics on titanium alloy machining, comparing the cutting temperature in the traditional machining mode with laser-assisted machining. They further studied the temperature variations according to the laser beam diameter. The results indicate that the increase in laser power augmented the effective cutting speed. Lee et al. [13] studied the parameters of laser-assisted machining on a spherical surface. They observed that specifying a proper temperature for a spherical workpiece is more difficult than a flat surface. The optimum preheating temperature was obtained from about 550 to 726° C using finite element analysis. By increasing the speed of the spindle without pre-heating, the surface flatness did not improve significantly; however, exploiting LAM, surface flatness improved by about 14.5 to 59.1% after increasing the spindle speed. Langan et al. [14] studied the effects of process parameters on micro-laser assisted machining of silicon, which delivered a fine surface finish and reduced the possibility of fracture by increasing the ductility of the material during the machining process. By investigating the results and a wide range of machining parameters, it has been shown that LAM can yield good results in terms of reducing residual stresses and good relative crystallinity. However, poor selection of process parameters is shown to be very detrimental, entailing high residual stresses and multiphase silicon. Based on the research studies in the literature, LAM faces a challenge of proper selection of process parameters to reveal the desired outputs. If the process parameters are not selected carefully, the process may fail and its competitiveness will become questionable. The aim of this paper is to study the surface quality in the process of LAT of hard steel and to determine a proper process parameter to conduct a successful LAT process.

2. Experiments

The AISI 4340 steel cylinders of 30 mm diameter and 100 mm length with an initial hardness of 560 HV were used for laser-assisted turning experiments. In all experiments, DCMT11T304 carbide inserts are used under different chip formation conditions. Following each experiment, the inserts were replaced to ensure the same conditions for all experiments. In this research, a turning machine (Harding M/C Tools) was used to carry out machining experiments. The laser system was attached to the machine tool using a fixture. The YFL-600 fiber laser with a maximum power of 600 W was used for the experiments. This laser (with 1082 nm wavelength) has excellent beam quality and high optical efficiency and it is not sensitive to the dust, shock, and vibration of the working environment, and does not require optical adjustments. The compressed air was used to protect the laser lens from overheating and prevent the collision of the chips to the lens. The laser head assembly was adjusted by a fixture mounted on the tool post of the turning machine. To maximize the laser power absorption on the workpiece surface, it is necessary to select an appropriate coating on the workpiece surface because, in the absence of suitable coatings, a portion of laser radiation is absorbed by the surface while the rest is reflected. Thus, the industrial gouache coating is employed on the surface of the workpiece. A roughness measurement device with a precision of 0.001 μm (Marsurf PS1 model) was utilized to examine the effect of the machining conditions on the surface roughness. To measure the roughness, the surface of the samples was primarily cleaned from any contamination, and the average surface roughness (Ra) in the direction of the feed motion of the tool was then obtained in three different positions. Fig. 1 shows the equipment used in this research from the preparation stage to the measurement.

In this research, the experimental design was carried out using the response surface method (RSM) to improve the reliability of the result, decrease the number of experiments, and maintain the accuracy. The parameters related to the turning process, i.e. cutting speed, feed, and depth, and a parameter related to the laser power source, are considered in five different levels according to Table 1. relying on the Central Composite Design (CCD), 30 experiments



(a) (b)

Fig. 1. Equipment used in this research (a) machine tool, (b) roughness meter device.

Table 1
Essential parameters of the laser-assisted turning experiments and associated levels.

Factors	Unit	Levels				
		Level 1	Level 2	Level 3	Level 4	Level 5
Laser power (P)	Watt	530	500	450	400	350
Cutting speed (Vc)	m/min	240	190	140	95	45
Feed (f)	mm/rev	0.12	0.09	0.07	0.04	0.01
Depth of cut (a_p)	mm	1	0.7	0.5	0.3	0.1

Table 2
Design of experiment matrix of CCD technique and its results.

Test Number	P	v_c	f	a_p	Ra (μm)
1	400	95	0.04	0.3	0.9
2	500	95	0.04	0.3	1.4
3	400	190	0.04	0.3	0.7
4	500	190	0.04	0.3	1.1
5	400	95	0.09	0.3	1.6
6	500	95	0.09	0.3	0.85
7	400	190	0.09	0.3	1.5
8	500	190	0.09	0.3	0.7
9	400	95	0.04	0.7	1.6
10	500	95	0.04	0.7	1.05
11	400	190	0.04	0.7	1.4
12	500	190	0.04	0.7	0.95
13	400	95	0.09	0.7	1.8
14	500	95	0.09	0.7	0.9
15	400	190	0.09	0.7	1.7
16	500	190	0.09	0.7	0.7
17	350	140	0.07	0.5	1.8
18	530	140	0.07	0.5	2.1
19	450	45	0.07	0.5	1.3
20	450	240	0.07	0.5	0.5
21	450	140	0.01	0.5	1.2
22	450	140	0.12	0.5	1.8
23	450	140	0.07	0.1	0.55
24	450	140	0.07	1	1.7
25	450	140	0.07	0.5	0.7
26	450	140	0.07	0.5	0.71
27	450	140	0.07	0.5	0.7
28	450	140	0.07	0.5	0.69
29	450	140	0.07	0.5	0.695
30	450	140	0.07	0.5	0.7

Table 3
The analysis of variance for surface roughness model of laser-assisted turning.

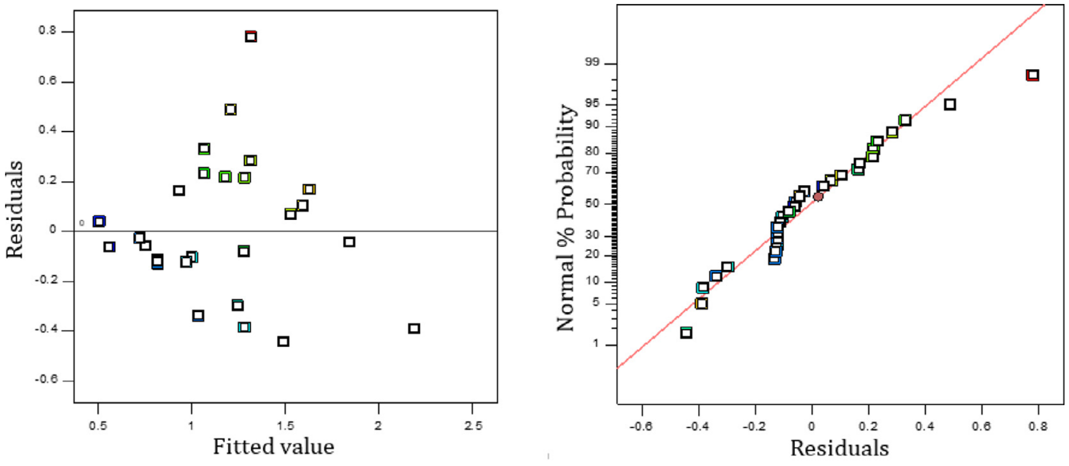
Source	Sum of Squares	DOF	F-Value	P-value	Contribution %
P	0.89	1	9.35	0.0058	14.08
v_c	0.37	1	3.89	0.0613	5.85
f	0.33	1	6.69	0.0169	5.22
a_p	0.64	1	3.45	0.0766	10.12
Residual	2.09	22			33.07
Lack of Fit	2.09	17	2788.49	less than 0.0001	
Pure Error	2.208×10^{-4}	5			
Cor Total	6.32	29	9.35	0.0058	100.00

were designed, and random experiments were further performed to preclude systematic errors.

3. Results and discussion

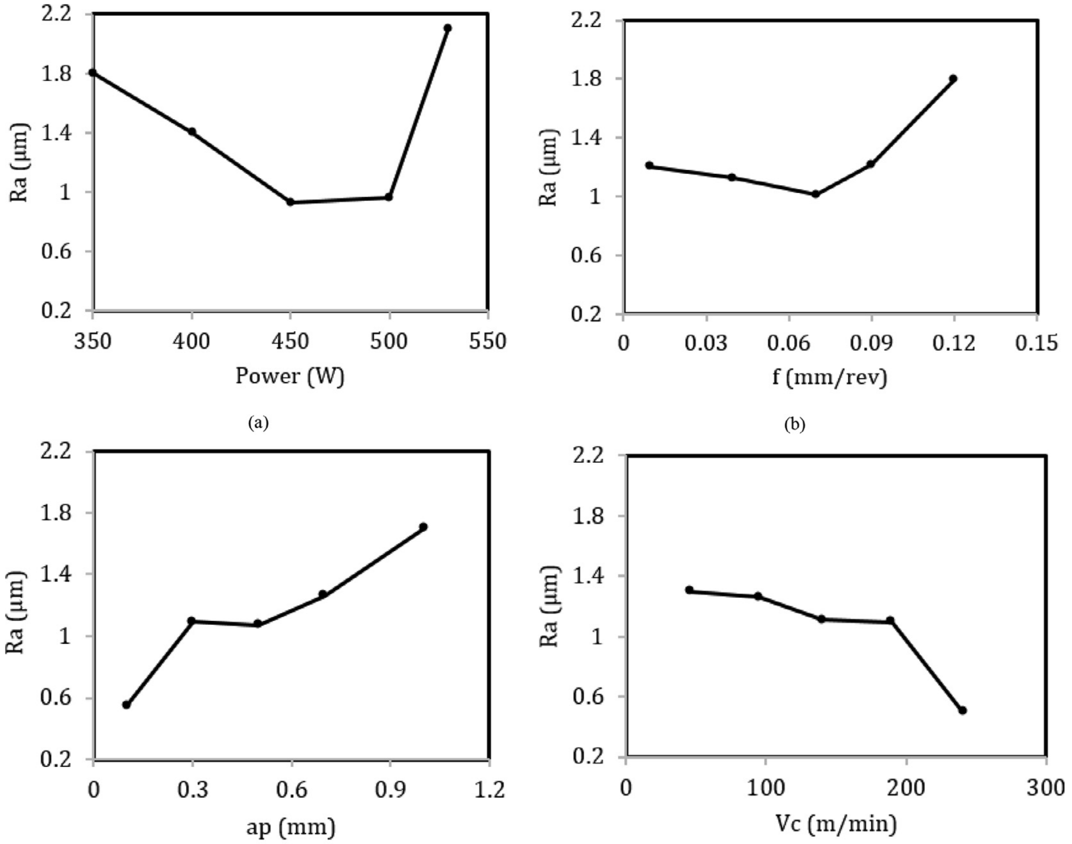
As mentioned above, 30 experiments were executed using the given design of the experiment. Following each experiment, the average surface roughness (Ra) of the machined area were measured. Table 2 shows the machining and heat source parameters along with the measured output. Surface roughness is a parameter of surface integrity that was considered as the desired output in this study. Table 3 shows the analysis of variance (ANOVA) of the surface roughness. According to Table 3., p-values less than 0.05 (reliability greater than 95%) indicate the significance of the relevant factors. The average surface roughness was obtained in 5 different regions of the specimens. Table 3 further shows the contribution of each factor. The results of statistical analysis show that the laser power with 14.08%, depth of cut with 10.12%, and cutting speed with 5.85% had the highest effect on surface roughness, respectively.

Fig. 2a shows a relatively good distribution of the residuals of the developed model with the predicted values. Fig. 2b shows the normal distribution of the residuals. Fig. 3 demonstrates the



(a) (b)

Fig. 2. The diagram of residuals for the surface roughness model: a) residuals b) Normal distribution of residuals.

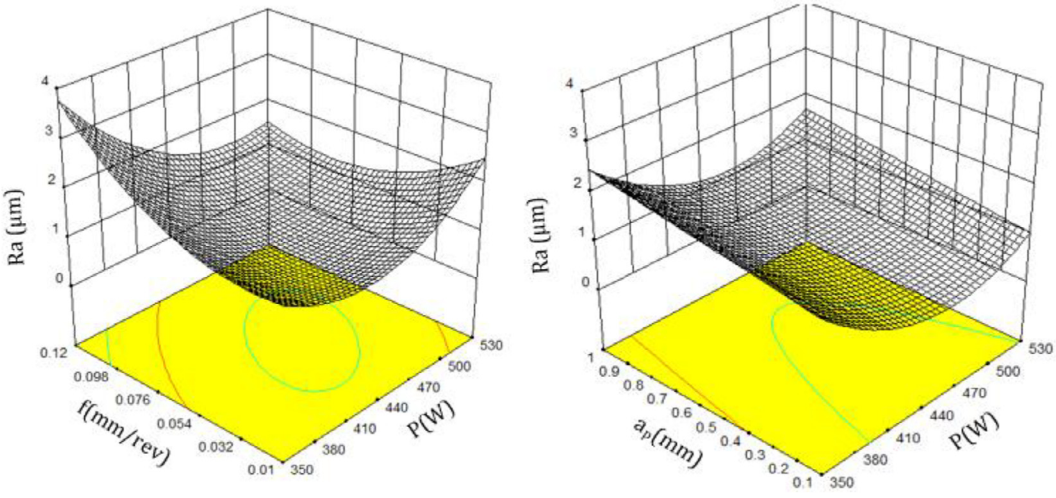


(a) (b) (c) (d)

Fig. 3. Surface roughness variation for different machining parameters: a) Laser power, b) Feed rate, c) Depth of cut, and d) Cutting speed.

graph about the effect of machining parameters on the mean surface roughness. As observed, with the increase in laser power up to 450 W, the roughness of the surface was significantly reduced, but increased power can cause a significant increase in heat and surface damage (surface burn), eliminating the surface flatness. According to the effects of feed on surface roughness, when the feed was low, the destructive effects of heat increased the roughness, but with the increase in the feed rate up to 0.07 mm/rev, a good combination of heat and feed was achieved, improving the surface quality. A further increase in the feed led to an increase in the un-cut chip thickness, followed by a higher surface roughness after the increase in the force and vibration of the tool.

Generally, at higher depth of cut values the regime of cutting is very close to the hard machining, consequently increasing the depth of cut increases the surface roughness due to increased cutting forces and vibration of the cutting tool. The effect of surface



(a)

(b)

Fig. 4. Response surface of interaction between a) feed rate and laser power, b) depth of cut and laser power on laser-assisted turned surface roughness.

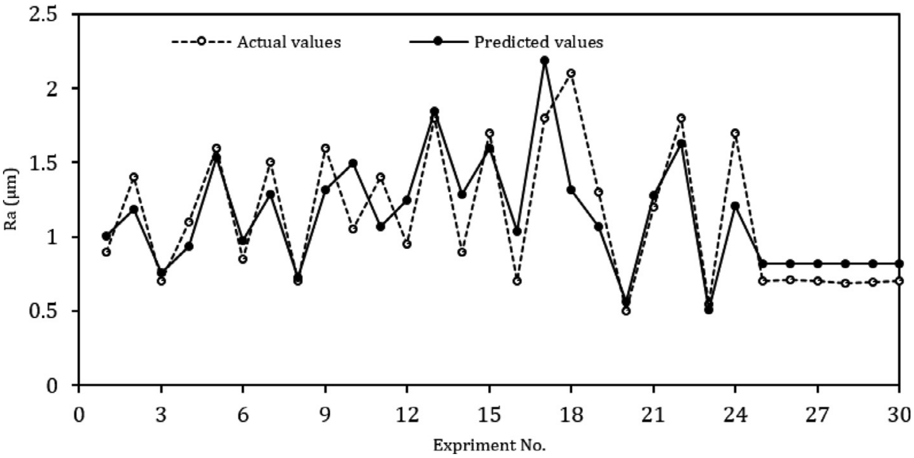


Fig. 5. Comparison of the results of experiments and the proposed mathematical model of surface roughness.

roughness improvement with the increase in cutting speed is also shown. The reason for the improvement in the surface quality by increasing the cutting speed can be observed in the ease of deformation and reduction of cutting forces.

The effects of surface roughness on different laser powers are shown in Fig. 4a where at a laser power of 400 W, the surface roughness is increased with the increase in the velocity, which is also common in machining. Because of the increase in feed, the tool vibrates more, and the surface becomes sharper.

With the increase in the laser power up to 450 W, surface roughness shows two different behaviors. Low speeds resulted in thermal damage, an increase in surface roughness while higher speeds lead to surface abrasion. When the laser power reaches 500 W, higher feeds further improves the surface quality. Because the machining area is softened by the heat, the machining and vibration forces of the tool are reduced. Fig. 4b shows the interaction effects of depth of cut and laser power on surface roughness. The general trend is to increase the surface roughness by increasing the depth of cut because the hardness of the workpiece is high, thereby increasing the inclination depth and the tool vibration, and intensifying the surface roughness. Moreover, the contrast between the laser power and the depth of cut is an important issue. It is to be noted that at a fixed depth of cut, increasing the laser power up to an optimum value improves the surface quality because the heat penetration to the subsurface layers increases and, when the depth of cut is low burns and damage to the surface becomes unavoidable. Eq. (1) shows the mathematical relation obtained for estimating the roughness of a hardened AISI 4340 steel sample in a laser-assisted turning. It should be noted that the Design Expert software is used for the ANOVA and to obtain the effective coefficient of each of the input parameters and also the interaction of the input parameters on the surface roughness. The parameters that have the greatest impact on the surface roughness are formulated according to its coefficient. Fig. 5 compares the results obtained from empirical tests and the mathematical model where the approximate error was measured to be 17.5%.

$$\begin{aligned} Ra = {} & +20.4029 - 0.09175P - 2.5911 \times 10^{-3}Vc \\ & +41.2514f + 0.7788a_p - 0.1471P \times f + 1.0.47 \times 10^{-4} \\ & P^2 + 216.630f^2 \end{aligned} \tag{1}$$

4. Conclusion

In this research, the AISI 4340 hardened steel with an initial hardness of 560 HV was investigated in laser-assisted turning.

Important parameters of machining, including cutting speed, feed, depth of cut, and laser power were defined in five levels. The effects of these parameters on surface roughness are evaluated through response surface methodology. The result of this study showed that increasing the laser power up to 450 W significantly reduces the roughness of the surface, but increased power can cause significant heat accumulation and surface damage (surface burn). The effects of the feed rate on surface roughness showed that the increase in feed rate results in an increased uncut chip thickness, followed by a higher surface roughness due to an increased cutting force and vibration of the cutting tool. The increase in the depth of cut resulted in the increasing surface roughness due to increased machining forces and cutting tool vibrations. The effect of surface roughness improvement with the increase in cutting speed was further shown. The surface quality can be improved by increasing the cutting speed owing to the ease of deformation and reducing cutting forces.

CRediT authorship contribution statement

Farzad Ahmadi Khatir: Investigation, Writing - Original draft, Software, Visualization, Validation. **Mohammad Hossein Sadeghi:** Conceptualization, Supervision, Methodology, Writing - review & editing. **Samet Akar:** Software, Validation, Methodology, Writing - review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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