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A new approach to enhance final surface quality in drilling operation: evaluation of using alumina micro-particle additives on oil-water emulsion cutting fluid

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Abstract

Reaming is a common finishing process for improving the drilled holes surface quality. Choosing an appropriate finishing method in drilling process has a significant effect on the surface quality of holes and in decreasing the process total cost and time. In this study, four similar holes were drilled on the AISI 4340 workpiece with different two pair feed rates. The drilling process was performed with a conventional cutting fluid, an emulsion of water and ECOCOOL 3015 GS-W. The surface roughness values after drilling process were measured using a portable roughness tester. Then, two distinct sizes of alumina micro-particles were used in the cutting fluid discretely to perform finishing process of the holes with a specific cylindrical tool. A comparison of the surface roughness measurements after the finishing process showed a significant decrease in the arithmetic surface roughness and ten-point mean roughness values of the drilled holes. The values were very close to the surface roughness limits in reaming process of the holes.

1. Introduction

Machining and polishing of high strength and hard materials require employing abrasive methods in manufacturing processes. In abrasive grinding as a conventional method, an abrasive rotational wheel is used to remove material from the workpiece and achieve a high surface quality. In modern abrasive machining processes, such as polishing, ultrasonic magnetic abrasive finishing, and abrasive waterjet machining, the wide range of the abrasive particles have been developed [1]. Bielmann et al. investigated the effect of the abrasive particles size on polishing rate and surface roughness quality during tungsten chemical mechanical polishing. The results showed that particles size and contact surface area between abrasive particles and polished surface are two important factors to control process quality [2]. Zhou et al. proposed a new method based on ultrasonic vibration combined with magnetic abrasive finishing to improve surface quality in titanium parts after the milling process. The experimental values declared that this method was more efficient to enhance the final surface quality of titanium parts [3]. Brar et al. suggested an effective

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method based on the combination of the electrochemical machining (ECM) and abrasive flow machining (AFM) to promote the surface quality of complex internal holes of metallic parts [4]. In contrast to the abrasive grinding method, the abrasive particles have variable situations and different linear and angular speeds in the modern machining and grinding methods Some researchers have been broadly proposed other new methods based on using abrasive particles such as alumina particles added to oil lubricants to decrease the tool wear, forming load, friction coefficient values, and to enhance the final surface quality [5, 6]. Drilling is a common cutting process that uses a rotary cutting tool named drill to manufacture an internal hole with the circular cross-section in solid materials. Spindle speed, the feed rate of the cutting tool, depth of cut, and machine tool vibration are important considerations to determine the surface quality range. A hole with a rough surface can cause the concentration of residual stresses and raise the failure risk in solid material. Then, a secondary operation such as reaming is necessary to have precision and smooth surface after drilling process. In many cases, arithmetic surface roughness may typically change from 0.6 to 6.3 µin for reamed holes [7, 8]. In this paper, in order to control the final cost and total producing time of the manufactured holes in the drilling process, a new method is proposed to eliminate the reaming process as a secondary operation and manufacture the high surface quality for holes. First, four similar circular holes (with an internal diameter of 24 millimeters) were drilled on the AISI 4340 steel workpiece. For each of the two holes, the feed rate value were selected 0.06 and 0.04 millimeters per revolution (mm/rev) in the drilling process, but the number of spindle speed for each hole was constant. After drilling process, the measurement of the surface quality of the manufactured holes was done using a roughness tester. Arithmetic surface roughness (R_a), ten-point mean roughness (R_z) and maximum roughness ($R_{\max}$) was measured. Next, in order to promote the surface quality of the holes, two alumina micro-particles (45 and 90 μm) were employed with a specific tool for the finishing process. After finishing, surface roughness profile for each hole was achieved. The effect of alumina particles size and feed rate values on the final surface of the holes were investigated.

2. Workpiece material

The wor kpiece material used in the experimentation was a block of AISI 4340 steel with $130 \times 50 \times 30\,\mathrm{mm}^3$ dimension. This steel has good strength, high surface hardness, and adequate creep resistance properties. It also has good machining characteristics in the annealed or normalized and tempered conditions. The chemical composition of the steel is given in Table 1.

Table 1. Chemical composition of AISI 4340 steel.

Element	Weight (wt%)
C	0.4
Mn	0.68
P	0.01
S	-----
Si	0.18
Ni	1.7
Cr	0.65
Mo	0.22

3. Determining the drilling process parameters

In order to specify the effect of feed rate value on the surface quality in the drilling process, two holes were drilled with 0.06 (mm/rev) and another two holes with 0.04 (mm/rev). But the spindle speed in drilling process for each hole was kept constant. The cutting fluid was a blend of water and a mineral oil-based named ECOCOOL 3015 GS-W, a milky-white emulsion with high chemical stability. ECOCOOL 3015 GS-W is usually used for the machining of high alloy steels and cast irons. Table 2 shows the drilling process parameters for manufacturing the four circular holes using oil-water emulsion cutting fluid.

Table 2. Drilling process parameters performed with oil-water emulsion cutting fluid.

Parameter	Value
Spindle rotation, rpm	500
Feed rate, (mm/rev)	0.06 for two holes 0.04 for two holes
Depth of cut (D), mm	22
Hole diameter, mm	24
Space between two consecutive holes, mm	8
Dill diameter, mm	24
Cutting fluid	ECOCOOL 3015 GS-W (7%) and water (93%)

After drilling process, the internal surfaces of the holes were investigated to determine the surface roughness values. A portable roughness tester (model MarSurf PS1) was used to measure $R_{\max}(\mu m)$, $R_z(\mu m)$ and $R_a(\mu m)$. After transferring the data to a computer, the surface roughness profile was drawn, and the values of its roughness parameters were determined. The probe cut-off length for determining the surface roughness was equal to 8 mm according to the ISO 4288 standard. Figures 1 to 4 show the surface roughness profiles for each hole according to Table 2 parameters

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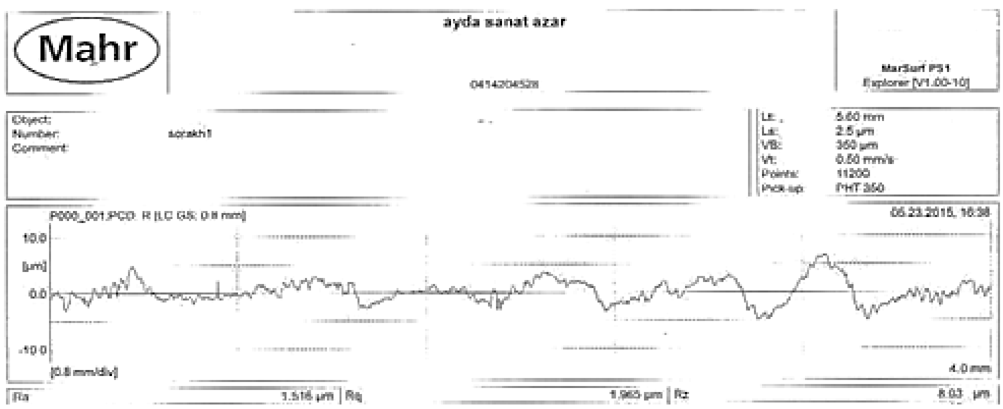

Fig. 1. Surface roughness profile for the first hole (0.04 (mm/rev) feed rate and 500 (rpm) spindle rotation speed).

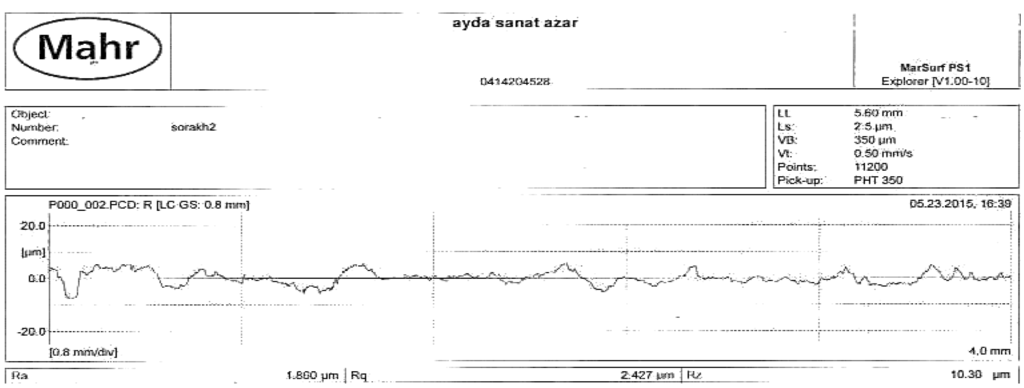

Fig. 2. Surface roughness profile for the second hole (0.06 (mm/rev) feed rate and 500 (rpm) spindle rotation speed).

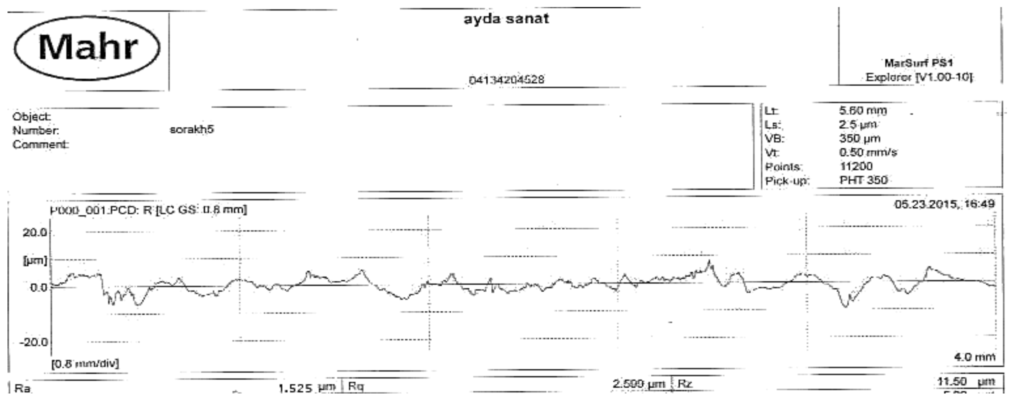

Fig. 3. Surface roughness profile for the third hole (0.04 (mm/rev) feed rate and 500 (rpm) spindle rotation speed).

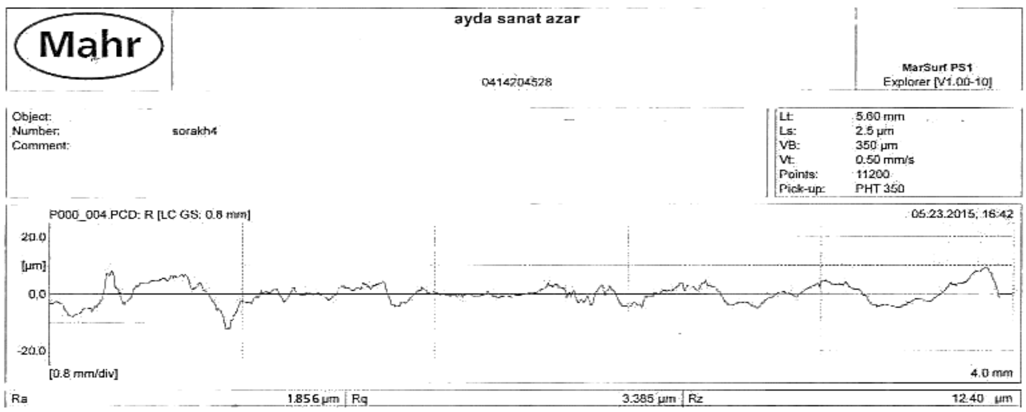

Fig. 4. Surface roughness profile for the fourth hole (0.06 (mm/rev) feed rate and 500 (rpm) spindle rotation speed).

4. Characteristics of alumina micro-particles

Alumina is a ceramic material with proper physical stability and high abrasive property. Furthermore, it is abundant and inexpensive [9]. Another reason, making alumina a proper abrasive in the machining process, is its high sintering temperature ($500^{\circ}C-600^{\circ}C$) compared to other engineering ceramics [9]. In this paper, two different sized alumina particles (45 and 90 μm) were used in combination with the cutting fluid (Table 2) to enhance the surface quality of the drilled holes.

5. Characteristics of specific tool for abrasive finishing of the drilled holes

In order to facilitate the alumina micro-particles rotation inside the holes during the drilling process and remove the holes roughness, a cylindrical specific tool with the initiated design was used for the finishing process. Direct contact between the alumina micro-particles and the holes during tool rotation, decreasing the alumina micro-particles consumption, preparing the easy control of concentricity between tool and holes, and uniform abrasion of the internal surfaces are some notable advantages of the designed tool. The specific tool for abrasive finishing of the drilled holes along with its drawings are depicted in Fig. 5.

Considering the alumina micro-particles high mechanical properties, the selected material for finishing tool was AISI 6150 alloy steel. This steel is a chromium-vanadium steel with high wear resistance, and it is usually used in manufacturing shafts and gears. A stepped section with a 26 mm diameter was considered in the designed tool as a cover to prevent the alumina micro-particles and cutting fluid from throwing inside the 24 mm holes during the finishing process. Tables 3 and 4 show the equivalents of this steel in several standards and the chemical composition of the steel AISI 6150, respectively.

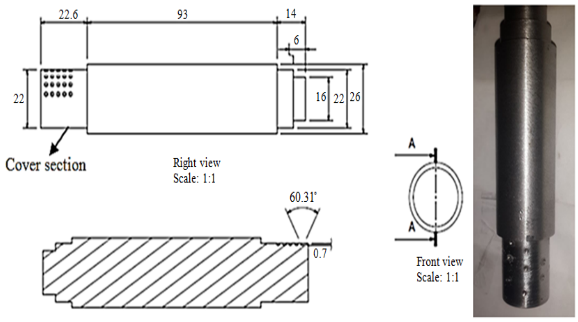

Fig. 5. The drawings (sizes in mm) and the selected tool for abrasive finishing of the drilled holes.

Table 3. The equivalents of steel AISI 6150 in different standards.

Standard	Sweden	American SAE	Germany DIN	France AFNOR
Designation	SS2230	ASTM A231 SAE J770	1.8159	50 CV 4

Table 4. Chemical composition of AISI 6150 steel.

Element	Weight (wt %)
C	0.46
Mn	0.72
P	0.03
S	0.012
Si	0.15
V	0.17
Cr	1.00

6. Mixing the cutting fluid and alumina micro-particles

First, to provide the proper portion of the cutting fluid and each alumina particles, the volume of the space between tool and holes is computed by the following formula:

$$V = \frac{(D^2 - d^2)\pi}{4} \times H \qquad (1)$$

where D is the internal diameter of the hole (24 mm), d is the finishing tool diameter (22 mm), and H is the hole depth (22mm). To provide cutting fluid containing alumina micro-particles, a combination of alumina particles with mineral-base oil ECOCOOL 3015 GS-W was performed. According to different researches, the weight factor of alumina micro-particles that should be mixed with the cutting fluid is 0.1- 0.2% [9, 10]. However, in all experiments the optimum percent of alumina micro-particles additives is chosen 0.15% [11].

7. Performing of the finishing process for the drilled holes

In this step, after checking the concentricity of the finishing tool and drilled holes, the cover section of the finishing tool was set inside the hole. Then, the free space between the finishing tool and hole was filled with the provided cutting fluid. It is notable that for both holes the cutting fluid consisted of the 45 μm alumina particle and for the other holes it was a mixture of 90 μm alumina particle. The rotation speed for the finishing process was selected 180 rpm to avoid the cutting fluid from throwing out. Rotation of the finishing tool causes alumina particles and cutting fluid to move from one place to another with the similar rotational speed. This rotational movement of the alumina particles facilitates the finishing process of the holes. After finishing process, the internal surface of the holes was investigated to determine the surface roughness values. The probe cut off length for determining the surface roughness was equal to 8 mm. The probe cut-off length for determining the surface roughness was equal to 8 mm. The surface roughness profiles of each hole are shown in Figs. 6 to 9.

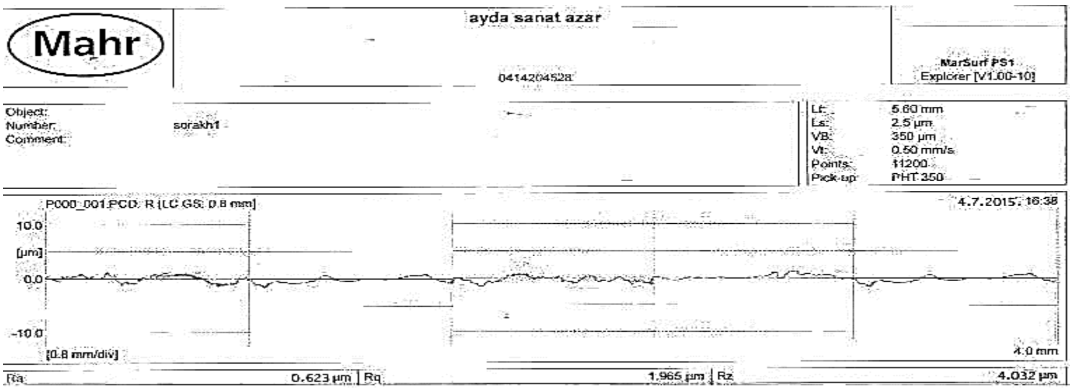

Fig. 6. Surface roughness profile of the first hole (drilled with 0.04 (mm/rev) feed rate, 500 (rpm) spindle rotation speed, and cutting fluid containing 45 μm alumina particles).

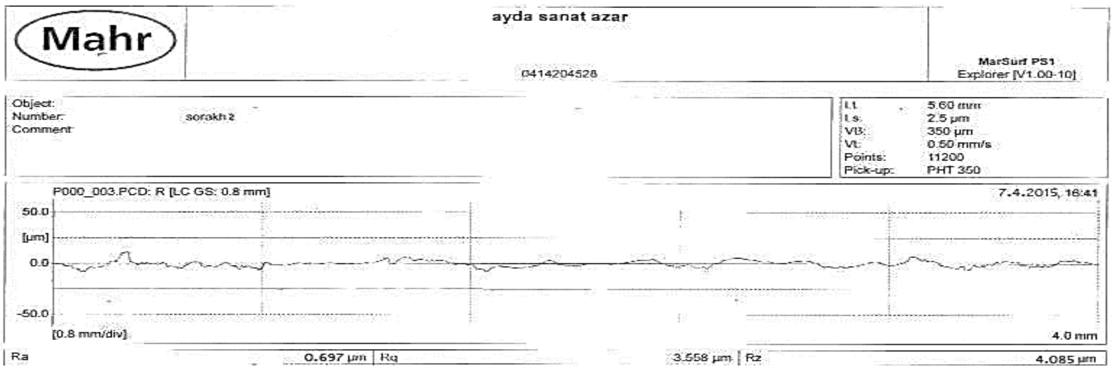

Fig. 7. Surface roughness profile of the first hole (drilled with 0.06 (mm/rev) feed rate, 500 (rpm) spindle rotation speed, and cutting fluid containing 45 μm alumina particles).

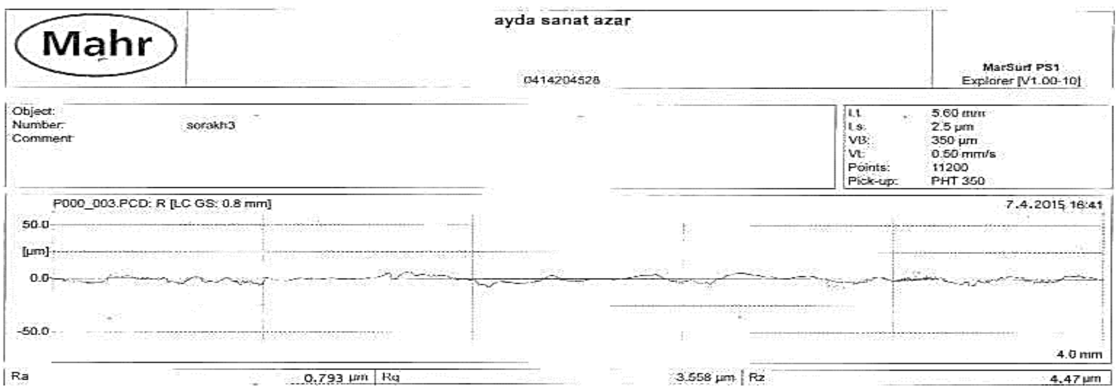

Fig. 8. Surface roughness profile of the first hole (drilled with 0.04 (mm/rev) feed rate, 500 (rpm) spindle rotation speed, and cutting fluid containing 90 μm alumina particles).

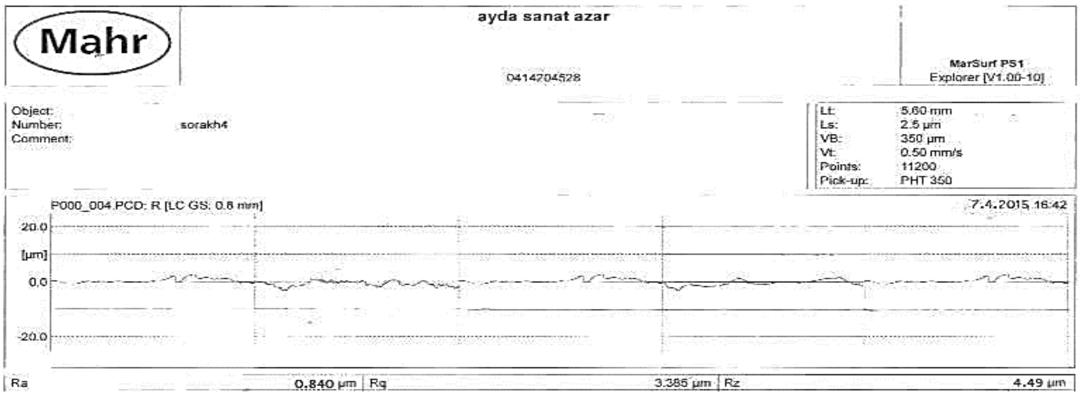

Fig. 9. Surface roughness profile of the first hole (drilled with 0.06 (mm/rev) feed rate, 500 (rpm) spindle rotation speed, and cutting fluid containing 90 μm alumina particles).

Table 5. Surface roughness values for manufactured holes after drilling and finishing processes.

	Alumina micro-particles size							
	45µm				**90µm**			
	First hole		**Second hole**		**Third hole**		**Fourth hole**	
	Feed rate 0.04 (mm/rev)		Feed rate 0.06 (mm/rev)		Feed rate 0.04 (mm/rev)		Feed rate 0.06 (mm/rev)	
	After drilling	**After finishing**	**After drilling**	**After finishing**	**After drilling**	**After finishing**	**After drilling**	**After finishing**
R_a (µm)	1.516	0.623	1.860	0.697	1.525	0.793	1.856	0.840
R_z (µm)	8.03	4.032	10.30	4.085	11.50	4.47	12.40	4.49

8. Results and discussion

In this paper, a non-contact finishing method consists of alumina micro-particles and cutting fluid was presented. To evaluate the surface quality of the finished holes, surface roughness profile was extracted for each hole, separately. According to the elicited surface roughness profiles for drilling and finishing processes, significant improvements with using alumina micro-particles occurred in 0.06 (mm/rev) and 0.04 (mm/rev) feed rates. It seems that the finishing process depends on centrifugal force derived from cutting fluid circulation and finishing tool rotation in the hole and throwing alumina particles toward the internal surface of holes. Therefore, the required machining power to remove materials from the surface of the hole in microscale can be provided. The proper weight factor of the alumina micro-particles in the ECOCOOL 3015 GS-W is another important parameter in this finishing process. The results of experiments for surface roughness values after drilling and finishing processes are classified in Table 5. In addition to Table 5, the most important findings of this paper including surface roughness values (R_a, R_z) during finishing process with Alumina micro-particles are illustrated. According to Table 5, the results show that:

1. Using the microsized alumina particle with a conventional cutting fluid resulted in a significant decrease in the surface roughness values (R_a) for all holes in the finishing process.
2. The arithmetic surface roughness (R_a) values decreased in finishing process for the small size of alumina particles (45 μm) and the low feed rate. Choosing an adequate size for the alumina particle and feed rate value in drilling and finishing processes are an excellent alternative for reaming process to achieve high surface quality and has a significant effect in decreasing the process total cost.
3. According to the cutting fluid type, ten-point mean roughness (R_z), is significantly different. The average value of ten-point mean roughness using alumina micro-particles is 4.269 μm (for all holes), which is lower than that of the drilled holes (10.557 μm).
4. The results indicate that the smaller size of alumina particle with low feed rate cause the surface roughness to decrease and the final surface quality of the holes to promote.
4. The dimensional control of the finished holes diameter show that the achieved tolerance with this method is in the range of ± 0.02, but reaming holes tolerance values are ± 0.01.

9. Conclusions

Choosing an appropriate finishing method in drilling process has a significant effect on the final quality of the holes and the total cost of the process. In this study, four similar holes have been drilled on an AISI 4340 workpiece with two different feed rates (0.04 and 0.06 mm/rev). The drilling process was performed with a conventional cutting fluid containing water and ECOCOOL 3015 GS-W. The surface roughness values of the drilled holes were measured with a portable roughness tester. Then, two different sizes of alumina micro-particles were used discretely in the cutting fluid to perform finishing process of the holes with a specific cylindrical tool. Then, the surface roughness values after the finishing process were compared with the drilling steps. The results show that in comparing with reaming process, the alumina micro-particles are an excellent alternative to manufacture holes with high surface quality in low feed rate values of the finishing processes.

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