Experimental Study on Magnetic Abrasive Honing of Inner Surface of Tube AISI304

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Abstract: To overcome the limitation of honing process, the present work proposes magnetic abrasive honing (MAH) process whereby abrasive stones are replaced by magnetic abrasives. This process is combination of magnetic abrasive finishing (MAF) and honing. MAF which is one of the finishing processes can improve the quality of workpiece surface with various geometries, removing the chips in micrometer scale by magnetic field forces. This study set to apply longitudinal vibration to the tube workpiece in MAF process; hence, this process is called MAH. The effects of rotary speed of workpiece, cross-hatch angle, and mesh number were investigated on the surface roughness of AISI 304. Magnetic abrasives were combination of SiC particles as abrasives and iron particles as ferromagnetic particles in lubricant of SAE 40 oil. The results revealed that the longitudinal movement of workpiece is effective on MAH, as the surface roughness decreased with increasing the cross-hatch angle. Surface roughness decreased with increase of rotary and mesh number. The major changes in surface roughness (58%) were obtained in cross-hatch angle of 45º rotary speed of 800 rpm and mesh size of 400. The microscopic picture showed that three-body wear mechanism is dominant for fine grits.

Keywords: AISI 304, Honing, Inner surface, Magnetic abrasive, Surface roughness

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1 INTRODUCTION

1.1. Definition and Importance of Subject

Honing of the interior surfaces is a finishing process for cylindrical workpieces. The tools used in the honing are abrasive stones, simultaneously performing both rotational and longitudinal movements to finish the interior surface of cylindrical workpiece by scraping material from the interior surfaces. Due to simultaneous rotational and reciprocating motion of stones, a cross-hatch pattern on the surface can be generated. Honing is used after conventional machining process such as boring, drilling, and grinding to achieve desired surface roughness as well as dimensional and shape tolerance. However, there are some limitations in the honing process such as: 1) It is difficult to fabricate tools with diameter under 10 mm especially 2 mm; 2) Applied pressure on stones can deforme thin-walled workpiece; 3) It is impossible to finish non-cylindrical holes (or interior surfaces) such as conical hone; 4) In the process as a two-body abrasive finishing, low surface roughness (Ra<0.025μm) cannot be achieved. To overcome these limitations, the present study proposes MAH process in which abrasive stones are replaced by magnetic abrasives. This process is combination of honing and MAF.

In MAF which is one of the new finishing processes, magnetic abrasives act as the cutting tool in which the magnetic field controls cutting force. Ferromagnetic particles, influenced by magnetic field, push the abrasive grits on the surface and removes chips in micrometer dimensions from workpiece. In traditional finishing processes such as lapping and grinding, there are some drawbacks, so the high cutting forces lead to surface defects such as microcracks, not satisfying the quality of workpiece. However, in MAF, the cutting force is very low; surface finish and accuracy are high, and the surface defects are minimum [1-2]. This technique is an effective method to finish many products with various geometries such as flat surfaces [3-6], cylindrical surfaces [7-11], spiral polishing [12], sharpening of cutting tools [13], and deburring of holes [14-16]. Findings show that MAF is a useful method for finishing various surfaces and can finish the surfaces better compared with conventional grinding methods.

1.2. Explanation of References

The quality surface of inner surface of tubes used as wave guides tubes, sanitary tubes, vacuum tubes, and liquid piping system for sensitive applications required for aviation devices component is important. MAF is beneficial for finishing inner surfaces of tube workpieces [17-20]. Yamaguchi and Shinmura [21] proposed a mechanism in which poles rotate around the tube workpiece to produce highly finished inner surfaces. Wang and Hu [22] used MAF to decrease surface roughness of vacuum tube under 0.3 μm. Wang et al. [23] used Cr2O3 abrasive in wet finishing using distilled water in MAF of inner surfaces. Wet finishing using distilled water produces efficient finish surface compared with dry finishing. Yamagushi et al. [24] utilized MAF process to finish internal surface of non-ferromagnetic tubes with complex shape (bent and straight sections).

1.3. Illustration of the New Work

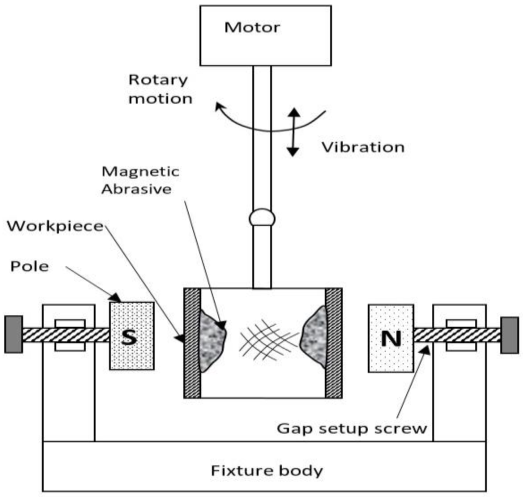
According to the researches regarding the magnetic abrasive finishing especially inner surfaces, the effect of longitudinal movements in AISI 304 tube has not been investigated yet. This study proposes a mechanism for MAF of inner surface of tubes. This mechanism is similar to honing, and the tube workpiece has two motions: 1) rotary and 2) reciprocating movement (vibration). The reciprocating movement of workpiece results in more uniform roughness and improves surface quality. Therefore, the effect of cross-hatch angle (produced by longitudinal vibrations), rotary speed of workpiece, and mesh number of abrasives were investigated on surface roughness of inner surface of AISI 304 tube.

2 MATERIALS AND METHODS

2.1. Magnetic Abrasive Honing Setup Fabrication

The MAH setup is schematically presented in “Fig. 1 (a)”. This setup consists of a mechanism for making mechanical vibration, a motor for rotation of workpiece, and a fixture for holding poles. The workpiece can reciprocate in vertical direction, while rotating about its axis. This workpiece movement in the vertical direction (longitudinal movement) increases the path length which abrasives migrate on the inner surface of the tube workpiece, and thus more peaks can be removed, and surface quality will be improved. “Fig. 1 (b)” shows the experimental setup.

“Fig. 2 (a)” schematically shows the acting forces on inner surface of workpiece during the longitudinal movement of workpiece in finishing process. The inner surface of workpiece is not flat and has micro peaks and valleys. The normal force Fy pushes the abrasives against the surface, and cutting force FC is a mechanical force arising from the workpiece rotary and vibrations. The friction between abrasives and inner surface can remove the peaks and produce smooth surface. The cutting is done by abrasives whenever Fc can overcome material resistance to deformation. Therefore, by applying sufficient magnetic field, the reciprocation of the workpiece can remove more peaks and reduce surface roughness. In MAH of tube workpieces, the tube workpiece has simultaneously two rotary and longitudinal movements.



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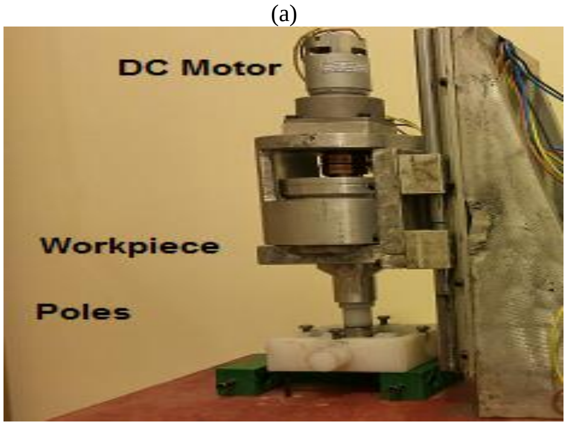
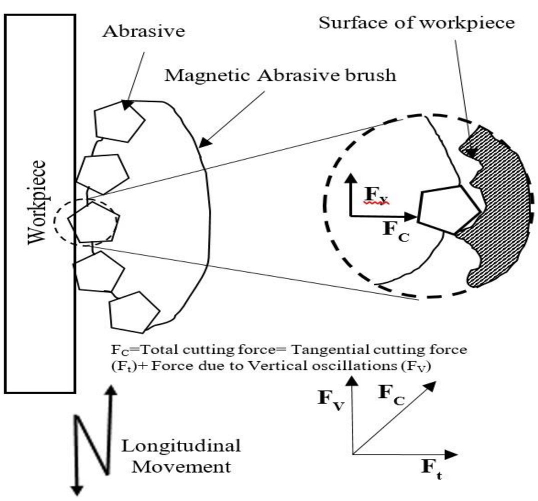


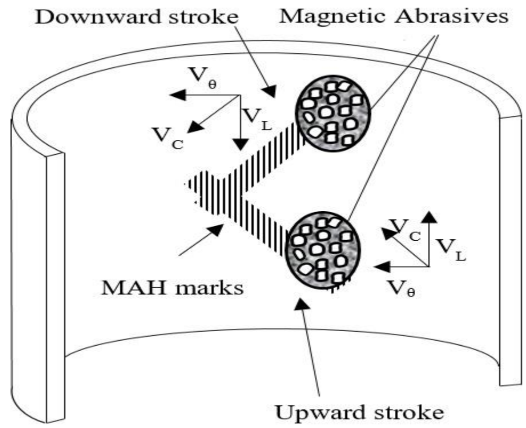
(b)

Fig. 1 (a): Schematic and (b): actual view of MAH process.

"Fig. 2 (b)" shows the surface pattern which was created in MAH. In the present work, to develop magnetic lines, two permanent magnetic poles were used for MAF of surface of tube workpiece.

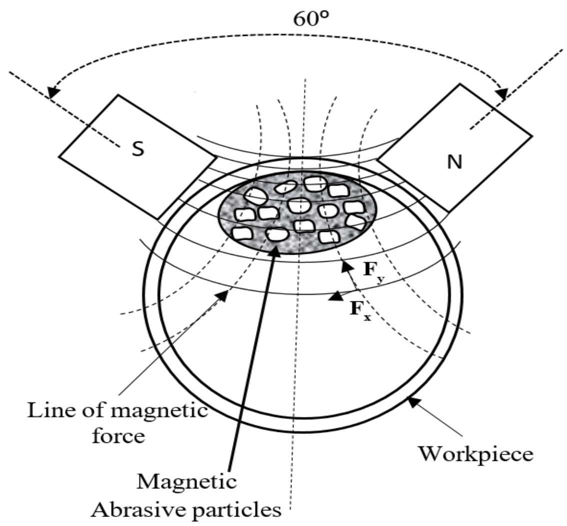


(a)



(b)

Fig. 2 (a): The effect of longitudinal movement in MAH and (b): kinematic and surface structure in MAH.



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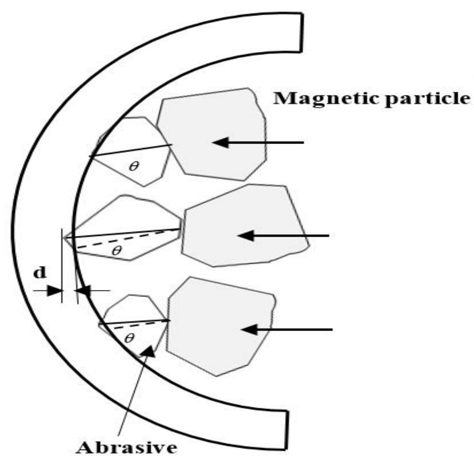


(b)

Fig. 3 (a): MAF schematic view of internal surfaces and (b): MAF process of internal surfaces.

The arrangement of poles and the directions of Fx and Fy produced by magnetic lines are partially shown in "Fig. 3 (a)". This arrangement was proposed by Wang et al. [22]. In magnetic abrasive finishing, acting forces on ferromagnetic particles from magnetic field lines push the abrasives against the peaks, and therefore the abrasives remove the material from the inner surface of workpiece and improve the surface quality ("Fig. 3 (b)").

2.2. R_a Measurement

The surface quality of tube inner surface was evaluated by surface roughness (R_a parameter). PERTHOMETER M2 has been done to measure surface roughness. The traversing length and cut-off values were 2.5 and 0.5 mm, respectively. Five measurements have been done over the surface in direction of longitudinal axis for each test. The percentage of surface roughness change can be obtained through the following equation:

$$\%\Delta R_a = \frac{R_{a_0} - R_{a_f}}{R_{a_0}} \times 100 \qquad (1)$$

R_{a0} is initial surface roughness, and R_{af} is surface roughness after finishing.

2.3. Materials

AISI 304 stainless steel was used as a workpiece. AISI 304 has various applications in industries such as gas and petroleum, petrochemical, and food industries. "Table 1" presents the composition of this alloy. SiC particles in mesh numbers of 120 (mean diameter of 115 µm), 220 (mean diameter of 57.5 µm), and 400 (mean diameter of 17.3 µm) were used as abrasive particles (AP), and Fe particles with mean diameter of 300 µm were used as ferromagnetic particles (FP). The ratio of AP to FP was 35% (percentage by weight). A lubricant should be used for mixing AP and FP and creating a good adhesion. SAE 40 oil was used as a lubricant.

Table 1 Chemical composition of AISI 304 workpiece

Alloying elements	C	Mn	P	S	Si	Cr
Percentage	0.08	2.00	0.045	0.03	0.75	18.00
Alloying elements	Ni	N				
Percentage	8.00	0.1				

2.4. Design of Experiments

The design of experiments (DOE) is a useful tool to keep the number of experiments at minimum. DOE is a useful tool to establish the relation between input variables and responses. In MAH, three variables such as rotary speed of workpiece (N), cross-hatch angle (α), and mesh number (M) are considered. Variables of N, α, and M in three levels were considered. In this work full factorial DOE was considered, and thus twenty-seven experiments were done. The levels of variables are presented in "Table 2". "Table 3" shows the experimental conditions.

Table 2 Levels of variables

Variables	Level 1	Level 2	Level 3
Rotary speed (rpm)	400	600	800
Cross-Hatch Angle (degree)	15	30	45
Mesh number	120	220	400

Table 3 Experimental conditions

No.	Name of the parameter	Value of the parameter
1	Workpiece	AISI 304 stainless steel outer diameter=Ø20mm, Inner diameter= Ø16mm, Length= 30mm Initial surface roughness: 0.3-0.4 µm
2	Magnet	Four ND-Fe-B permanent magnet. Two magnets: 10mm×20mm×60mm Magnetic flux density: 1.4 T
3	Mixed-type magnetic abrasive	Iron particles: average particle size of 300 µm SiC abrasive: average particle size of 115 µm, 57.5 µm and 17.3 µm Sic/Fe=percentage by weight is 35% Lubricant: SAE40 oil
4	Working gap	1 mm
5	Finishing length	25 mm
6	Finishing time	40

2.5. Cross-hatch angle

In MAH, AP has two movements: 1) tangential movement arising from rotary speed of workpiece, and 2) longitudinal movement arising from reciprocating motion of workpiece. Hence, AP has two feed rates: 1) tangential (V_θ) which is constant, and 2) axial (V_L) which is reciprocating movement. V_θ (m/min) is presented as following:

$$V_\theta = \frac{\pi DN}{1000} \qquad (2)$$

Where D and N are the inner diameter of tube in mm, and rotary speed in (rpm) respectively. The cross-hatch angle (α) is the angle between the vectors of V_θ and VL, so AP migrates in a direction along this angle. Cross-hatch angle is defined as following:

$$\tan(\alpha)=\frac{V_\theta}{V_L} \tag{3}$$

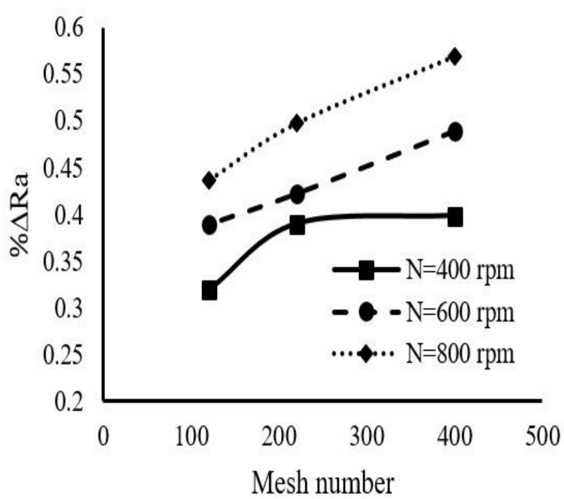
$$\alpha=\arctan\left(\frac{V_L}{V_\theta}\right) \tag{4}$$

3 RESULTS AND DISCUSSION

In following the effect variables on $\%\Delta R_a$ and morphology in MAH will be discussed.

3.1. Effect of Mesh Number and Rotary Speed on Surface Roughness

Figure 4 shows the effect of mesh number and rotary speed on $\%\Delta R_a$ in different frequencies, in all cross hatch angles, $\%\Delta R_a$ increases with increase of mesh size. In MAF, APs are placed beneath FPs so that FPs push APs against the surface, and therefore, APs can remove peaks on the surface of workpiece to improve surface quality. With the same FP mesh number, the amount of AP grits with small size (mesh number of 400) beneath FP exceeds AP grits with large size (mesh number of 120), so the average pressure on the AP arising from FP for fine AP is smaller. In MAF, with penetration of AP into the surface, it rolls between FP and workpiece surface. As the average pressure on the AP arising from FP increases, the penetration of AP into the surface of workpiece increases and leads to deeper scratches. Therefore, AP with mean diameter of 17.5 µm (mesh number of 400) produces superior surface roughness compared with AP with mean diameter of 115 µm (mesh number of 120). Figure 4 shows the effect of N on $\%\Delta R_a$. With increasing N from 400 rpm to 800 rpm, $\%\Delta R_a$ increases.



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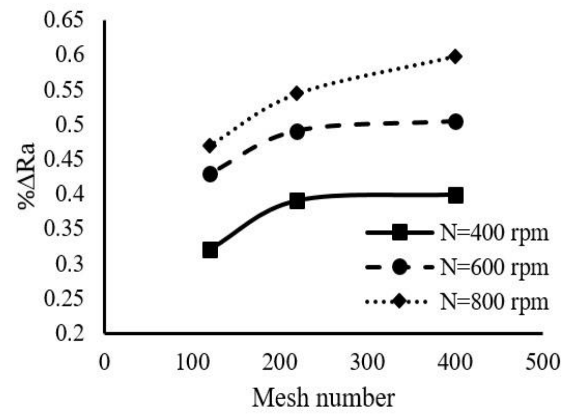

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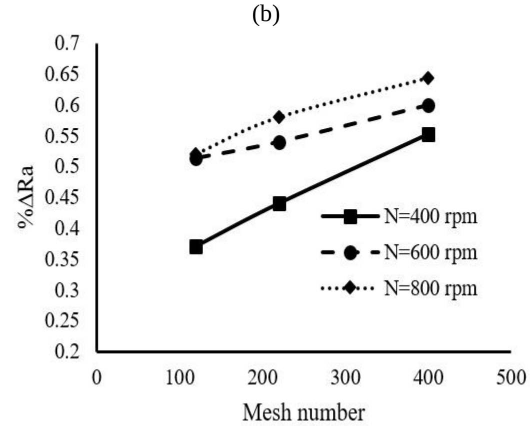


(c)

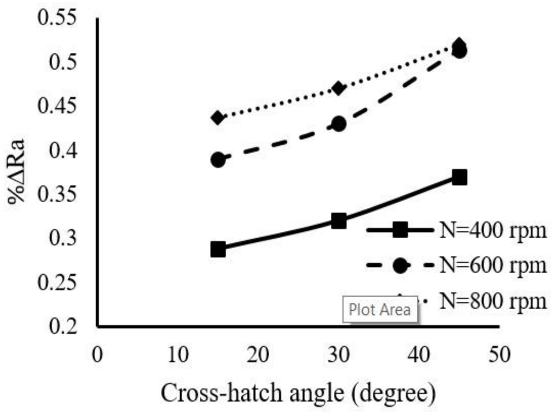
Fig. 4 The effect of Mesh number and rotary speed on surface roughness in cross-hatch angle of: (a): 15º, (b): 30º and (c): 45º.

In fact, by increasing the rotary speed in constant finishing time, the contact length of AP with inner surface of workpiece increases, thus more material can be removed. Accordingly, the surface roughness decreases.

3.2. The Effect of Cross-hatch Angle on Surface Roughness

The main difference between MAF and MAH process is longitudinal oscillation. In MAF, the workpiece only rotates, and reshuffling of APs purely depends on workpiece self-deformability. In MAF, the contact length of AP on the surface is short and therefore AP removes low material from peaks (MRR is minimal). In MAH, AP enters the finishing zone and exits (at top and bottom of the stroke), so APs remix. Then in MAH, the APs' intermixing depends on workpiece self-deformability and reversing the workpiece at the top and bottom of the stroke. Due to the longitudinal and circular movement of APs on the workpiece, the contact length of AP on surface of workpiece in MAH is more than MAF.

Therefore, the number of peaks can be removed in MAH more than MAF, leading to higher material removal rate (MRR) in MAH. “Fig. 5” depicts the effect of scratch angle on %ΔRa for various mesh numbers and rotary speeds of workpiece; in different mesh numbers and rotary speeds, %ΔRa decreases with increase of the scratch angle.



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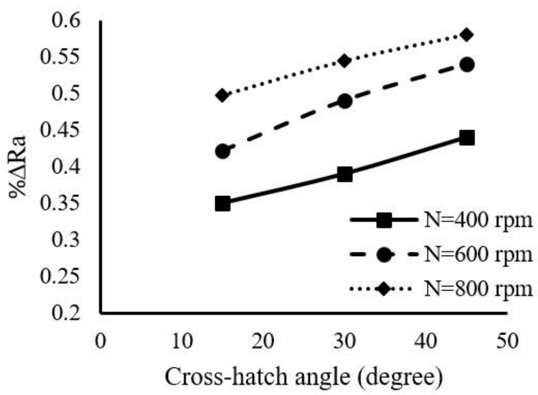

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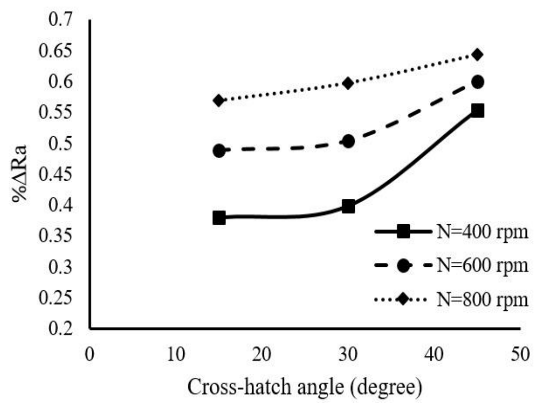
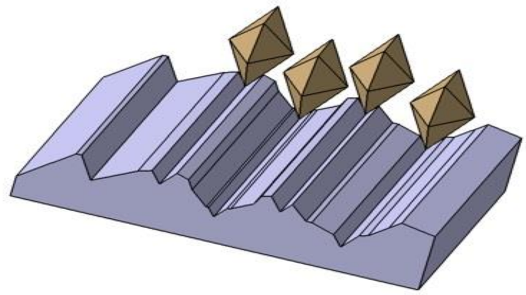


(c)

Fig. 5 The effect of cross-hatch angle and rotary speed on surface roughness in mesh number of: (a): 120, (b): 220 and (c): 400.

Figure 6 (a) schematically shows the linear movement of abrasives in MAF, while the workpiece has net rotary speed. In (a), the contact length between APs and workpiece is parallel to the initial roughness lay, so the contact length is minimum. Accordingly, when the abrasives move in the direction of roughness (produced in grinding), the abrasives remove material form peaks and valleys. This causes lack of significant reduction of the height of peaks and valleys. In MAF, reshuffling of AP is due to the workpiece self-deformability. After certain time, AP becomes blunt; therefore, MRR and %ΔRa decrease.



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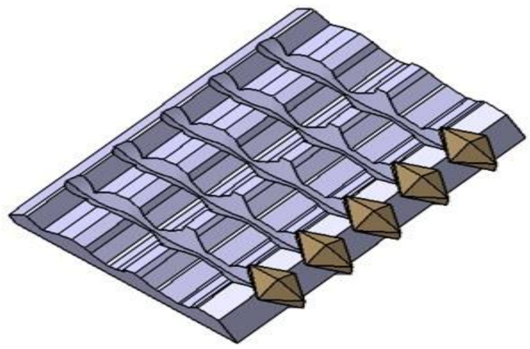

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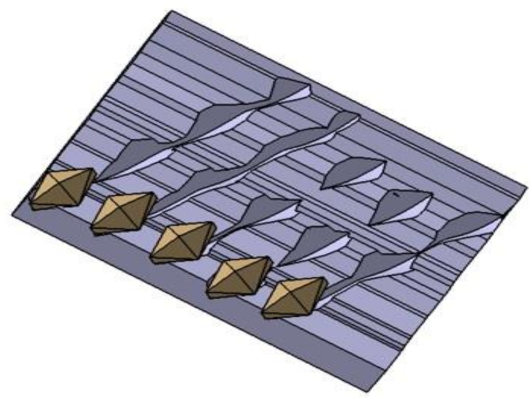

(c)

Fig. 6 Migration of abrasives in direction of: (a): scratches, (b): perpendicular to scratches and (c): diagonal.

Figure 6 (b) schematically shows the vertical movement of abrasives, when the workpiece has net reciprocating movement. Accordingly, when the abrasives move in perpendicular to roughness, due to rolling motion of APs on the peaks and valleys, AP removes more material from the peaks to valleys. Hence, the surface roughness decreases. Therefore, %ΔRa in Figure (b) is more than Figure (a). In this case, the contact length is the minimum between AP and the workpiece, but due to path reversing, if the workpiece results in intermixing (or reshuffling) of APs, the APs can effectively remove material from surface and improve the surface quality. Figure 6 (c) shows the abrasives which migrate in inclined path at angle (α) to the roughness direction. In MAH, abrasives migrate in inclined path, thus in this case, APs migrate in longer distance in compared with MAF as compared to "Figs. 6(a) and 6(b)". It can be concluded that in MAH material removal rate is faster than MAF, and therefore finishing rate is faster in MAH. In MAH compared to MAF, reciprocating of workpiece contributes to remixing and reshuffling of Aps, and thus the abrasive edges in touch with surface will be sharp. The number of sharp edges is more in MAH in compared with MAF. This leads to an increase in MRR and finishing rate.

3.3. Morphology

Figure 7 shows the optical microscopy images of the texture of inner surface of tube. "Fig. 7 (a)" shows the surface texture before MAH, while grinding scratches can be seen. In this figure, the surface is rough, and the roughness lay is shown. Figures 7 (b), (c), and (d) show the surface texture after MAH by cross-hatch angle of 15º, in rotary speed of 600 rpm for mesh number of 120, 200, and 400, respectively. Due to the coarse AP with mesh number of 120, cross-hatch angle clearly was resulted from reciprocating motion of AP on the workpiece surface. These images confirm that the honing process has been done by magnetic abrasives.

The magnetic force caused by FP on coarse AP is more than fine AP; as a result, the penetration of coarse APs into the surface is more than fine AP, thus the motion path of AP on the surface is visible. Tangential forces push the AP forward and separate a very small material from the surface called micro-chip. This phenomenon leads to reduction of peaks on the surface, and therefore gradual reduction of surface roughness (as surface roughness measurements show).

The mechanism of finishing in MAF is three-body (FP, AP, and workpiece), so in this mechanism, the abrasive grits tumble on the surface under tangential forces. Figure 3 (b) displays that each abrasive particle rolls between ferromagnetic particle and workpiece surface, while abrasive particle penetrates into the surface with depth of d. Depth of penetration (d) depends on the hardness and size of abrasives, workpiece material, and magnetic force, and directly affects the surface roughness in MAF.

The magnetic force on large abrasives is higher compared with fine abrasives; %ΔRa for large abrasives is less compared with fine abrasives (due to surface scratching) ("Figs. 7 (a) to (c)"). The pressure on fine abrasives is less compared with large abrasives, and therefore the abrasives penetrate into the surface with small penetration depth, as a result, not producing scratches on the surface. Since fine abrasives are used, the surface is perfectly smooth, and the roughness is very low compared with other figures.

In "Fig. 7 (a)", parallel scratches represent two-body mechanism of grinding. In "Fig. 7 (b)", the parallel scratches are removed, but inclined scratches are produced by AP. This figure represents two-body and three-body mechanisms of finishing, because of the coarse grains, two-body mechanism is dominant. In Figure 6 (c), scratches are reduced, and in "Fig. 6 (d)", the scratches are hardly seen. Figure 6 (d) shows that three-body mechanism of finishing is dominant.

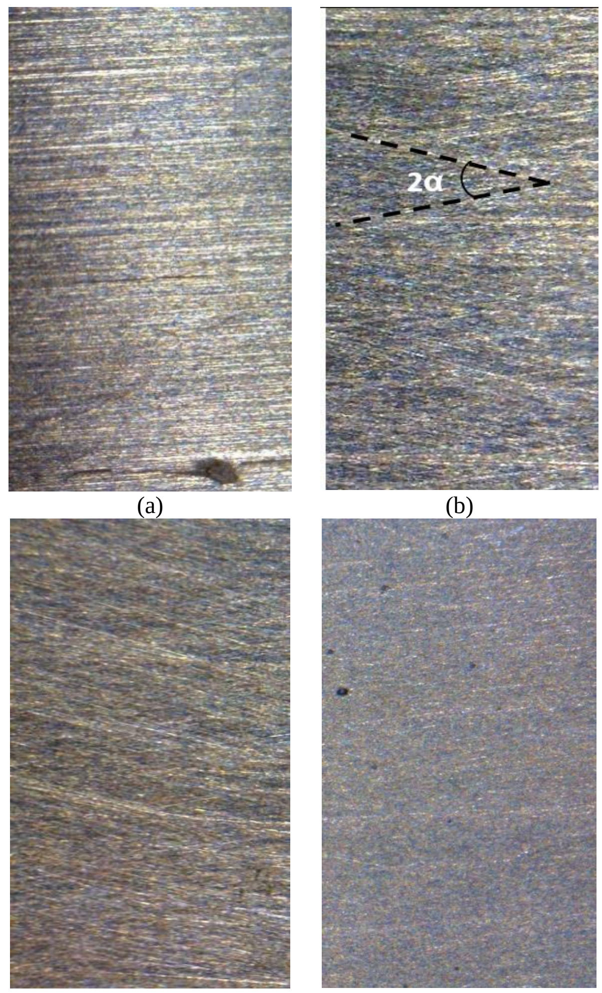

Fig. 7 Optical microscopy images of surface a) before MAH, and after MAH with b) α=15º, N=600 rpm, M=120, c) α=15º, N=600 rpm, M=220, d) α=15º, N=600 rpm, M=400.

4 CONCLUSION

The main objective of this work was investigation of cross-hatch angle, mesh number and rotary speed of workpiece on %ΔRa of AISI 304 tube workpiece in MAH process. Reciprocating movement of abrasives in MAH causes the abrasives to remix, as a result, producing a smoother surface roughness. The following conclusions are obtained from the experimental results in LVMAF process:

1. With increasing the mesh number of abrasives, the surface roughness decreased. Regarding the experimental conditions, in mesh number of 400, the minimum surface roughness was achieved. The morphology showed that two-body mechanism is dominant in MAH with coarse AP, and three-body mechanism is for fine AP.
2. Contact length of AP on the surface increases by workpiece rotary speed; hence, MRR increases. With increasing the workpiece rotary speed from 400 to 800 rpm, the surface quality improved. The minimum surface roughness was obtained in rotary speed of 800 rpm.
3. By increasing the cross-hatch angle, contact length of AP on the surface increases. With increasing the cross-hatch angle from 15 to 45 degrees, the surface roughness decreased. The best surface roughness was obtained in scratch angle of 45.
4. The maximum percentage change of surface roughness (%ΔRa=585) was obtained under the best conditions of scratch angle of 45, rotary speed of 800 rpm, and mesh number of 400.
5. Optical microscopy images showed the MAH texture and cross-hatch angle on the inner surface of workpiece, indicating that AP migrates in inclined path, and as a result, AP can remove more peaks on the surface. The images showed that the fine abrasives removed roughness and produced smooth surface.

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