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Influence of Various Conditions on Quality of Burnished Surface in Developed Roller Burnishing with Active Rotary Tool

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This paper deals with the burnishing characteristics of a newly developed roller burnishing method. This method can control the sliding direction between the roller and cylindrical workpiece by inclining the axis of the roller with respect to the workpiece axis. The outer surface of a round aluminum alloy bar was targeted. The influence of the burnishing conditions on the burnished surface quality was investigated, and the surface quality was mainly evaluated based on the surface roughness, profile, and external appearance. The burnished surface quality was strongly influenced by the pressing force, inclination angle of the roller, and the number of tool passes. A superior surface quality can be achieved by increasing the number of tool passes.

Keywords: roller burnishing, burnishing conditions, surface quality, aluminum alloy

1. Introduction

Various studies have been widely performed as a surface finishing and modifying of metal workpiece. Shimada et al. [1] developed the simulation method for plane honing based on statistical analysis of grinding. Kikuchi et al. [2] investigated the fine particle peening method to form a hydroxyapatite surface layer on the titanium alloy as a surface modification. Roller burnishing process is one of the typical surface finishing and modifying methods. It is a highly efficiency finishing process and can generate smooth surface with high wear resistance and fatigue strength. Hamadache et al. [3] investigated the characteristics of the subsurface of a round steel bar finished using roller burnishing and turning techniques. Ravankar et al. [4] reported the effect of ball burnishing on Ti-6Al-4V in terms of wear resistance using an FEM model. El-Tayeb et al. [5] evaluated the surface and tribological characteristics of aluminum alloy finished using ball burnishing. Janczewski et al. [6] reported the effects of ball burnishing on the surface properties when using a low-density high molecular mass polyethylene material as the target surface. Duscha et al. [7] mentioned the residual stress of the surface layer of the finished surface obtained by the roller burnishing. Moreover, roller burnishing can be applied using common machine tools such as a lathe. The advantages of roller burnishing have resulted in various studies on value-added methods for this technique. Tian et al. [8] developed a laser-assisted burnishing method. Sanchez et al. [9] clarified the advantage of hot burnishing of AISI 1045 steel. Conversely, Huang [10] investigated the effects of supplying liquid nitrogen as a coolant during roller burnishing. Travieso-Rodriguez et al. [11] clarified the optimal parameters of a vibration-assisted ball burnishing process. Zhao and Liu [12] also theoretically investigated the rotary ultrasonic roller burnishing of a Ti-6Al-4V material. Ebeid and El-Taweel [13, 14] evaluated the surface quality obtained by a hybrid electrochemical smoothing and roller burnishing technique. Kodácsy and Liska [15] experimentally and theoretically investigated a magnetic-assisted roller burnishing process. Kovács [16] also investigated the tribological characteristics of a surface finished using a magnetic polishing and roller burnishing process. However, these high value-added surface finishing processes relating to roller burnishing are complex, and require special devices and/or machines in addition to a common burnishing tool.

Slide burnishing, in which a burnishing tool made from a high hardness material is slid across the target surface, has also been widely studied. For slide burnishing, the target surface is subjected to a horizontal frictional force in addition to a vertical compressive force, whereas only a compressive force is generated with roller burnishing. Therefore, investigations regarding slide burnishing targeting a high hardness material have been conducted. Sugita et al. [17] proposed ultra-precision machining method applying cutting and slide burnishing effects for tungsten-based alloys. Kuznetsov et al. [18] investigated nanostructuring burnishing which targets hardened steel with 55HRC. Moreover, the present authors [19, 20] developed a new diamond tip burnishing methods. However, the burnishing tip material used in slide burnishing is very expensive, because it requires significant high hardness and a smooth surface to obtain a long tool life and satisfactory burnished surface integrity. Additionally, Tanaka et al. [21] reported that gouging and flaking of the subsurface easily occur during tip burnishing, when a low hardness material is targeted.

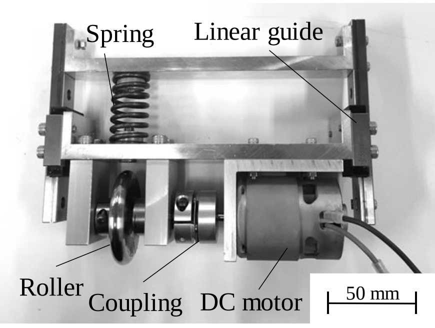
As an alternative, the present authors developed a simpler improved roller burnishing method, which generates rolling and sliding effects simultaneously for a cylindrical workpiece [22, 23]. In these papers, the advantage of generation of the sliding effect and sliding direction controllability was evaluated. However, the influence of the burnishing conditions on the burnished surface quality was not clarified.

This paper deals with the influence of the burnishing conditions on the burnished surface quality for a novel roller burnishing technique. The surface quality was evaluated based on the burnished surface roughness, profile, and external appearance. The burnishing conditions required to obtain a superior burnished surface were therefore clarified.

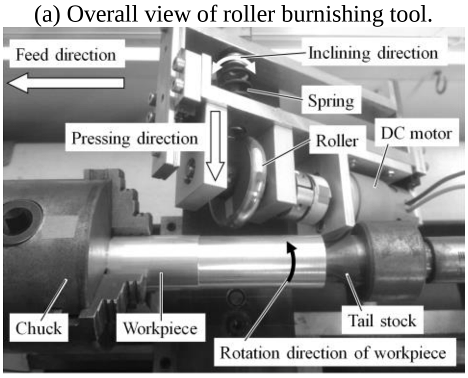
2. Experimental Method

2.1. Experiment Setup

Figures 1 (a) and (b) show the experiment setup. Roller burnishing tests were carried out using a bench lathe. The roller burnishing tool, which can rotate the roller actively using a DC motor, was fixed to the tool holder of the bench lathe at an inclination angle of α. The round workpiece bar was also independently rotated using the main spindle of the bench lathe. The pressing force between the roller and workpiece was determined using a compression spring. A burnished



(a) Overall view of roller burnishing tool.



(b) Installation image of roller burnishing tool on bench lathe.

Fig. 1. Experiment setup.

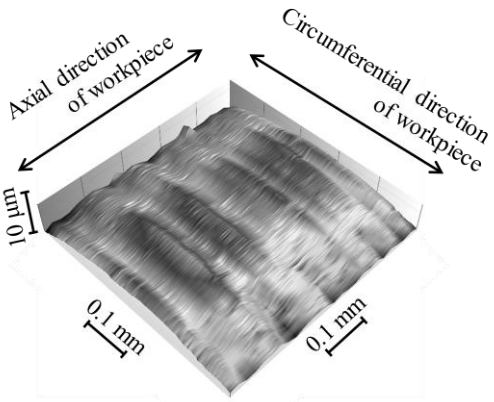
surface was obtained by feeding the burnishing tool toward the axial direction of the workpiece.

2.2. Experiment Conditions

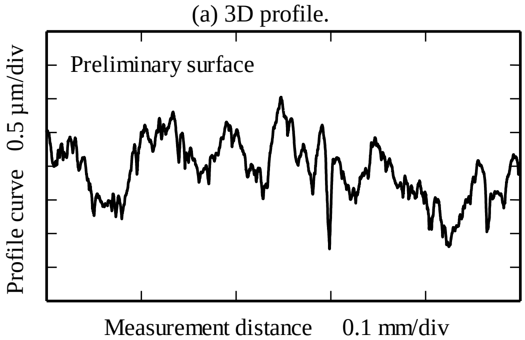
The experiment conditions are summarized in Table 1. An aluminum-based alloy, AA 2017, was used as the workpiece material. The profile of a burnished surface is strongly influenced by the profile of the preliminary surface prior to burnishing [24]. Therefore, all of the preliminary surfaces were prepared using a turning technique under the same cutting conditions. Figures 2 (a) and (b) show the 3D profile and sectional profile of the preliminary surface of the workpiece. The 3D profile and sectional profile were measured using a stylus-type profiler and roughness meter (SURFCOM NEX SD-12, TOKYO SEIMITSU CO., LTD.). Periodic unevenness in the axial direction could be observed from the profile of the preliminary surface, which was feed mark generated by the turning. The surface roughness in the axial direction of the preliminary surface was approximately R_a = 0.36 μm. The roller was made of stainless steel AISI 304 with a hardness of HV341. As a variation in the burnishing conditions, the sliding speed, which is the relative speed in the axial direction of the workpiece between the roller and workpiece at the burnishing point, was changed to within the range of v_s = 23–68 m/min. The pressing force of the roller onto the workpiece was changed to within the range of F = 30–120 N. In addition, the inclination angle of the roller was changed to within the range of α = 15–30°, where α = 0° indicates that the rotation axis of the roller is parallel to that of the workpiece. The sliding direction generated at the burnishing point was set to θ = 90°, which is the axial direction of the workpiece, because the best burnished surface can be obtained at this angle [23]. Thus, no sliding effect occurs in the circumferential direction of the workpiece at the burnishing point, and a sliding effect occurs only in the axial direction. The number of tool passes denotes the number of burnishing times on the same area of the workpiece under identical conditions, which was varied between N = 1–4 passes. The feed rate of the burnishing tool was set at f = 0.1 mm/rev. All the burnishing tests were carried out under dry conditions without a lubricant to achieve the same conditions. The burnished surfaces obtained through the burnishing tests were evaluated based on the surface roughness, sectional profile, 3D profile, and close-up view. The surface roughness, sectional profile, and 3D profile were measured using a stylus-type profiler and a roughness meter (SURFCOM NEX SD-12, TOKYO SEIMITSU CO., LTD.), and the close-up view was observed by optical microscopy (BX51M, Olympus Corporation). The burnished surface roughness was measured in the axial direction of the workpiece, and the cut-off value, measuring length, sampling interval, and form removal in the measurement of the surface roughness R_a were set at 0.8 mm, 4.0 mm, 0.15 μm,

Table 1. Burnishing conditions.

Workpiece	Aluminum-based alloy AA 2017	
	Diameter D_w = 25 mm, Hardness HV124	
	Roughness R_a = ~ 0.36 μm	
Burnishing roller	Stainless steel AISI 304, Diameter D_r = 50 mm	
	Curvature radius of outer periphery R_r = 4.0 mm	
	Roughness in rotation axis direction Ra = ~ 0.06 μm	
Burnishing conditions	Sliding speed	v_s = 23–68 m/min
	Circumferential speed of roller	v_r = 45–136 m/min
	Circumferential speed of workpiece	v_w = 39–118 m/min
	Pressing force	F = 30–120 N
	Inclination angle of roller	α = 15–30°
	Sliding direction	θ = 90°
	Number of tool passes	N = 1–4
	Tool feed rate	f = 0.1 mm/rev
	Lubrication	Dry



(a) 3D profile.



(b) Sectional profile.

Fig. 2. Profile of preliminary surface.

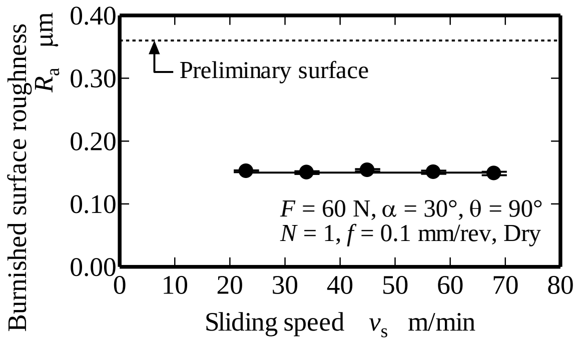


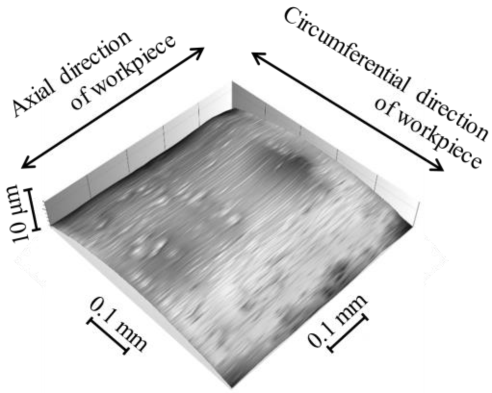
Fig. 3. Influence of sliding speed on burnished surface roughness.

and least square line, respectively. Moreover, the measurement results are presented in the figure as an average value of five measurements, and the standard deviation (±2σ) is also shown for the average data as an error bar.

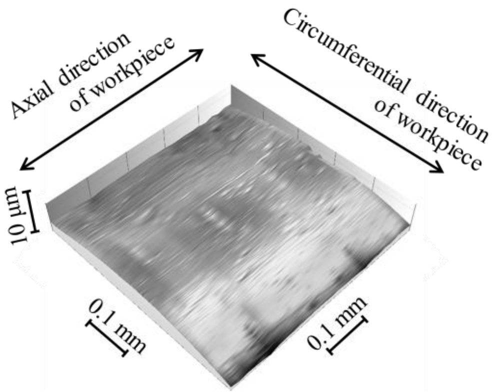
3. Experiment Results and Discussion

3.1. Influence of Sliding Speed on Burnished Surface

Figure 3 shows the relationship between the sliding speed v_s and burnished surface roughness R_a. The pressing force, inclination angle of the roller, and number of tool passes were set to F = 60 N, α = 30º, and N = 1, respectively. The surface roughness of the preliminary surface is also shown in the figure as a straight dotted line. As the figure indicates, the standard deviation of the surface roughness obtained by the burnished surface was very small, and roughness data with less irregularity were obtained. The burnished surface roughness at any sliding speed was remarkably improved compared with the preliminary surface. Additionally, no influence of the sliding speed on the burnished surface roughness was observed.



(a) v_s = 23 m/min.



(b) v_s = 45 m/min.

Fig. 4. 3D profiles of burnished surface for different sliding speed.

Figures 4 (a) and (b) show 3D profiles of the burnished surface obtained with a sliding speed v_s = 23 and 45 m/min. Moreover, Figs. 5 (a) and (b) also show sectional profiles of them. The other burnishing conditions were the same as those shown in Fig. 3. The periodic unevenness in the axial direction of the workpiece on the preliminary surface was clearly smoothed for both burnished surfaces. Especially, the convex profiles on the preliminary surface were

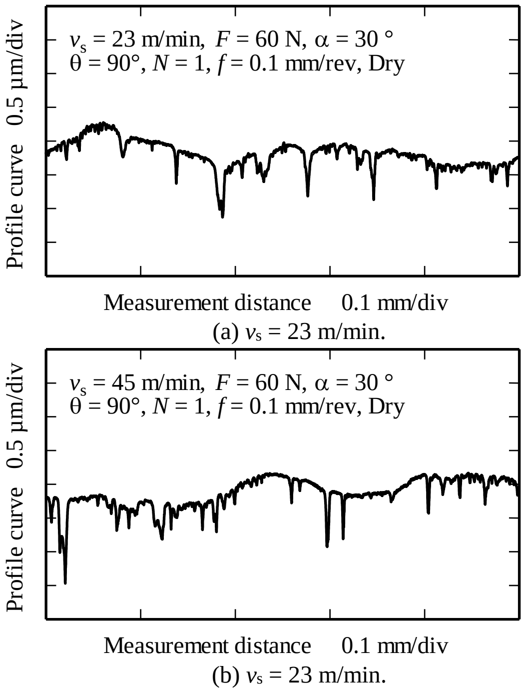


Fig. 5. Sectional profiles of burnished surface for different sliding speed.

suppressed, and the flat profile can be observed in the burnished surface. In this experiment, the sliding direction was fixed at θ = 90°, which is the axial direction of the workpiece, even when the sliding speed was changed. The authors previously clarified that the sliding direction between the roller and workpiece has a strong influence on the burnished surface roughness [23]. Therefore, it can be seen that the sliding speed does not affect the burnished surface profile when the sliding direction is constant at θ = 90°. In addition, these results confirmed that the frictional heat generated by the speed difference between the roller and workpiece had little influence on the burnished surface within the range of the sliding speed under these burnishing conditions. Futamura et al. [25] reported that the surface profile was notably flattened when the sliding speed between the ball and target surface was high during the ball burnishing. However, this report shows that the sliding effect is more effective for smoothing than the rolling effect when disregarding the sliding speed. On the contrary, with our developed burnishing technique, the sliding speed in the axial direction of the workpiece is satisfactory high (v_s = 23–68 m/min), and thus it can be determined that a high sliding speed has no influence on the burnished surface. In addition, the thermal influence from frictional heat was also considered in the flattened mechanism, but it was clarified that such influence was not observed within the range of the sliding speed applied in the present experiment because the sliding speed was observed to have no influence on the burnished surface.

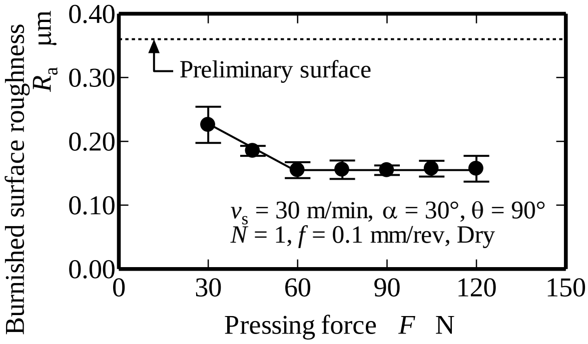
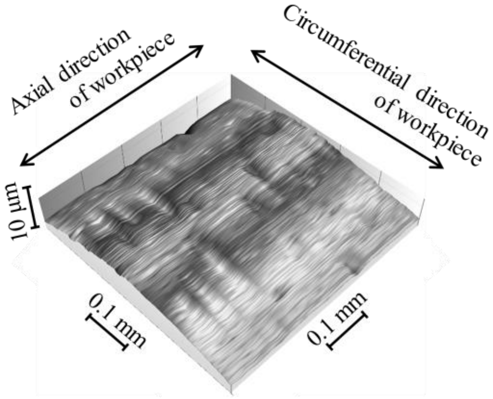


Fig. 6. Influence of pressing force on burnished surface roughness.

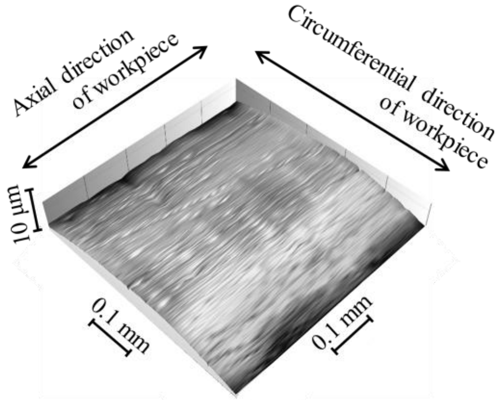
3.2. Influence of Pressing Force on Burnished Surface

In a conventional burnishing method, the pressing force is one of the dominant conditions of a burnished surface. El-Axir [26] clarified that the burnishing force has the most significant effect on the surface roughness for roller burnishing. Korzynski [27] investigated the relationship between the burnishing force and displacement of the tops of the surface asperities while burnishing using a spherical tool. Therefore, in this section, the influence of the pressing force on a burnished surface is examined. Figure 6 shows the relationship between the pressing force and burnished surface roughness. For the burnishing conditions, the sliding speed was set to v_s = 30 m/min, and the other conditions were same as the burnishing tests described in Section 3.1. The burnished surface roughness was improved with an increase in the pressing force within the range of F = 30–60 N. However, the influence of the pressing force on the burnished surface roughness was saturated within the range of greater than F = 60 N, and no influence of the pressing force was observed.

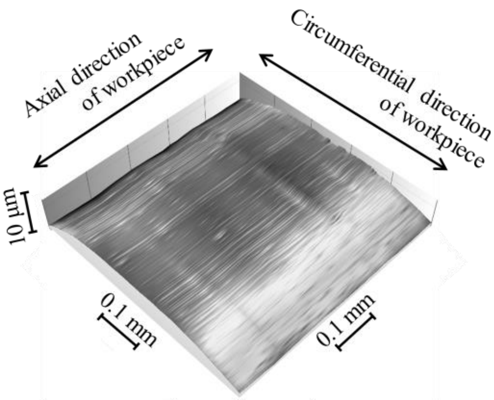
Figures 7 (a)–(c) show the 3D profiles of a burnished surface obtained with a pressing force of F = 30, 60, and 120 N. The other burnishing conditions were the same as those shown in Fig. 6. As shown in Fig. 7 (a), the periodic unevenness in the axial direction of the workpiece on the preliminary surface remained slight, and an improvement in the surface profile could be observed. In contrast, little difference in the surface profile between F = 60 and 120 N, as shown in Figs. 7 (b) and (c), was observed. A similar tendency of the surface roughness improvement to become saturated with increasing pressing force in the developed roller burnishing method was also obtained [23]. This tendency results from work hardening of the workpiece at the burnishing point and a decrease in the contact pressure between the roller and workpiece due to the elastic and/or plastic deformation of the roller and workpiece. Based on these results, the pressing force has a strong influence on the burnished surface, although an optimum value does exist.



(a) F = 30 N.



(b) F = 60 N.



(c) F = 120 N.

Fig. 7. 3D profiles of burnished surface for different pressing force.

3.3. Influence of Inclination Angle of Roller on Burnished Surface

The advantage of the developed burnishing method is that it can flexibly control the sliding direction and sliding speed at any inclination angle of the roller. However, the influence of the inclination angle of the roller on the burnished surface has yet to be clarified. Therefore, in this section, the effect of the inclination angle of the roller on the burnished surface roughness and profile under the same sliding direction and speed is clarified. Figure 8 shows the relationship between the inclination angle of the roller and burnished surface roughness. The sliding direction was set to θ = 90° in either inclination angle of the roller. The burnished surface roughness was improved with an increase in the inclination angle of the roller.

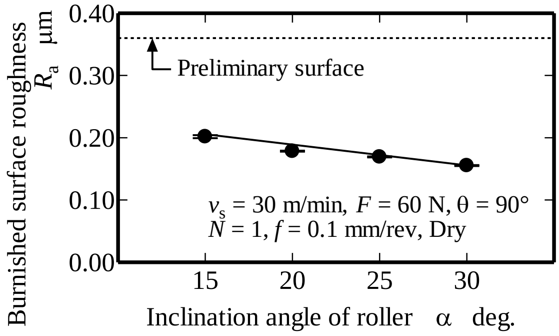
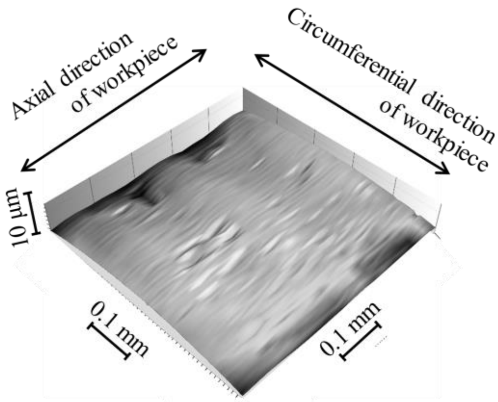
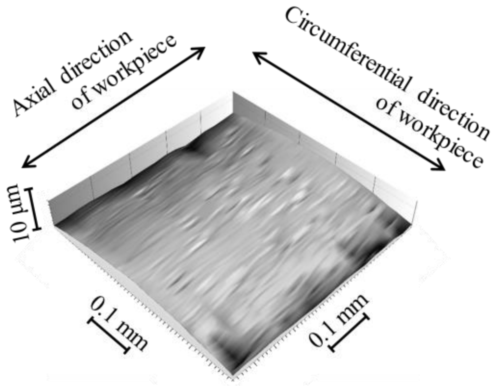


Fig. 8. Influence of inclination angle of roller on burnished surface roughness.



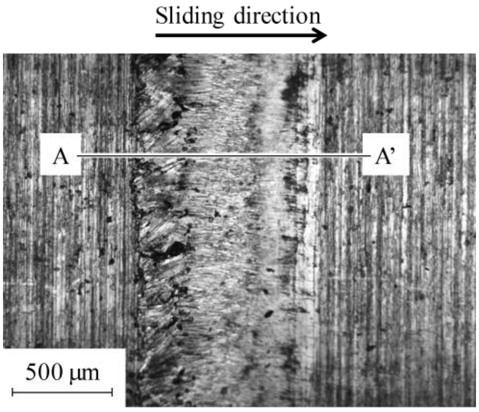
(a) α = 15º.



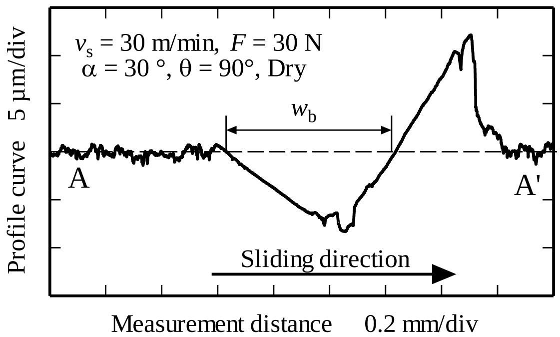
(b) α = 30º.

Fig. 9. 3D profiles of burnished surfaces for different roller inclination angles.

Figures 9 (a) and (b) show 3D profiles of a burnished surface obtained at roller inclination angles of α = 15 and 30°. The other burnishing conditions were the same as those shown in Fig. 8. Both 3D profiles also show a difference in the surface roughness, as indicated in Fig. 8, and a smoother surface can be achieved with a roller inclination angle of α = 30°. Under these burnishing conditions, the sliding speed and direction were fixed at v_s = 30 m/min and θ = 90°, respectively. Therefore, it can be seen that the difference in the burnished surface from the inclination angle of the roller is due to the difference in



(a) Close-up view.



(b) Sectional profile.

Fig. 10. Close-up view and sectional profile of burnished scar obtained through burnishing without a tool feed at α = 30°.

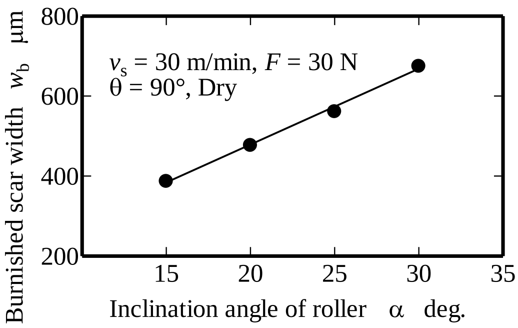


Fig. 11. Relationship between inclination angle of roller and width of burnished scar.

the contact state between the roller and workpiece at different angles.

Figures 10 (a) and (b) show a close-up view and a sectional profile of a burnished scar with a roller inclination angle of α = 30°. This burnished scar was obtained from the roller pressing at the same position on the rotated workpiece for approximately 20 s without a tool feed in the axial direction of the workpiece. The pressing force was set to F = 30 N, and the burnishing conditions other than the tool feed rate and pressing force were the same as those in Fig. 8. The sectional profile was measured from the A-A' direction, as shown in Fig. 10 (a). As shown in Fig. 10 (b), the burnished scar was mainly composed of concave and convex portions. The convex portion was generated by a plastic flow, and can be observed only on the right side of the concave portion owing to the

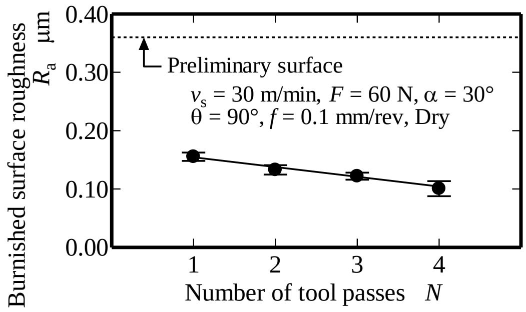


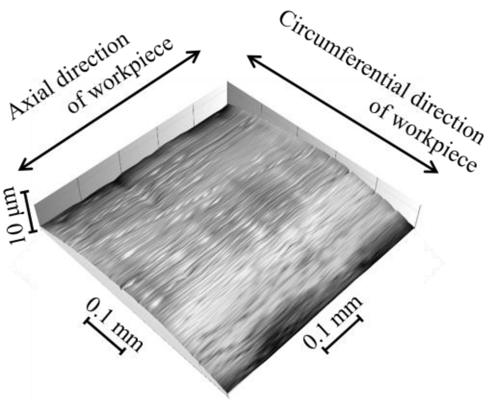
Fig. 12. Influence of number of tool passes on burnished surface roughness.

sliding direction. Here, the width of the concave portion indicating the contact area between the roller and the workpiece is defined as w_b, as shown in Fig. 10 (b). Figure 11 shows the relationship between the inclination angle of the roller and the burnished scar width w_b. From the figure, the burnished scar width increased with the increase in the inclination angle of the roller. Therefore, the contact state between the roller and workpiece is different due to the difference in inclination angle of the roller. Moreover, it is considered that this increasing tendency of the burnished scar width with the increasing inclination angle of the roller is also observed under the burnishing conditions with a tool feed, although the burnished scar width and profile are different from those produced under the burnishing conditions without a tool feed.

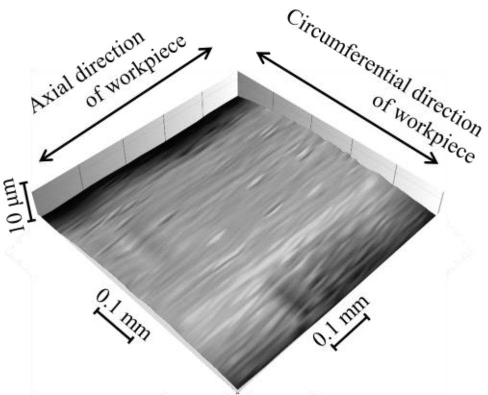
In the experiment shown in Figs. 8 and 9, the tool feed rate was fixed at f = 0.1 mm/rev. Therefore, the overlapping of the burnishing area by the tool feed occurred at any inclination angle of the roller. Consequently, it can be seen that the difference in the burnished surface roughness and profile by the inclination angle of the roller is caused by the difference in the overlap of the contact area between the roller and workpiece owing to the feeding of the burnishing tool.

3.4. Influence of Number of Tool Passes on Burnished Surface

As described in section 3.3, increasing the overlapping area of the burnished scar effectively improves the roughness of a burnished surface. Thus, in this section, the influence of the number of tool passes on a burnished surface is evaluated. Figure 12 shows the relationship between the number of tool passes and the roughness of a burnished surface. The number of tool passes indicates the number of times burnishing is applied under the same burnishing conditions for the same target region. As Figure 12 indicates, the burnished surface is improved with an increase in the number of tool passes, and the roughness of the burnished surface at N = 4 reaches approximately R_a = 0.1 μm. By applying four tool passes, an improvement of approximately 30% is possible compared to a single tool pass. Figures 13 (a) and (b) show 3D profiles of a burnished surface obtained for tool passes of $N = 1$ and 4, and Figs. 14 (a) and (b) show sectional profiles of them. As these figures indicate, an unevenness in the axial direction of the workpiece was slightly observed for $N = 1$. In contrast, a satisfactory burnished surface profile was obtained for $N = 4$. In particular, the depth of the concave profile was decreased for $N = 4$. Figures 15 (a)–(c) show an external view of the preliminary and burnished surfaces obtained for $N = 1$ and 4, as shown in Figs. 13 and 14. The specularity of the burnished surface obtained for $N = 4$ is higher than that for $N = 1$. These results indicate that the number of tool passes has a strong influence on the burnished surface quality, and the same effect can be also expected by decreasing the tool feed rate.



(a) $N = 1$.

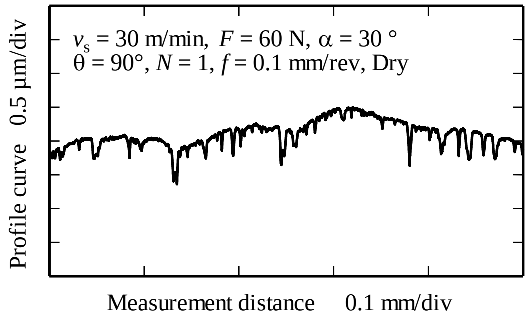


(b) $N = 4$.

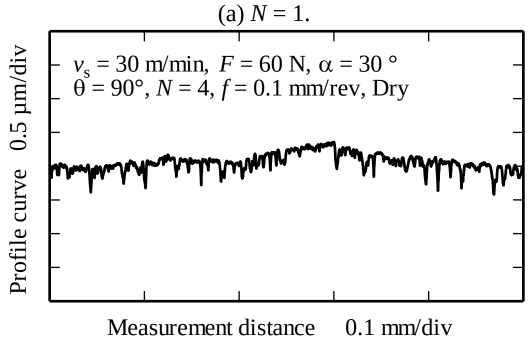
Fig. 13. 3D profiles of burnished surfaces for different numbers of tool passes.

4. Conclusions

The influences of various conditions on the quality of a burnished surface using roller burnishing with an active rotary tool, which can add a sliding effect to the rolling effect while controlling the sliding direction and speed, were investigated. A round aluminum-alloy bar was targeted as the workpiece, and the sliding direction was set in the axial direction of the workpiece. The burnished surface quality is mainly evaluated based on the surface roughness, profile, and



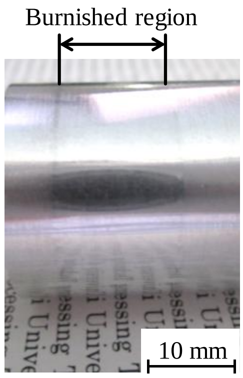
(a) $N = 1$.

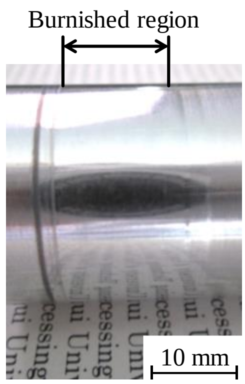


(b) $N = 4$.

Fig. 14. Sectional profiles of burnished surfaces for different numbers of tool passes.

(a) Preliminary surface.





(b) $N = 1$. (c) $N = 4$.

Fig. 15. External view of preliminary and burnished surfaces.

appearance. The results of these investigations can be summarized as follows:

1. No influence of the sliding speed between the roller and workpiece was observed on the quality of the burnished surface when the same sliding direction was used.
2. The pressing force of the roller to the workpiece has a strong effect on the quality of the burnished surface until the pressing force reaches lower than

60 N, and the effect of the pressing force becomes saturated at a pressing force of greater than 60 N.

3. The burnished surface quality was improved with an increase in the inclination angle of the roller within the range of 15–30°. The width of the burnished scar, which can be obtained by burnishing without a tool feed, was increased with an increase in the inclination angle of the roller.
4. The number of tool passes has a significant effect on improving the quality of a burnished surface, and an improvement in surface roughness of approximately 30% can be achieved by increasing the number of tool passes from one to four. A burnished surface with satisfactory specularity can be achieved when four tool passes are applied.

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