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Comparison of Roller Burnishing Method with Other Hole Surface Finishing Processes Applied on AISI 304 Austenitic Stainless Steel

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Component surface quality and selection of the optimum material are the main factors determining the performance of components used in machine manufacturing. The level of hole surface quality can be evaluated by the measurements regarding surface roughness, micro-hardness, and cylindricity. In this study, data had been obtained for different hole drilling methods. The characteristics of materials obtained after applications were compared for different hole-finishing processes to identify best hole drilling method. AISI 304 austenitic stainless steel material was used. Surface finishing of holes were performed using drilling, turning, reaming, grinding, honing, and roller burnishing methods. The results of the study show that the roller burnishing method gives the best results for mechanical, metallurgical properties, and hole surface quality of the material. On the other hand, the worst characteristics were obtained in the drilling method.

Keywords AISI 304 austenitic stainless steel, drilling, microstructure, roller burnishing, surface roughness

1. Introduction

Surface quality plays an important role in hole drilling processes which are widely used in machine manufacturing industry. Investigations are done to improve surface quality of the drilled holes. Surface quality affects abrasion resistance, loading capacity, tool lifetime, and fatigue properties of machine components. A coarse finishing surface increases abrasion, decreases fatigue strength, and complicates the production of components within given tolerances (Ref 1, 2).

Surface finishing methods such as drilling, turning, reaming, grinding, honing, etc. are widely used in machine manufacturing industry. These methods remove metal to achieve the desired surface quality. Machining process may cause further surface abrasion and geometric tolerance problems. Selection of the best process is important for desirable surface finishing characteristics in manufacture of components. Roller burnishing provides fairly good surface quality because it does remove chipping and it is a simpler process, compared to other methods (Ref 3-5).

In roller burnishing method, cylindrical balls with rigid and smooth spherical tips are applied to the surface of workpiece under certain forces. As a result of this process, plastic deformation occurs on the contacted surface as seen in Fig. 1. Surface irregularities are eliminated with deformation effect of process. A smooth surface is obtained, and a rigid layer is formed on the surface with strain hardening as a result of intensive plastic deformation on the surface of the material. This hardened layer formed on the surface provides a significant increase in the abrasion resistance (Ref 5, 6).

Special ball or ball burnishing tool design and combinations are required specifically for burnishing. Roller burnishing process is shown in Fig. 2 for spherical rolling element. First, contact with metal surface occurs in zone (A), and yield point of metal is exceeded in zone (B). Plastic deformation in zone (C). The most important feature of the burnishing process is the significant increase in the surface hardness as a result of this plastic deformation during the process (D). Within zone (C) after plastic deformation, little elastic recovery is realized (E). Within this zone, rolling element contacts the material finally making the surface smooth and shiny. Stress generated on the workpiece during rolling decreases from the surface toward the bottom part of the surface. This stress penetrates 1-2 mm deep depending on the kind of the material, rolling forces, and working method which are burnishing, honing, drilling, lathing, and reaming. When the rolling force is removed, residual compressive stresses occur on the surface (Ref 7).

In the literature, many studies have investigated the effects of form and the material of roller burnishing tool, machine, and process parameters on the roller burnishing process. However, there has not been any study that compares the roller burnishing process with other alternative hole finishing processes. Hole surface quality is very important in aeronautics and automotive industry (Ref 8-13). The purpose of this study is to examine the effects of hole-finishing methods on mechanical and metallurgical properties of obtained surfaces.

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2. Experimental Studies

2.1 Material and Specimen Preparation

The chemical composition of AISI 304 austenitic stainless steel material used in this study is given in Table 1. This material is widely used in aeronautics and automotive industries. Test specimens were drilled from rod-shaped material after surface cleaning at CNC machine. Then, drilling methods were applied to the specimens. Test specimens were cut in Ø 50×25 mm as seen in Fig. 3. In Fig. 4, the surface characteristics of the material before and after the burnishing process are shown dimensionally and graphically. As seen in the figure, tolerance before the process was $\pm$0.0125 mm, and it decreased to $\pm$0.006 mm after the process. It means an efficiency of almost 400%.

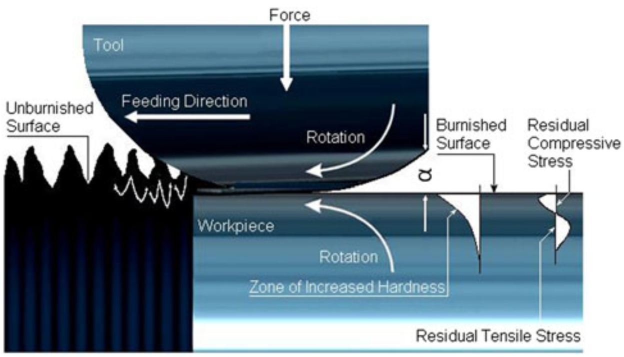

Fig. 1 Schematic illustration of the roller burnishing process

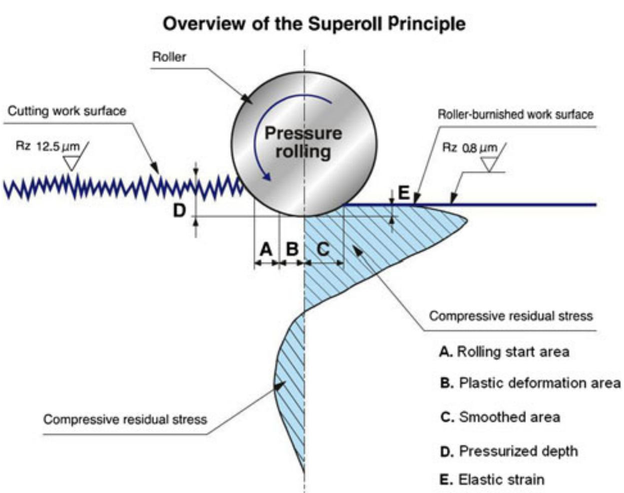

Fig. 2 Schematic display of residual stress distribution during roller burnishing (Ref 7)

2.2 Hole Drilling Processes

Primarily inner diameters of test specimens were drilled. This process was carried out on CNC machine of Taksan TTC-630. Turning conditions were kept the same for all the specimens. The cutting parameters were selected as cutting speed 50 m/min, and feed rate 0.2 mm/revolution.

Table 1 Chemical composition of AISI 304 austenitic stainless steel material (wt.%)

V	Si	Mn	Mo	Cu	Cr	Ni	Fe	C	Co
0.116	0.498	0.979	0.217	0.228	17.30	8.06	72.30	0.0476	0.147

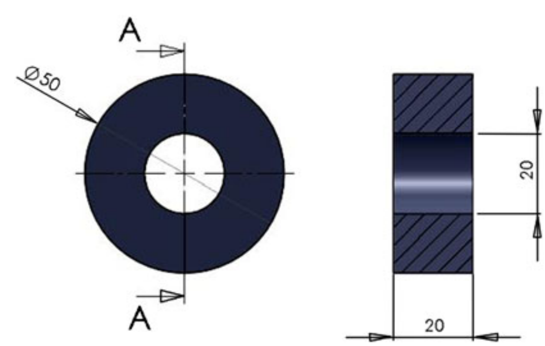

Fig. 3 Test specimen

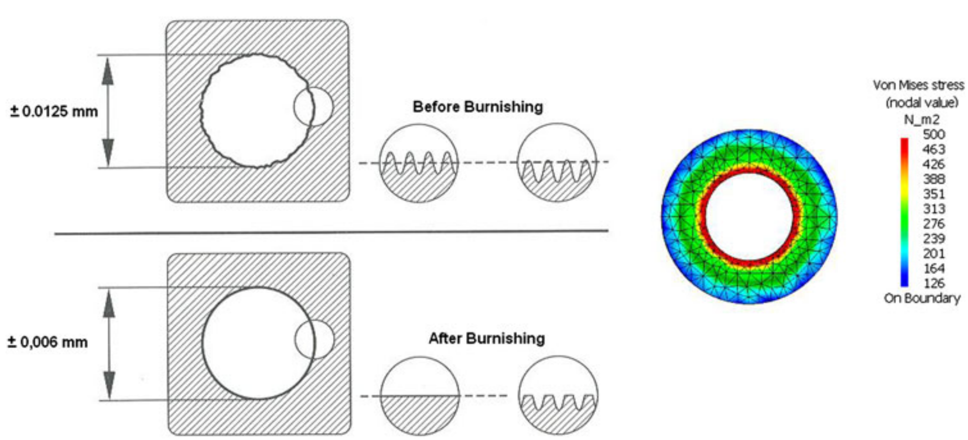

Fig. 4 Appearance of burnished surface and surface geometry modeling of roller burnishing process (Ref 9)

2.3 Surface Processes Applied After Hole Drilling

All the specimens were drilled using a CNC machine. Then, turning, grinding, reaming, honing, and roller burnishing were applied on these specimens as finishing processes for the AISI 304 Austenitic stainless steel material. Roller burnishing is applied on a group of specimens which was drilled at the inner diameter on an upright drill machine. The SEM view of the burnished surface is given in Fig. 5. In the figure, the penetration zone and the resulting surface change can be observed. Tools and test apparatus used in the burnishing process are shown schematically in Fig. 6.

In order to avoid the insertion of chips between tools and workpieces, balls were cleaned continuously during burnishing. This was carried out using Superoll coolant which has anticorrosion and cooling effects. Roller burnishing conditions and parameters were kept the same for all the specimens as seen in Table 2. Optimum rolling time was selected, as cyclicity is negatively affected by increase in rolling time. Another rolling parameter which has significant effect on cyclicity is the rolling depth (penetration depth). The penetration depth is chosen as 0.025 mm, taking into account the burnishing margin assigned by the manufacturer of the roller burnishing toolkit for the austenitic stainless steel material.

It is known that increase in rolling depth to a certain extent yields better hole cyclicity. However, for all the materials, selecting excessive rolling tolerances and rolling depths result in oxidation of surface and metal removal (Ref 7, 14, 15).

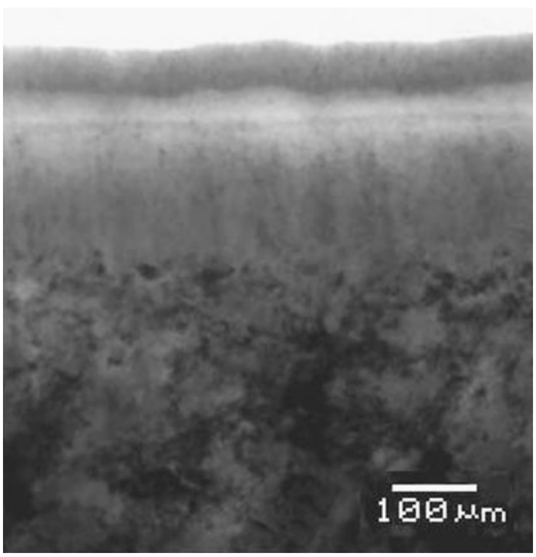

Fig. 5 Surface SEM view after roller burnishing (Ref 3)

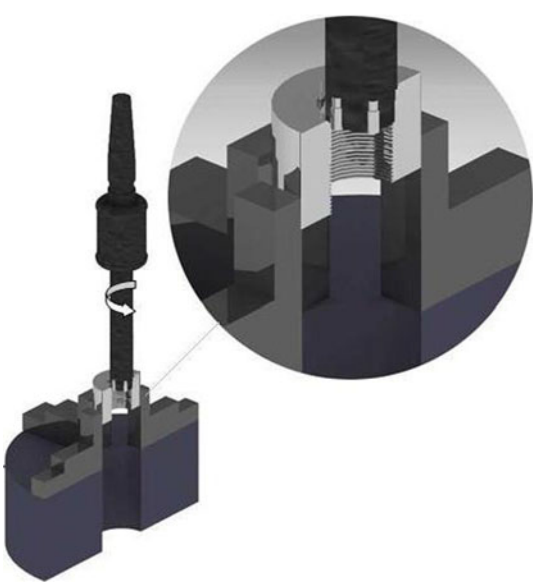

Fig. 6 Experimental apparatus used in roller burnishing

2.4 Metallographic Studies

After each of the hole finishing processes, specimens with the dimensions of $12 \times 12 \times 10$ mm were cut from each test specimen. Afterward, these specimens were prepared for microstructure examination with standard metallographic processes (sanding and polishing). The specimens were etched using a mixture of "5 g $CuCl_2$ + 100 mL HCI + 100 mL ethanol + 100 mL distilled water." Leica optical microscope was used to view microstructures. Cyclicity was tested using Hommel-Etamic equipment. Surface roughness measurements (Roughness parameters DIN EN ISO 4287) were carried using Hommel Tester T8000 laser measurement equipment.

3. Results and Discussion

3.1 Effect of Hole Finishing Processes on Microstructure of Material

Detailed metallographic examination was performed on surfaces of specimens before (Fig. 7) and after (Fig. 8) application of each hole surface finishing process. Changes in microstructures were observed depending on the characteristics of each process. When the surface morphologies are examined,

Table 2 Rolling parameters

Rolling force	50 kgf
Number of revolution	230 rpm
Rolling speed	1.25 m/s
Rolling depth (penetration)	0.5 mm
Rolling diameter	20 mm
Rolling condition	Greasy

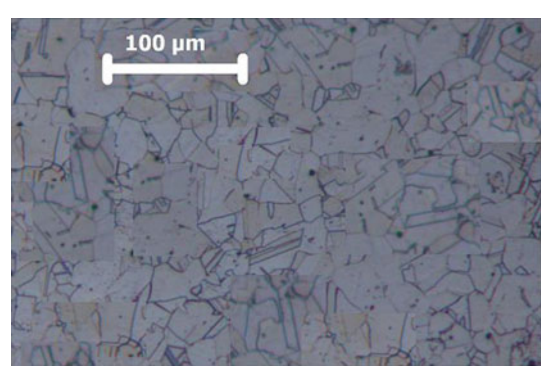

Fig. 7 Microstructure of material

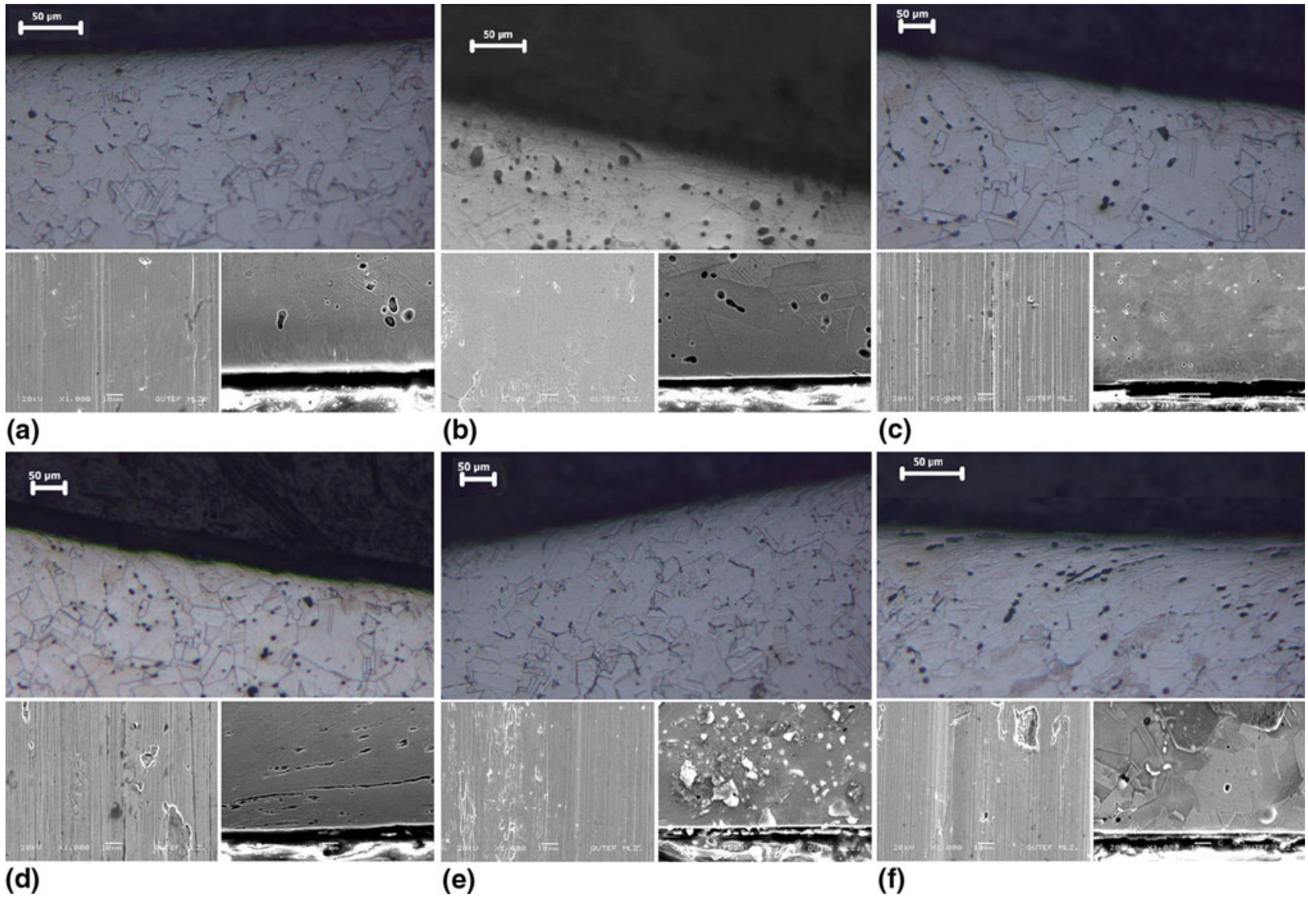

Fig. 8 SEM pictures and comments related to surface finishing methods. (a) Roller burnishing; (b) honing; (c) turning; (d) drilling; (e) reaming; (f) grinding

it is observed that microstructures obtained by honing and burnishing methods are similar and that the surface roughness is low. In drilling method, more deformation occurs on the hole surface, and hence, a distinctive coarse microstructure can be observed. Turning process yields smoother surface than that obtained by drilling. In grinding and reaming, a medium quality of surface is obtained. As compared to other methods, grains remain more homogenous and less affected from deformation during burnishing. Coolant is applied during turning and honing processes. Change in microstructure occurs in relation to the heat generated in certain depths on the surface.

Hole surface finishing processes were applied on the specimens, and SEM photographs of these surfaces were taken with 1000 magnification. These photographs demonstrate microstructures of hole surfaces (a), hole surface properties (b), and top view of zones affected by processes (c). When the surface obtained by roller burnishing is examined in micro level (a), it is clearly observed that material was pounded and transferred during rolling. As is well known, it can be seen that the roughness is minimized by filling in the cavities with higher tips and that surface hardness increases in relation to the plastic deformation which occurs during rolling. When the hole surface is examined (b), a surface having roughness less than that of the one obtained by other methods respectively and a similar microstructure throughout the surface can also be observed. When the burnished surface is examined perpendicularly (c) (in order to see the penetration zone), two different microstructures are observed in the zone affected by burnishing process. It is evaluated that tracing from the edge of the hole toward inside, finer microstructure turns into coarser, and this new structure determines the hole surface properties. Penetration zone effects can be seen from the hole surface toward inside.

When the microstructure of the surface obtained by honing is examined (a), a heat-affected zone at a micro level was realized with the effect of heat generated during the process. When the hole surface quality is examined (b), an almost smooth surface can be observed. Hole surface penetration after honing is examined (c), it is seen that the surface and the region in the vicinity were affected by the process. We can observe the heat-affected zone in this region. A surface quality having roughness at low level was obtained as was obtained in the case of roller burnishing. When the microstructure of the surface obtained by fine surface turning is examined (a), a rough and wavy surface is seen. An uneven microstructure, which was formed by the deformation stresses and frictional forces, can be observed. When the hole surface is examined (b), a surface formed by deep cavities and tips bearing along chips cut can be observed. This method is evaluated as the second worst method yielding microstructure and one with highest surface irregularities. When the hole surface penetration after turning process is examined (c), deformation effects at a certain thickness from the edge toward inside can be seen. The chips formed on the hole surface can also be clearly observed. When the surface obtained by drilling is examined in a microlevel (a), a wavy and irregular surface is seen, being formed due to the effect of microstructural deformation and abrasion. When the hole surface quality is examined (b), an excessively irregular surface with deep dashes formed by deep cavities and tips can be seen. We also can see deep craters formed by chips. When hole surface penetration zone after drilling process is examined (c), it can be observed that material is drifting from the hole surface toward a certain depth with the effect of deformation and that rupture occurred as a result. It can be concluded that drilling is the worst method among hole finishing processes yielding worst surface properties.

When the microstructure of the surface obtained by reaming is examined (a), it can be evaluated that least deformation and friction in the hole surface microstructure is achieved by reaming. Although there is no significant deformation in the microstructure, a very small change occurs within a very limited zone on the hole surface as compared to the other methods. Main reasons for these are the very small amount of metal removal, and no significant heat formation because of less friction. When the hole surface is examined (b), a rather smooth surface can be observed although to a lesser extent as compared to roller burnishing and honing. When hole surface penetration after reaming process is examined (c), we can see the effect of a process in a very small region. Besides, it can be concluded that the chips formed during cutting was not detached and hence yield negative effect on surface quality. Hole surface quality obtained by reaming can be evaluated as the third best option after roller burnishing and honing.

When the microstructure of the surface obtained by grinding is examined (a), owing to the effect of heat input generated during the process, a layer formation similar to but thicker than that formed during honing process, can be observed. As the heat generated is much more, a significant deformation in the microstructure from the hole surface toward inside is realized. When the hole surface is examined (b), we can observe a resulting surface having roughness of medium quality. Linear dashes related to the process characteristics can be seen on the surface. It is also observed that chips and abrasive pieces detached from the surface due to the ductile structure of the material were immersed back to the surface within some regions. When the penetration zone from the hole surface toward inside is examined perpendicularly (c), considering the heat effect, formation of the zone affected by the process can be seen easily. It is also observed that the penetration zone is limited and that the material preserves its microstructure after this zone. It can be concluded that deformation although in small ratios occurred throughout the surface obtained by grinding and its vicinity. Hole surface obtained by grinding has medium surface quality as compared to other hole surface finishing processes.

3.2 Effect of Rolling Parameters on Surface Properties

Performance of roller burnishing is relatively complicated and depends on many factors and their results. Optimum rolling conditions depends on parameters such as feed rate, rolling force, penetration depth and number of roller passes. When one or more of these parameters are not selected properly, chipping and crack formation, fracture, and also rupture occur on the surface. In this study, interpretations are based on optimum parameters for all processes, including the burnishing process. Although just one data source is presented in the study, almost 10 other data sets were evaluated in the study. The optimum values are based on them.

Figure 9 gives the surface obtained by applying parameters grater than the optimum rolling parameters on two different specimens taken from AISI 304 stainless steel material. It is well known that AISI 304 stainless steel material is more ductile than other groups of steel materials. However, despite the fact that they are ductile, when rolling parameters are selected more than the optimum parameters, crack formation, fracture, and rupture occur on the hole surface as shown in Fig. 9. Therefore, the selection of rolling parameters is very important. Unavoidable results are given in Fig. 9 when the selection is not made properly.

3.3 Analysis of Changes in Material Microstructure Due to Hole Finishing Processes

Although a decrease in hardness values depending on the heat generated during all the processes other than roller burnishing was observed, an increase in surface hardness was measured for roller burnishing as seen in Fig. 10. Microhardness values from the hole edge toward inside the workpiece was measured with 0.1-mm distances on each specimen, are shown in Fig. 11.

Hardness reduction is higher in drilling, turning, and grinding processes than that in reaming and honing processes as a result of heat generation. There is an increase in hardness within 1-mm thickness in roller burnishing, whereas for all other methods hardness decreases. It is observed that changes in hardness values in all processes other than grinding are very

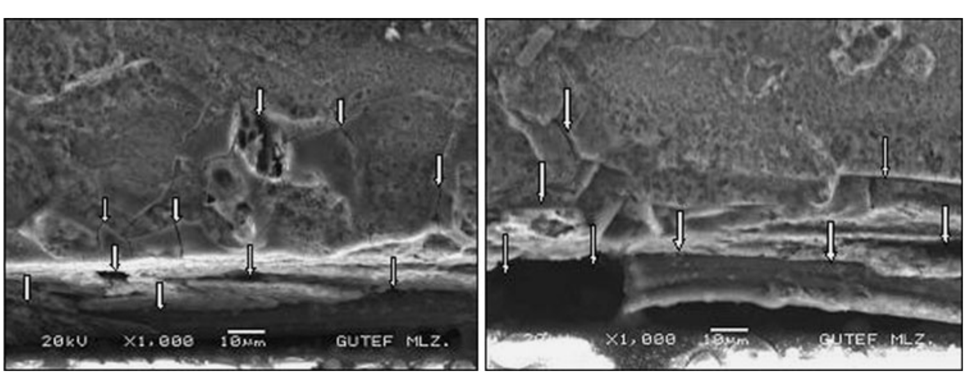

Fig. 9 Surface view obtained with inappropriate parameters

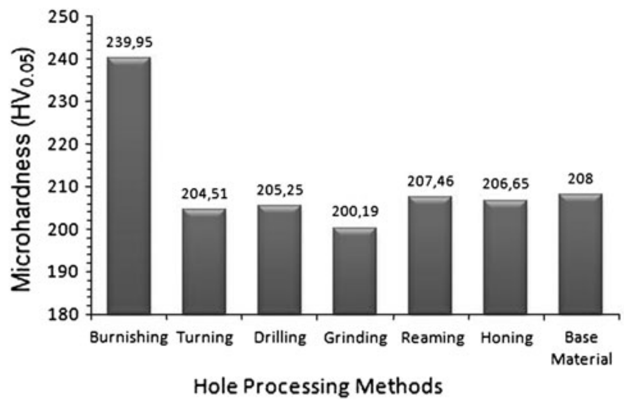

Fig. 10 Comparison of surface hardness values according to hole processing methods

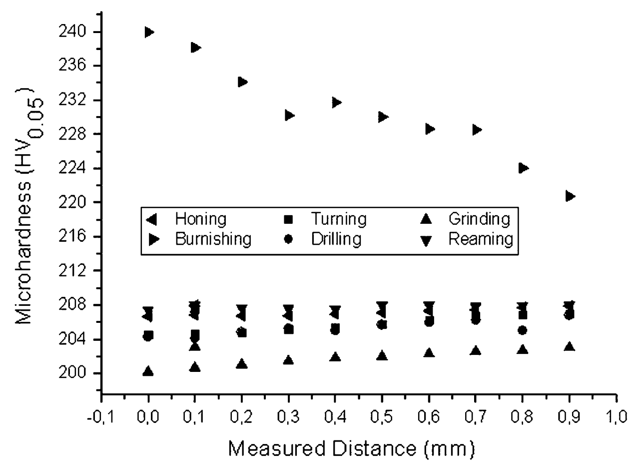

Fig. 11 Change in micro-hardness values according to different surface treatment methods

close to each other. A decrease in hardness values of AISI 304 stainless steel material occurs due to the heat generated during grinding process. Strain hardening occurs due to the intensive plastic deformation during roller burnishing, and hence, a significant increase in hardness is obtained. When all other methods are evaluated, the best hardness values can be obtained by roller burnishing. Roller burnishing causes an increase in surface hardness for all types of material (Ref 16). The results obtained in this study are in accordance with the literature as well.

3.4 Effect of Hole Drilling After Turning Processes on Cyclicity

Roller burnishing process causes significant changes in microhardness values and cyclicity properties of test specimens. For example, when a shaft is examined (Fig. 12), it can be seen that the diameter of the shaft turns out to be same when measured with different measuring devices, but when it is magnified, irregular topography can be observed on the surface. These tips carry most part of the load when a force is applied on the shaft and hence yields stress concentrations (Ref 17, 18).

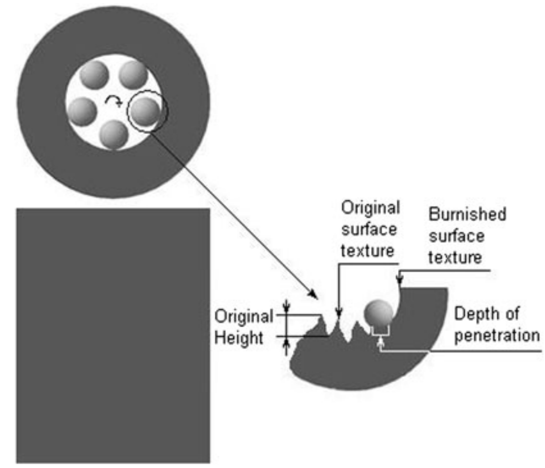

Fig. 12 Examination of a shaft

In this study, cyclicity tests were carried out on Hommel-Etamic laser cyclicity measurement device. Cyclicity has an important effect on mechanical properties of components. Distortion of cyclicity results from tool abrasion, incorrect positioning of tool, or uneven distribution of forces during cutting. Cyclicity range is affected by many parameters such as cutting speed, feed rate, cut depth, number of passes, etc. (Ref 19-21).

The number of passes is the most important parameter which affects the cyclicity and surface characteristics during roller burnishing. Increase in the number of passes yield a decrease in cyclicity. This decrease can be referred to the strain hardening caused by plastic deformation (Ref 3, 18, 22). Therefore, in this study, the number of passes was kept as minimum, and roller burnishing was made at one pass. Rolling force is another parameter that affects cyclicity during roller burnishing. When rolling forces exceeds a certain limit, discontinuities on the surface can be generated due to cutting losses on the surface.

The results of this experimental study show that a better cyclicity range was achieved with roller burnishing than those obtained by conventional finishing methods. One of the most important purposes of this study is to examine the effects of roller burnishing process on cyclicity. Figure 13 gives the effect of conventional finishing methods as compared to that of roller burnishing on cyclicity of test pieces. As can be seen in Table 3, the best cyclicity and cylindricity properties are achieved with the roller burnishing process. Honing process gives the second best result. Cyclicity properties obtained by grinding and reaming have medium values. Turning and drilling processes are the two methods by which the worst results were obtained. Another property examined in this study is the evaluation of cylindricity of the surface obtained after processing. When the cylindricity values are considered, the best cylindricity is obtained by roller burnishing process as seen in Fig. 14.

3.5 Effect of Hole Drilling After Turning Processes on Surface Roughness

Surface roughness graphics for different surface finishing methods are shown in Fig. 15. The best surface quality was obtained by roller burnishing. Feed rate is one of the important

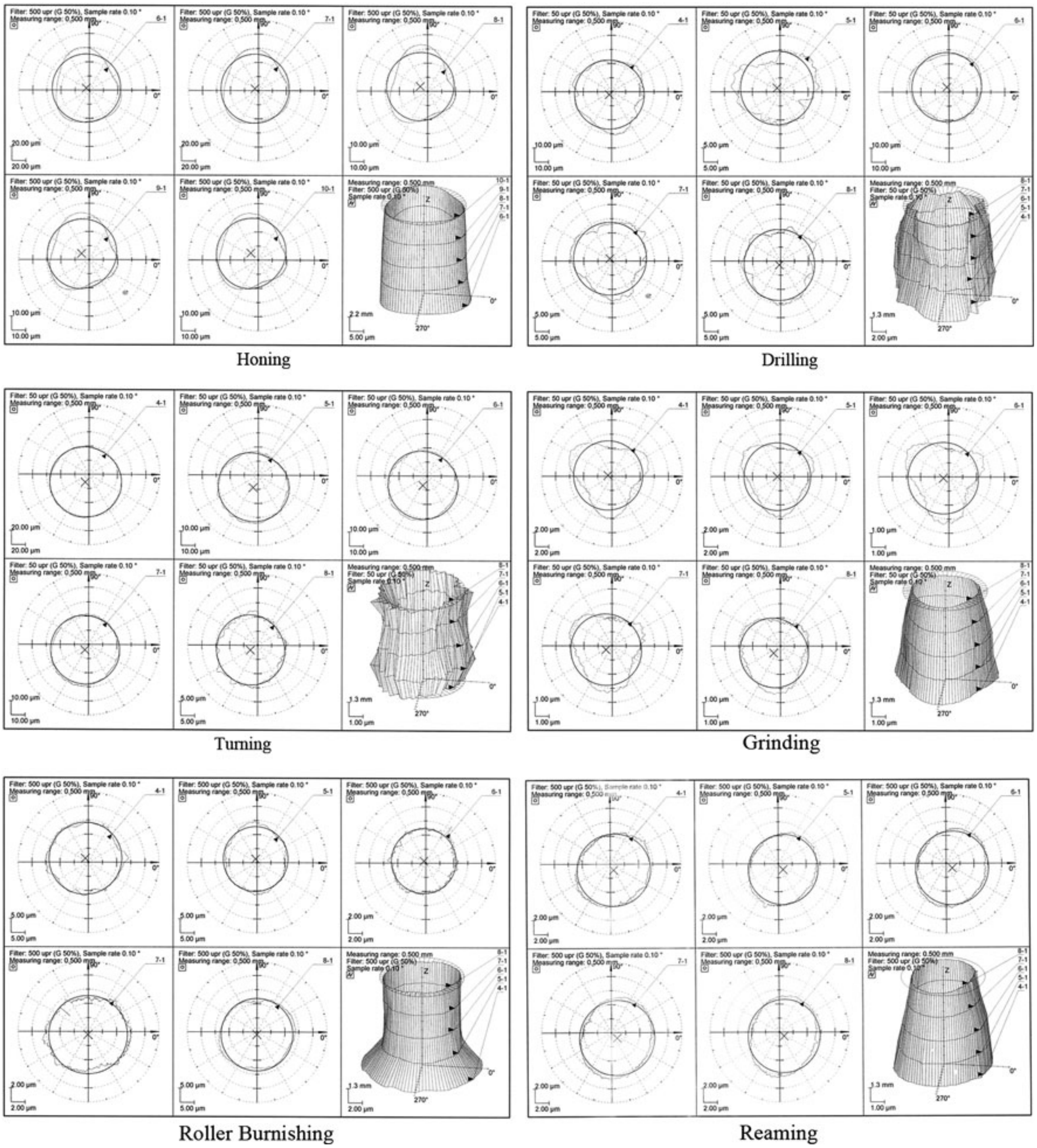

Fig. 13 Change in cyclicity according to different surface treatment methods

Table 3 Comparison of surface roughness parameters according to hole processing methods

	Surface roughness parameters, μm									
Hole processing method	**Ra**	**Rp**	**Rs**	**Rq**	**Rv**	**Rt**	**Rz**	**Rc**	**R3z**	**R3y**
Roller burnishing	0.076	0.195	15.56	0.124	0.412	3.02	0.607	0.62	0.281	0.759
Honing	0.090	0.279	13.46	0.12	0.372	2.38	0.65	0.456	0.40	0.692
Turning	2.87	7.037	88.93	3.31	5.426	14.28	12.47	9.62	10.82	11.77
Drilling	5.023	12.5	180.3	6.32	12.63	36.08	25.12	14.94	11.9	14.53
Reaming	0.723	1.653	34.77	0.98	1.99	8.7	3.643	2.75	0.98	2.515
Grinding	0.142	0.359	9.29	0.221	0.758	2.32	1.117	0.607	0.526	0.813

parameters, which affects the surface roughness during roller burnishing. In previous studies, it was observed that increase in the feed rate yields an increase in surface roughness. This phenomenon can be ascribed to the excessive vibration on the treated surface caused by rolling element at high feed rates. It was determined that the feed rate should not exceed 2 m/s and that the ideal feed rate should be within the range of 1-1.9 m/s (Ref 16, 23-26).

In this study, feed rate was taken as 1.25 m/s by taking into consideration the effects of feed rate on the surface roughness. Surface quality values are close to each other in roller burnishing and honing methods. Because of strain hardening as a result of intensive plastic deformation during roller burnishing, maximum hardness values were measured from these specimens. It should be taken into consideration that the scales are different in the graphics given in Fig. 15, although they seem to be close to each other. Hole surface roughness values obtained by each method are given in Table 3.

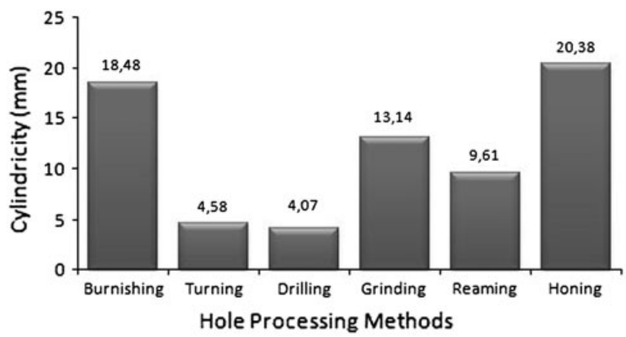

Fig. 14 Comparison of cylindricity values according to hole processing methods

4. Conclusions

When compared to its alternative methods, roller burnishing method has many advantages. Results obtained from this study are given below:

- Roller burnishing process requires the least time compared to all other hole finishing techniques.
- The best cyclicity can be obtained by roller burnishing. The highest microhardness values were also measured on roller burnished specimens.
- Plastic deformation in drilling and turning processes occurs at the highest levels and that excessive deformation on surfaces deteriorates surface quality.
- Surface properties of honing and roller burnishing processes are very close to each other, and rolled surface demonstrates more uniform structure.
- Optimum combination of surface characteristics and mechanical properties can be obtained by roller burnishing process.
- An increase in the abrasion resistance of the finished surface is obtained in roller burnishing process. Roller burnishing process removes notch effects on the surface of the finished hole, the engineering life of which increases apparently.
- Selection of roller burnishing process is important; if one or more of these parameters are not determined correctly, oxidation and flaking through the surface will be unavoidable.
- Roller burnishing is an environmental friendly process.

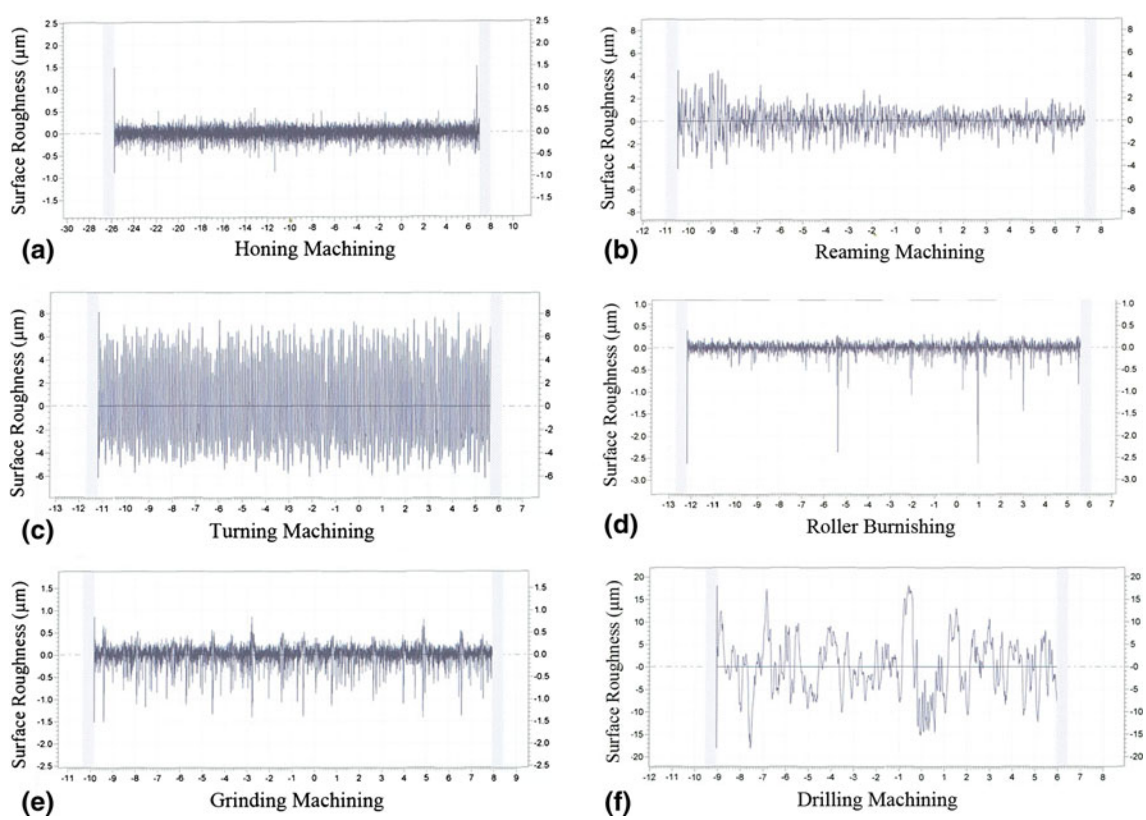

Fig. 15 Change in surface profiles according to different hole processing methods

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References

1. A.M. Hassan and A.S. AL-Bsharat, Influence of Burnishing Process on Surface Roughness Hardness and Microstructure of Some Nonferrous Metals, *Wear*, 1996, **199**, p 1–8
2. M. El-Air, An Investigation into Roller Burnishing, *Int. J. Mach. Tools Manuf.*, 2000, **40**, p 1603–1617
3. N.R.K. Ellenberger, I. Nester, U. Liu, G.Y. Schulte, and R.O. Ritchie, On the İnfluence of Mechanical Surface Treatments—Deep Rolling and Laser Shock Peening—on the Fatigue Behaviour of Ti-6Al-4V at Ambient and Elevated Temperatures, Elsevier, *Mater. Sci. Eng. A*, 2003, **355**, p 216–230
4. M.H. Axir and A.A. Ibrahim, Some Surface Characteristics Due to Centre Rest Ball Burnishing, *J. Mater. Process. Technol.*, 2005, **167**, p 47–53
5. H. Czichos, *Tribology, a System Approach to the Science and Technology of Friction Lubrication and Wear*, Elsevier, 1978, p 130–132
6. B.J. Hamrock and D. Dowson, Isothermal Elastohydrodynamic Lubrication of Point Contacts, Part III: Fully Flooded Results, *J. Lubrication Technol.*, 1977, **13**, p 264–276
7. A.M. Hassan and O.M. AI-Wahhab, Surface Characteristics of Some Roller Burnished Non-ferrous Components, *Mater. Manuf. Process.*, 1998, **13**(4), p 505–515
8. S. Thamizhmnaii, B.B. Omar, S. Saparudin, and S. Hasan, Surface Roughness İnvestigation and Hardness by Burnishing on Titanium Alloy, *J. Achiev. Mater. Manuf. Eng.*, 2008, **28**, p 139–142
9. C.Y. Binu and B. Ramamoorthy, An Investigation into the High Performance of TiN-Coated Rollers in Burnishing Process, *J. Mater. Process. Technol.*, 2008, **207**, p 350–355
10. T.A. El-Taweel and M.H. El-Axir, Analysis and Optimization of the Ball Burnishing Process Through the Taguchi Technique, *Int. J. Adv. Manuf. Technol.*, 2009, **41**, p 301–310
11. K. Pałka, A. Weroński, and K. Zaleski, Mechanical Properties and Corrosion Resistance of Burnished X5CrNi 18-9 Stainless Steel, *J. Achiev. Mater. Manuf. Eng.*, 2006, **16**, p 57–62
12. M.A. Korzynski and J. Pacana, Fatigue Strength of Chromium Coated Elements and Possibility of İts İmprovement with Slide Diamond Burnishing, *Surf. Coat. Technol.*, 2009, **203**, p 1670–1676
13. F.J. Shiou and C. Hsu, Surface Finishing of Hardened and Tempered Stainless Tool Steel Using Sequential Ball Grinding, Ball Burnishing and Ball Polishing Processes on a Machining Centre, *J. Mater. Process. Technol.*, 2008, **205**, p 249–258
14. N.H. Loh and S.C. Tam, Effects of Ball Burning Parameters on Surface Finish: A Literature Survey and Discussion, *Prec. Eng.*, 1988, **10**(4), p 215–220
15. O.M. Abd AL-Wahhab, "The Effects of Roller-Burnishing on Some Properties of Non-Ferrous Metals," M.Sc. Thesis, Jordan University of Science and Technology, 1996
16. U. Pettersson and S. Jacobson, Influence of Surface Texture on Boundary Lubricated Sliding Contact, *Tribol. Int.*, 2003, **36**(8), p 57–64
17. R.L. Murthy and B. Kotiveerachari, Burnishing of Metallic Surfaces a Review, *Prec. Eng.*, 1981, **3**, p 172–179
18. R. Rajasekariah and S. Vaidyanathan, Increasing the Wear-Resistance of Steel Components by Ball Burnishing, *Wear*, 1975, **34**, p 183–188
19. U.S. Dixit and P.M. Dixit, A Study of Residual Stresses in Rolling, *Int. J. Mach. Tools Manuf.*, 1997, **37**(6), p 837–853
20. S.W. Bouzid, N.B. Salah, and J.L. Lebrun, Influence of Machining by Finishing Milling on Surface Characteristics, *J. Mach. Tools Manuf.*, 2001, **41**, p 443–450
21. Y.K. Chou, Hard Turning of M50 Steel with Different Microstructures in Continuous and Intermittent Cutting, *Wear*, 2003, **225**, p 1388–1394
22. Yu.G. Shneider, Characteristics of Burnished Components, *Mach. Tooling*, 1967, **38**(1), p 19–22
23. K.H. Zum-Gahr, *Microstructure and Wear of Materials*, Elsevier, 1987, p 80–82
24. F. Klocke, E. Brinksmeier, and K. Weinert, Capability Profile of Hard Cutting and Grinding Processes, *Ann. CIRP*, 2005, **54**, p 557–580
25. P. Zhang and J. Lindemann, Effect of Roller Burnishing on the High Cycle Fatigue Performance of the High-Strength Wrought Magnesium Alloy AZ80, *Scr. Mater.*, 2005, **52**, p 1011–1015
26. S. Thamizhmanii and B. Saparudin, A Study of Multi-Roller Burnishing on Non-Ferrous Metals, *J. Achiev. Mater. Manuf. Eng.*, 2007, **22**, p 95–98