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Research Article

Influence of Ultrasonic Burnishing Technique on Surface Quality and Change in the Dimensions of Metal Shafts

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This paper presents ultrasonic burnishing as a mechanical surface treatment for improving the quality of rotating shafts. Ultrasonic burnishing is a modern method for finishing workpieces to produce a good surface quality. This process improves the surface quality and increases the surface hardness of the workpiece, and the surface roughness of the workpiece improves. As a result, wear resistance and fatigue life increase. Furthermore, these improvements are achieved without expensive equipment or long processing times. In this paper the influence of the ultraburnishing technique on the change in diameter and its effects on the out-of-roundness of rotating shafts are investigated. This paper also takes a look at the magnitudes of the improvement of the surface roughness as a result of using ultrasonic burnishing. Three different materials, aluminium, 34-CrNiMo6 tempering steel, and S355J2 structural steel, are examined. The results showed that ultrasonic burnishing is a treatment that improves the quality of components. Ultrasonic burnishing also has a reducing effect on the final diameter and out-of-roundness and increases the hardness of the workpiece. It can also be stated that the material of the workpiece does not have a significant effect on the magnitude of the reduced surface roughness values.

1. Introduction

The ultrasonic method investigated in this paper is mainly used for finishing metal surfaces. The method is based on forging at an ultrasonic frequency. The ultrasonic transducers convert high-frequency electrical power into ultrasonic vibration which leads to the finishing head of the ultrasonic tool to forge the surface of the material with the desired impact rate of up to over 20,000 impacts per second. The finishing head is hard metal and is placed at a right angle to the work piece. The finishing head is attached to a spring system which provides a constant contact force. The spring can be compressed to the desired extent, leading to higher contact forces as the deflection increases [1–4].

Other mechanical surface treatments such as the burnishing ball technique have been widely used to improve the physical-mechanical properties of metallic components [1]. As a consequence of plastic deformations, compressive residual stress states, work hardening, microstructural alterations, and a favourable roughness are produced, improving fatigue strength and wear resistance [1]. This mechanism is performed by a rolling element that moves over the toolpaths on the surface, applying a regular compression force at the same time. According to Rodríguez et al. [1], ball-burnishing improves both the physical and mechanical properties of turned parts. Many researchers in the past have investigated the influence of deep ball-burnishing using different parameters for finishing rotating parts, but there are few studies that investigate its influence on out-of-roundness or the final diameter. The residual stresses in the workpiece before and after burnishing and ultrasonic burnishing were examined [1, 2, 5–7].

The method investigated here does not remove material from the work piece. However, ultrasonic burnishing has a plastic deforming effect on the material. The pressing of the finishing head against the work piece and the dynamic force created by the ultrasonic oscillation system creates plastic deformation which causes the roughness peaks to flow towards the valleys, leading to a new topography on the surface [1, 3, 8]. The process is based on making small plastic deformations on the surfaces of the parts, which cause the displacement of material from the "peaks or ridges" to the "valleys or depressions" of the surface microirregularities.

Ultrasonic burnishing could be used as an alternative finishing method where the finishing tool can be installed directly in the tool holder of a machining centre, providing more accuracy and possibly faster lead times as the number of fastenings and the amount of clamping are reduced. With the quality of surface roughness achieved in relation to the time used, the burnishing method could be used as an effective method in finishing injection moulds and gearwheels [2]. Ultrasonic burnishing can replace other finishing processes, such as grinding or hand polishing.

This method is relatively new and not much research regarding this topic has been performed. Studies by Huuki et al. [2] and Hokkanen [3] investigate this burnishing method but no research has been released regarding the out-of-roundness and diameter changes after ultrasonic burnishing has finished. Out-of-roundness is the radial deviation of the actual profile from the ideal roundness, where the out-of-roundness value is the difference between the smallest and largest radius of the profile [9].

Manufacturers make quality measurements to assure their customers in order to meet generally required standards and to optimise their own production. Surface roundness plays an important role in the required tolerance and fit especially during part assembly [10]. The surface roughness of engineering parts is a significant design specification that is known to have considerable influence on properties such as wear resistance and fatigue strength. Perfectly flat surface can never be generated. Surfaces have always irregularities in the form of peaks and valleys [10].

Roundness is often one of the quality parameters that is measured. The manufacturer has a few good reasons to find out what the circular track is made of [1]. Primarily, the manufacturer must be able to prepare the roundness of products for which there is a need in the market. Second, they must be able to do that, in such a way that the costs do not spiral out of control.

In the process of mechanical design, the dimensioning of components and assemblies plays a major role in retaining control over the design. One of many pertinent factors in dimensioning is the tolerance factor. Tolerance, in this context, is the amount of variation in a dimension which can be permitted, or tolerated, without impairing the functional fitness of the component [11]. It is normal to display measurements with a plus or minus tolerance, which allows for some margin of error.

Out-of-roundness measurements need to be particularly pronounced in the bearings production of bearings. This is also important in the case of axles, axle shafts, and rolls. Circular forms are common in industrial components and arise in various applications such as bearings and rotating shafts [11]. If, for example, the components in the bearings are not accurately round, premature failures and system breakdowns may occur. Roundness measurement is needed across all industries which use circular parts [11]. This is why it is vital to measure and know the effects of finishing methods on out-of-roundness and final diameter.

Table 1: Diameters and surface roughness values before burnishing.

Material	Diameter [mm]	Surface [μm]	Hardness [HV]
Aluminium	87.51	1.5	115
	87.53	3.26	113
	87.56	5.3	111
34-CrNiMo6	87.99	1.7	347
	87.99	2.6	348
	88.04	5.6	336
S355J2	71.155	1.7	213
	71.165	3.5	211
	71.185	6.2	209

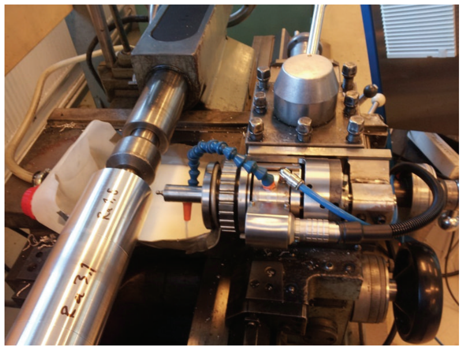
This paper particularly investigated the effects of ultrasonic burnishing on the out-of-roundness and diameter of the workpiece and also how the initial surface roughness affects the finished surface. The aim of this study is to offer a detailed analysis of this issue at the empirical level. Three different workpiece materials, aluminium, 34-CrNiMo6 tempering steel, and S355J2 structural steel, are examined in this case. Consequently, the motivation for the current research work was to investigate important output parameters of ultrasonic burnishing such as out-of-roundness and final diameter. However, to the best of our knowledge, no empirical studies have examined the effect of ultrasonic burnishing on the final diameter of a workpiece.

Ultrasonic burnishing improves both the physical and mechanical properties of turned parts. In particular, this technique improves the surface quality and increases the hardness of the workpiece surface and the quality of the premachined surface does not dramatically affect the outcome of either the surface roughness or the out-of-roundness.

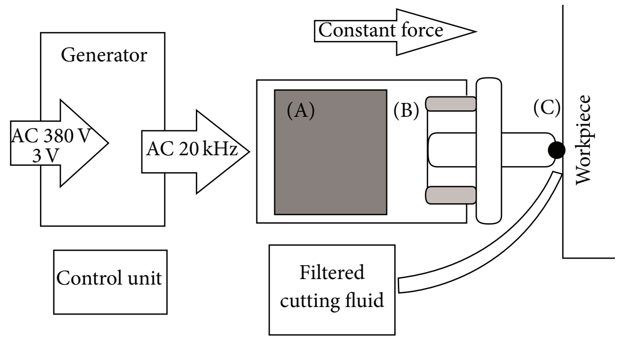
2. Materials and Methods

2.1. Preparations and Materials Used. The three different materials used in the investigation were aluminium (AW 6082 T6), a chrome-based tempering steel 34-CrNiMo6, and a structural steel S355J2. 600 mm long workpieces made of each of these were premachined into three 200 mm long sections, shaped like billets, with varying surface roughness values. The values of the initial situation can be seen in Table 1. The aluminium was chosen to demonstrate the effects on a softer material, whereas the 34-CrNiMo6 and S355J2 represented commonly used alloy steels. Table 1 also presents the hardness of the workpieces. The hardness of both the preturned and burnished surfaces was measured using a Gnehm Brickers 220 portable hardness tester.

2.2. Ultrasonic Burnishing System. The schematic of the ultrasonic burnishing system can be seen in Figure 1. The ultrasonic burnishing equipment is installed into a manual lathe and connected to the generator and control unit. The



(a)



(b)

FIGURE 1: The ultrasonic burnishing equipment installed on a manual lathe (a). Ultrasonic burnishing system (b) [1].

finishing head is compressed against the work piece where the spring ensures constant contact. The fluid is added between the finishing head and the work piece. The frequency can be controlled via the control unit. The equipment is powered by a generator.

The lathe used in this investigation is a manual lathe with a spindle power of 11 kW. The burnishing is performed with the HIQUSA ultrasonic burnishing equipment, with a wolfram-carbide ball 3 mm diameter (Figure 1). The cooling fluid used for the tempering and structural steel is a mineral oil-water mixture of a 5% concentration. The fluid cools the workpiece and tool. This fluid was proven to be ineffective with the aluminium workpiece as the surface roughness was rather worsened. Therefore the Rocol RTD compound was used as lubrication with the aluminium to achieve a smoother surface roughness. The burnishing parameters used for the 34-CrNiMo6 and S355J2 steels were 0.1 mm/rev for the feed and 100 r/min for the spindle power, with an impact frequency of 19,000 Hz. The burnishing parameters for the softer aluminium were 0.1 mm/rev for the feed, 80 r/min for the spindle power, and 18,000 Hz as the impact frequency. The burnishing for all three types of material was performed with the same finishing head, a wolfram-carbide ball with a diameter of 3 mm. The spring compression for the tempering and structural steel was 1 mm and it was 0.35 mm for the aluminium work piece.

2.3. Measurements. The measurements were performed in three phases: the out-of-roundness, the diameter, and the surface roughness measurements. The out-of-roundness measurements were performed with a Talyrond 31C measurement device (Figure 2) with a Talymin linear variable differential transformer. The measuring head is a sapphire ball with a diameter of 2 mm. The resolution of the device is 0.01 μm and the radial resolution of the spindle is 0.025 μm. The diameter measurements were performed manually with a micrometer. Multiple measurements were taken and an average was calculated. The surface roughness was measured with a Perthen perthometer M4P measuring device. The touch probe of the measuring devices measures the topology of a line on a surface.

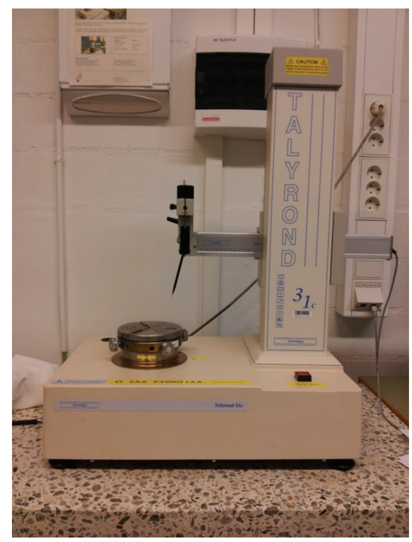


FIGURE 2: The out-of-roundness measurement device that was used.

3. Results and Discussion

This section presents the results on how ultrasonic burnishing affected hardness, surface roughness, dimensions, and out-of-roundness. Measurements were made on all three billets, all of which included three different premachined surface roughness values. The results of interest are how the measurements on the burnished surfaces correlate with the initial surface roughness.

Numerous studies have concluded that the surface roughness and the microstructure of the material are improved by the ultrasonic burnishing process [1, 12, 13]. The plastic deformation that occurs during the burnishing process flattens out the peaks and valleys left behind from the premachining face, reducing the surface roughness value [5]. In addition to the smoothing qualities of ultrasonic burnishing, the deformation of the material compresses the surface layer of the material, leaving it harder and more durable [1, 12]. This study has taken ultrasonic burnishing research further by

Table 2: Surface roughness results.

Material	Hardness [HV]
Aluminium	124 125 126
34-CrNiMo6	356 352 347
S355J2	225 220 221

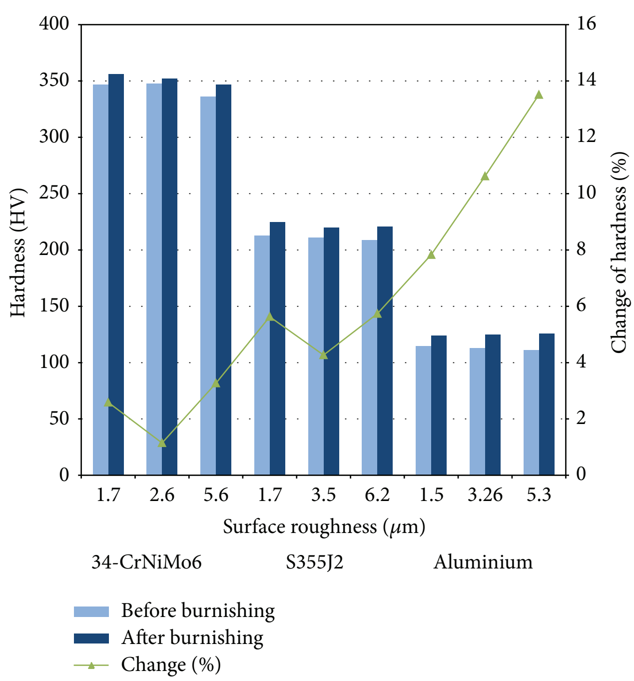


Figure 3: The hardness measurements of the workpieces before and after ultrasonic burnishing.

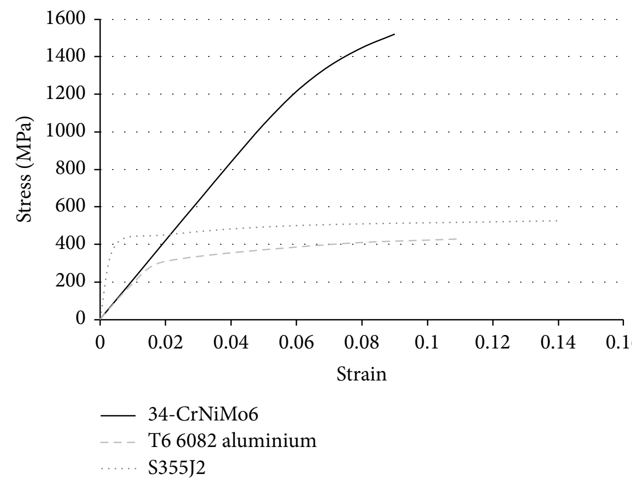


Figure 4: Stress-strain curves.

investigating the technology's impact on dimensions and out-of-roundness and how different materials and starting surface roughness affected the outcome.

3.1. Surface Hardness. Table 2 presents the hardness measurements of the workpieces after ultrasonic burnishing. The results show that the ultrasonic burnishing increases the hardness of the workpiece surface (by up to 13.5% Brinell of the aluminium), Figure 3. It can be seen that the increase in the surface roughness of the workpieces is obtained as a result of the ultraburnishing process. This action will lead to an improvement in the surface finish. The ultrasonic burnishing action increases the surface hardness as a result of this plastic flow of the metal.

During our ultraburnishing experiments, the hardness of the aluminium varied from 124 Hv to 126 Hv, the hardness of the 34-CrNiMo6 varied from 347 to 356 HV, and the hardness of the S355J2 varied from 221 to 225 HV. Due to ultraburnishing, the surface of the material became harder as a result of work hardening, due to mechanical load on the work piece. The increase in the hardness is attributed to work hardening associated with plastic deformation and to the compressive residual stresses induced in the metallic burnished surfaces [5]. It can be concluded that the ultrasonic burnishing improves both the physical and mechanical properties of turned parts. It is apparent that, when a metal/alloy is continually moving over a surface, the plastic deformation takes place, which in turn produces work hardening effect and creates harder surface [7].

The hardness measurements results shown in Figure 3 demonstrate that the average value for different premachined surfaces is quite close with 344 HV of the 34-CrNiMo6, 211 HV of the S355J2, and 113 HV of the aluminium. It can be observed from Figure 3 that the surface roughness of the premachined surface did not dramatically affect the outcome of the surface hardness. The ultrasonic burnishing increases the hardness despite the varying surface roughness values.

Burnishing force has a major influence on the residual stresses [2]. The amount of plastic deformation in the workpiece increases with the burnishing pressure and hence the magnitude of compressive residual stresses increase with increased burnishing force. The compressive residual stresses decrease the formation and growth of cracks subjected to cyclic loading. This enhances fatigue resistance. On the contrary the tensile residual stresses increases cracks growth. Hence, the residual stress on the burnished surface plays an important role, in determining the performance and fatigue strength of components [7]. Huuki et al. [2] investigated the residual stresses by ultrasonic burnishing. For example, residual stresses in workpiece 34-CrNiMo6 material 330 HV increased 500 MPa. Residual stresses in workpiece increased significantly [2]. It is apparent that the residual stresses are at least equal to or exceed the yield stresses 355 MPa S355J2 and 260 MPa aluminium after burnishing. The amount of 0.02 plastic deformation result to 500 MPa increase in residual stress of 34CrNiMo6 material after ultrasonic burnishing [2]. As shown in Figure 4 it can accordingly be estimated that similar compressive strain increases residual stresses in the order

Table 3: Surface roughness results.

Material	Premachined surface [μm]	Finished surface [μm]	Difference [μm]	Relative [%]
S355J2	1.7	0.3	1.4	−82.4
	3.5	0.35	3.15	−90.0
	6.2	0.45	5.75	−92.7
34-CrNiMo6	1.7	0.3	1.4	−82.4
	2.6	0.4	2.2	−84.6
	5.6	0.45	5.15	−92.0
Aluminium	1.5	0.2	1.3	−86.7
	3.26	0.3	2.96	−90.8
	5.3	0.45	4.85	−91.5
Average		0.36		−88.1

Table 4: Out-of-roundness results.

Material	Premachined surface [μm]	Finished surface [μm]	Difference [μm]	Relative [%]
Aluminium	7.40	7.37	0.03	−0.45
	20.08	7.32	12.76	−63.55
	22.93	7.83	15.1	−65.83
S355J2	11.03	5.37	5.66	−51.32
	19.95	7.65	12.30	−61.65
	23.23	8.43	14.80	−63.96
34-CrNiMo6	12.33	7.98	4.35	−35.23
	9.90	7.42	2.48	−25.08
	20.18	5.22	14.96	−74.14
Average		7.18		

of 50 MPa in 6082-T6 aluminum and S355J2 after burnishing. Ultrasonic burnishing produced highest compressive stresses in the surface of the workpiece. Compressive residual stresses occur on the workpiece surface after burnishing treatment.

Burnishing force has a major influence on the residual stresses. The amount of plastic deformation in the workpiece increases with the burnishing pressure and hence the magnitude of compressive residual stresses increases with increased burnishing force [2, 7]. The residual stress on the burnished surface plays an important role, in determining the performance and fatigue strength of components [7].

3.2. Surface Roughness. Surface roughness is measured for the premachined workpieces, as well as for the postburnished surfaces. Multiple measurements are made and average values are calculated for surfaces representing the same parameters. Average values representing the different surfaces are presented in Table 3. The surface roughness values decreased by an average of 88%. The rougher the premachined surface, the greater the difference between the surface roughness values. The surface roughness decreased by 1.3–5.75 μm, depending on the starting quality of the surface. The quality of a premachined surface did not dramatically affect the surface roughness outcome. The finished surfaces measured an average value of $0.36 \pm 0.16\,\mu$m.

Generally, it can be stated that the burnishing process improves the surface finish by reducing the peak-to-valley height of the surface asperities. As a result of the burnishing ball that is applied, the compressive action of the burnishing ball will cause the metal to flow plastically from the peaks to fill the valleys of the surface [5]. This action will lead to an improvement in the surface finish.

3.3. Out-of-Roundness. The out-of-roundness of the cylindrical work piece is measured on both premachined and burnished surfaces. The out-of-roundness is defined with a peak-to-valley (PV) value that describes the difference between the largest and the smallest radius within the geometrical form. Averages of measured PV values are presented in Table 4. The results are similar to those of the surface roughness; particularly, the out-of-roundness decreased dramatically and there was little deviation between the outcome values. The finished surfaces measured an average value of $7.18 \pm 1.96\,\mu$m.

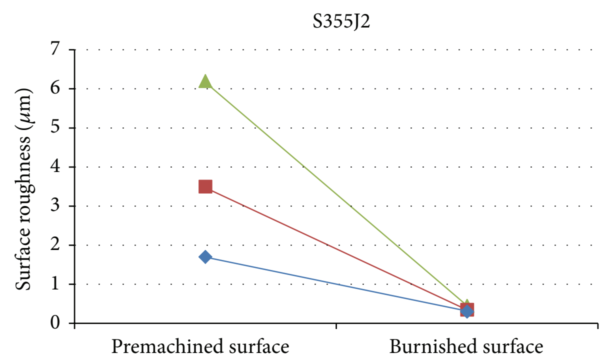


Figure 5: This shows how the burnishing process affected the surface roughness values of the S355J2 billets.

In addition to the PV values, graphical charts are created from the out-of-roundness measurements in order to highlight changes in geometrical features. Selected out-of-roundness charts are presented in the Appendix. The charts show that the geometrical attributes of a workpiece remain throughout the burnishing process.

3.4. Diameter. The average diameters of the premachined and finished surfaces of all three billets are shown in Table 5. The results show that the diameters of the billets were affected by the burnishing process. Moreover, the material used and the starting surface roughness also correlate with the change in dimensions. The diameters decreased with values of 0.005–0.03 mm, depending on the billet. The relative percentage shown in Table 5 describes the change in diameter in relation to the original premachined diameter.

The results show that the quality of the premachined surface did not dramatically affect the outcome of either the surface roughness or the out-of-roundness. An illustrative example in Figure 5 shows how the three different initial surface qualities end up with measured values very close to

Table 5: Diameter results.

Material	Premachined surface Ra [μm]	Premachined surface [mm]	Finished surface [mm]	Difference [mm]	Relative [%]
Aluminium	1.7	87.51	87.5	−0.01	−0.0114
	3.5	87.53	87.51	−0.02	−0.0228
	6.2	87.56	87.53	−0.03	−0.0343
S355J2	1.7	71.155	71.145	−0.01	−0.0140
	2.6	71.165	71.155	−0.01	−0.0140
	5.6	71.185	71.155	−0.03	−0.0423
34-CrNiMo6	1.5	87.99	87.985	−0.005	−0.0057
	3.26	87.99	87.985	−0.005	−0.0057
	5.3	88.04	88.02	−0.02	−0.0227

each other on the S355J2 workpiece. The results are different in relation to the initial surface roughness in the sense that with an increase in the coarseness of the quality of the premachined surface the differences are relatively larger. For example, PV values improved by an average of 68% when the initial surface roughness was in the range of Ra 5.6–6.2. The out-of-roundness improved by an average of 29% when the premachined surface measured Ra 1.5–1.7. The out-of-roundness pictures (shown in the Appendix) show how the PV value decreases but the geometrical attributes of the billets remain. The results show that the ultrasonic burnishing process does not significantly affect the geometrical form of the product that is burnished.

A previous study by Huuki et al. [2] on ultrasonic burnishing documented slight decreases in the diameters of turned products as a side-effect of the burnishing process. Our results agree that the plastic deformation that ultrasonic burnishing induced in the surface of the workpiece did indeed affect its dimensions. Diameters postburnishing showed measured values that were 0.005–0.03 mm less than the case with premachined billets. Ultrasonic burnishing is a preferred method due to the fact that the deforming forces are much smaller than with alternative forging methods [13]. Despite the lower forces used in ultrasonic burnishing, the dimensions were affected.

Table 5 shows that the softer the material and the rougher the initial surface, the more the diameter decreased. This is not a surprising find per se, as rougher surfaces have larger peaks and valleys to be leveled out compared to smoother surfaces [1]. The material hardness also correlates with the magnitude of the change in diameter because the softer the metals are, the more weakly they resist plastic deformation and the more easily their microstructures are compressed.

4. Conclusions

The influence of ultrasonic burnishing for finishing rotating different material parts was investigated in the present work. The results presented here give proof that in addition to surface roughness, the out-of-roundness, hardness and the diameter of turned products are affected by the ultrasonic burnishing process. Furthermore, the extent to which the out-of-roundness and the diameter are affected correlates with the initial surface roughness. The burnishing tests indicate that ultrasonic burnishing is a highly repeatable process with a high tolerance for variation in machining parameters.

On the basis of the experimental results achieved, the following are the major results:

(1) surface roughness decreased to an average of 0.36 μm. The material and initial surface roughness did not have a remarkable effect on the outcome;

(2) the out-of-roundness decreased to an average of 7.18 μm. The material and initial surface roughness did not have a remarkable effect on the outcome;

(3) the diameter decreased within a range of 0.005–0.03 mm. The softer the material and the coarser the initial surface roughness, the more the diameter was affected;

(4) ultrasonic burnishing increases the hardness of the surface of the workpiece when compared to premachined surfaces;

(5) compressive residual stresses occur on the workpiece surface after ultrasonic burnishing treatment.

5. Outlook

The study was restricted to testing only three different materials; therefore further research is urged in order to find out how other metals react to the burnishing process. This study has shown that changes in physical attributes do occur as a side effect of the burnishing process. Further research on the compatibility of materials would help shed further light on ultrasonic burnishing as a finishing technology and its effects on the workpiece. Furthermore, this study concluded that the different machining parameters and lubricants used had a crucial impact on the outcome. In fact, a poor choice of parameters resulted in a completely ruined surface. Further research on the machining parameters for successful ultrasonic burnishing on a material basis is encouraged and crucial for the potential commercial use of ultrasonic burnishing in the future.

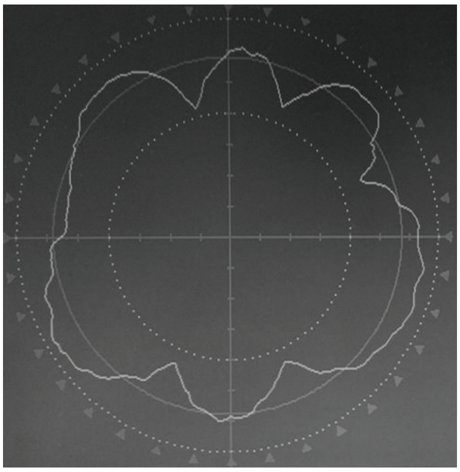


Figure 6: Out-of-roundness measurement results on premachined S355J2 steel. Ra3.5 and PV value 24.2 μm.

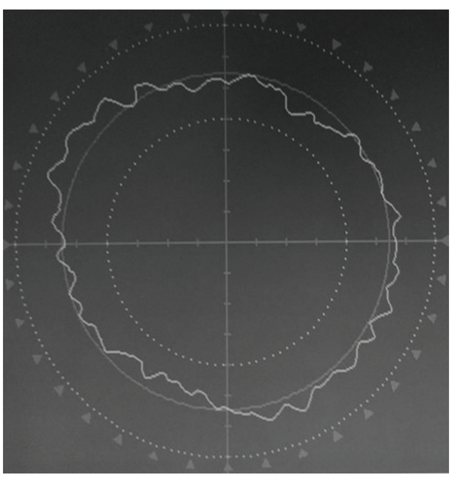


Figure 7: Out-of-roundness measurement results on ultrasonic burnished S355J2 steel. Ra0.35 and PV value 8.4 μm.

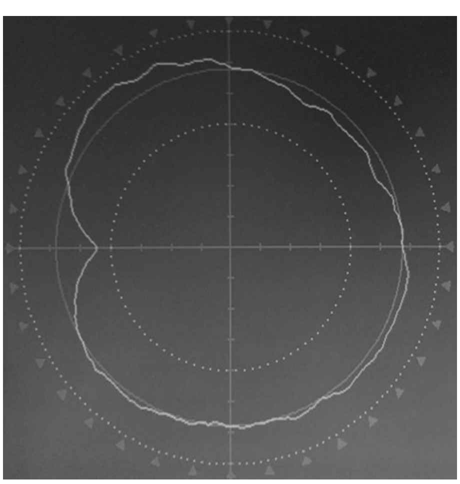


Figure 8: Out-of-roundness measurement results on premachined 34-CrNiMo6 steel. Ra5.6 and PV value 20.0 μm.

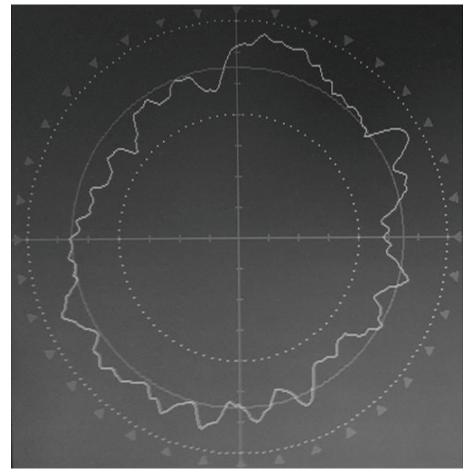


Figure 9: Out-of-roundness measurement results on premachined 34-CrNiMo6 steel. Ra0.45 and PV value 4.5 μm.

Appendix

Out-of-Roundness Pictures

See Figures 6, 7, 8, and 9.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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