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Influence of ultrasonic burnishing on the surface integrity of planar plates

Abstract

Ultrasonic burnishing is one of several surface treatment methods. The method is a relatively new treatment process used for finishing workpieces to produce good surface quality. This paper presents ultrasonic burnishing as a mechanical surface treatment for improving the quality of planar plates. This process improves the surface quality by increasing the surface hardness of the workpiece- and reducing its surface roughness. However, it is essential to know the effect of the method on residual stresses in the material. This study investigated at the residual stresses produced in two different materials: AISI 420 steel and Aluminum (alumec AA7075-T651). The magnitude of stresses was examined using an X-ray diffractometer. This study also evaluated the hardness and surface quality of the finished workpiece.

The results confirmed that the ultrasonic burnishing process is an effective surface treatment, increasing surface hardness and significantly improving the surface quality. Moreover, the process produces residual compressive stresses in the workpiece by deforming it at a sub-surface level.

Keywords

Ultrasonic Burnishing, Finishing, Hardness, Residual stress measurements, Surface Roughness, Surface quality, X-ray diffractometer, AISI 420, Aluminium

1 Introduction

Burnishing has been the focus of many studies (e.g., El-Axir 2008; Mahajan 2013). According to previous work, the process improves the properties of parts, increasing hardness, surface quality, and maximum residual stress in compression, and attaining higher wear resistance El-Axir (2008). As García-Granada (2017) states industry currently requires high-quality finishing of mechanical parts to increase their fatigue resistance and achieve a low friction ratio. Hassan AM and Al Bsharat AS (1996) showed burnishing achieves this by increasing the surface hardness of workpieces, which improves wear resistance. It also increases corrosion resistance and improves fatigue strength by inducing residual compressive stresses on the surface of the workpieces. In this context, the relevance of surface integrity is fundamental, so the development of finishing processes has become one of the main drivers of industrial innovation worldwide (García-Granada 2017). El-Khabeery et al., (2001) reported that residual stresses are probably the most important aspect in assessing integrity because of their direct influence on performance in service; compressive residual stresses generally improve component performance and life because they reduce service (working) tensile stresses and inhibit crack nucleation and propagation. Bougharriou et al. (2010) also found that the burnishing process improves surface quality. They reported that the burnishing produces decreases of about 75% and 59%, respectively, for the average and the total roughness of the surface profile. Moreover their results showed that the burnishing process generates compressive residual stresses in the surface layer. Studies on the burnishing process have been conducted by various authors mostly on conventional and CNC lathes for cylindrical workpieces (Mahajan 2013).

Previous research by Chomienne et al. (2016) and Zhang et al. (2015) demonstrated that the ball burnishing process has a significant influence on the residual stress state. Moreover, Huuki (2013) observed that the ultrasonic burnishing method increased residual stress significantly in materials after burnishing.

Burnishing methods are mainly used on rotating components that have high-quality requirements, such as automotive crankshafts, bearing parts or axles. The diamond burnishing tool is usually used in linear applications, i.e., on cylindrical workpieces (Korzynski et al. 2010; Swirad 2011). However, the burnishing technique can also be used, for example on flat surfaces, conical surfaces, profiled surfaces, and zones of sharp section changes (Rodríguez 2012). Gharbi (2011) noted that despite the large number of previous works on the burnishing of round workpieces, such as crankshafts and bearing races, the treatment of large flat surfaces by either roller or ball burnishing was yet to be fully investigated. Consequently, the Gharbi investigated the ball burnishing process of large flat plates made of AISI1010 steel.

Ultrasonic burnishing is promising surface treatment process, where the tool is set with constant force against the treated surface and forges the surface at an ultrasonic frequency. The results of a previous study on the ultrasonic burnishing of materials showed that for aluminium, 34-CrNiMo6 tempering steel, and S355J2 structural steel, burnishing increased the hardness of the surface by up to 13.5% and decreased surface roughness by 88% when compared to the untreated material (Huuki 2014). Moreover, the method is of interest when considering the finishing of injection molding dies. The burnishing tool could be installed on the machining center and used as finishing tool after machining the die. For molds surface finish quality is an essential requirement due to its direct effects on the appearance of the plastic product (Shiou et al. 2008). AISI 420 steel is one of the materials that can be used for fabricating as a molds.

In addition, Nemat and Lyons reported that surface roughness can be reduced up to 70% for soft steel and aluminum after ball burnishing. Moreover, Tadic (2013) demonstrated that burnishing generally improves surface roughness by between 40 and 90%. Surface microhardness is another parameter that determines surface quality, largely through its effect on wear resistance and fatigue strength (Tadic 2013). These studies provide evidence that burnishing methods increase the surface hardness of workpieces made of different materials when compared to pre-machined surfaces. As previously noted, the surface roughness and surface hardness of the burnished material are two priority criteria in terms of machined part quality (Nguyen, 2018).

Residual stresses are stresses that remain in the material after any external forces are removed. Usually, stresses are caused in particular, by casting and methods that exert a powerful deforming effect on the material, such as machining and forming. When measuring the residual stresses in a material, the objective is to acquire information about the strain state of the crystal lattice. It is assumed that the distortion of the crystal lattice is linear elastic. X-rays are produced and directed at the material, with the depth of penetration being shallow but sufficient to provide information about the interatomic distances. The materials being measured with an X-ray diffractometer must therefore be crystalline. Another requirement is calibration for the same material in a zero stress state, which allows the method to compare stress-free samples to the actual material of interest (Martinez 2003).

The atomic distances are calculated from the diffraction angle, which is the angle between the collimator tube angle of incidence to the surface of the material and the angle of the location of the intensity maximum in the detectors. With Bragg's law, it is possible to deduce the distances of the atoms in the crystal lattice by knowing the diffraction angle (Anderoglu 2005). Comparing atomic distances in the stress-free sample to the actual measurement will reveal a difference in distance if there is residual stress. The difference in these distances is proportional to the magnitude of the residual stresses. The grains in the crystalline lattice are not aligned in the same direction. Thus, multiple measurements with different tilts are required to take into account of the different orientations of the grains in the material.

The effect of roller burnishing on residual stress using X-ray diffractions for cylindrical test pieces was investigated, for example, by Sartkulvanich et al. (2007). Furthermore, Martinez (2003) used the X-ray diffraction technique to measure surface residual stress in Ti-6Al-4V samples subjected to shot peening (SP), laser shock peening (LSP) and low plasticity burnishing (LPB). In turn, Saï (2003) studied residual stresses for duplex stainless steel on cylindrical workpieces after burnishing using the X-ray diffraction (XRD) technique. Moreover, Rodríguez (2012) found that burnishing creates compressive stresses in components. These residual stresses are kept to about 1 mm depth, however, previous research has thus shown that the burnishing process exerts a significant effect on the residual stress state. Moreover, such studies have found that the influence of the burnishing parameters on the residual stress profile is extremely significant. These stresses may be unexpectedly high, especially if the piece is exposed to stress after machining.

Shiou et al. (2008) investigated the optimal spherical polishing parameters on a machining centre for STAVAX plastic mould stainless steel. The authors reported that the surface roughness improvement on the burnished surface of the test object was about 64%. Moreover, El-Tayeb,

(2007) found that burnishing was capable of improving surface roughness by as much as 40% for the test material. El-Tayeb reported, moreover, that roller burnishing also enhances the hardness of burnished aluminium 6061 by 20–30%. It is known that burnishing improves the surface characteristics by plastically deforming the surface layers. Furthermore, Goutam (2014) reported that conventional methods induce tensile residual stresses at the surface, whereas the burnishing process induces residual compressive stresses.

Travieso-Rodriguez et.al (2015) used the X-ray diffraction technique to measure surface residual stress in G10380 steel samples subjected to milled and treated with a ball-burnishing process assisted by vibrations. The authors reported that significant results are found in terms of final surface roughness. Specimens experienced a decrease of R_a of by 80%, which is highly improved in comparison to conventional burnishing treatments.

Based on the above review of the literature, the effect of the burnishing process on surface integrity for planar surface Stavax steel and aluminium appears to be under research-researched. Furthermore, in previous work, the ultrasonic burnishing method has mainly been tested for cylindrical workpieces. In contrast to previous investigations, the authors of the current paper discuss the effects on residual stresses, surface roughness and hardness of ultrasonic burnishing for planar test pieces. The present study used two different test materials: Stavax AISI 420 steel and aluminium (alumec AA7075-T651). These materials were selected due to their wide industrial use in mold applications. This study focuses on revealing the highest residual stresses for planar test materials and the surface integrity improvement caused by ultrasonic burnishing.

2 Materials and Methods

Ultrasonic burnishing was applied to two workpieces of Stavax AISI 420 steel and aluminium (alumec AA7075-T651). The AISI 420 workpiece size was 235 x 105 x 20 mm and the aluminium 150 x 50 x 55 mm. In this study the burnishing was executed with the HIQUSA ultrasonic burnishing equipment. All the pre-machined burnished areas were equally large (30 mm x 20 mm). After ultrasonic burnishing, the surface integrity of the workpieces was investigated by measuring, residual stresses, hardness, and surface roughness from the finished and unfinished surfaces.

Ultrasonic Finishing System

The process parameters were almost the same for both workpieces. The table feed was 5000 mm/mm, and the side shift for aluminium was 0.02 mm (Figure 1). Pre-machining was performed using a Mazak milling centre with a power of 22 Kw. To process the workpieces the ultrasonic equipment was installed on a NC machining centre (see Figure 2). An impact frequency of 20 kHz was used by the ultrasonic burnishing tool. The finishing head was a wolfram-carbide ball 3 mm in diameter. The head was attached to a spring system that produced a constant contact force. The spring compression varied slightly little for the different work materials due to their elastic properties. When the spring is set to specific compression, for example to 1 mm, the spring produces contact force. The force is measured with the force sensor. The contact force equal of 1 mm deflection is about 180 Newton and 0.025 mm deflection equals 90 Newton. The compression setting for 420 HV workpiece is 0.5 mm and 0.025 mm for aluminium in this study. Moreover, previous study showed (Salmi 2017) that the spring compression is a vital process parameter in burnishing also when taking productivity into consideration.

The cooling fluid used was a mineral oil water mixture of 5 % concentration. The main purpose of the fluid was to cool the workpiece and tool and to wash away the removed particles (Huuki 2013). The test piece to be burnished was clamped in a vise. The burnishing tool was mounted on the tool holder (Figure 2). The burnishing process was performed after milling without re-leasing the test piece from the vise in order to retain the same milling alignment and to avoid possible setup errors in fastening.

Process paramteres		
Workpiece material	Al	AISI 420
Test area	50 mm x 55 mm	20 mm x 20 mm
Spring compression	0.5 mm	0.025 mm
Table feed	5000 mm/min	5000 mm/min
Side shift	0.02 mm	0.01 mm

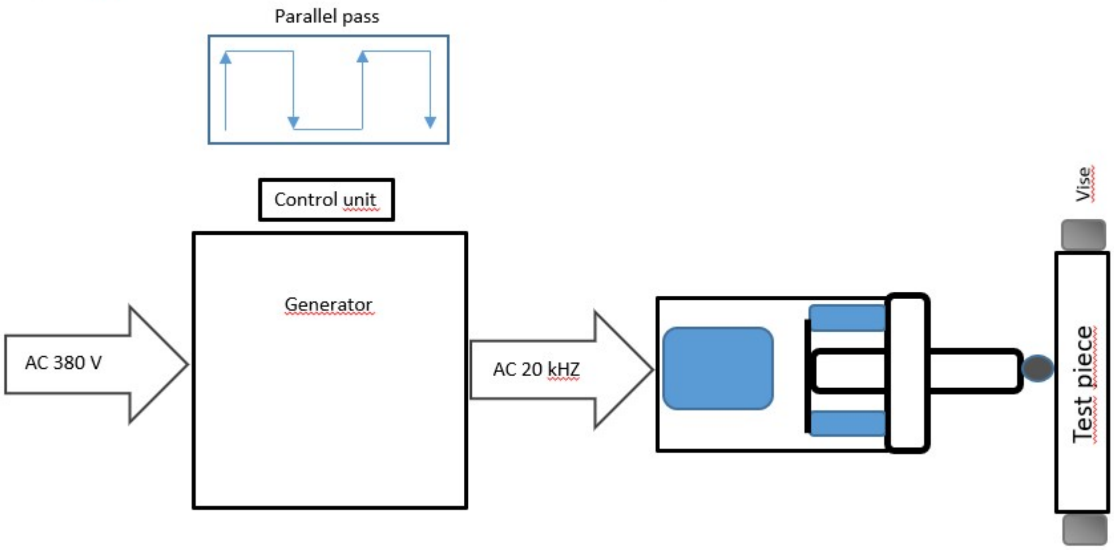


Figure 1. The schematic of the ultrasonic burnishing system – the measurements and data acquisition process. Aluminium and AISI 420 milling processing.

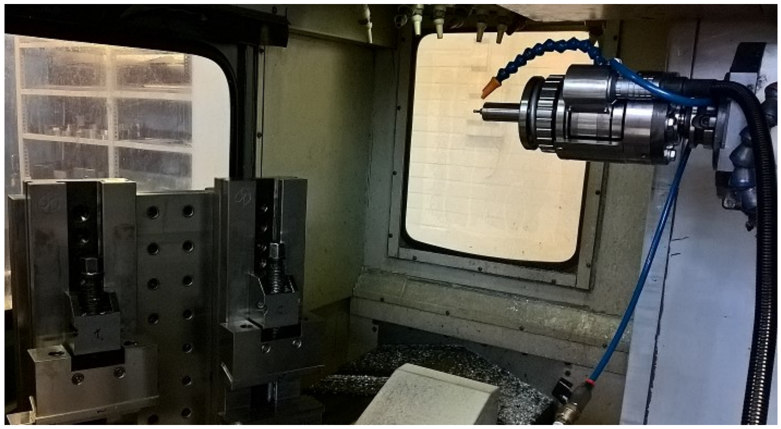
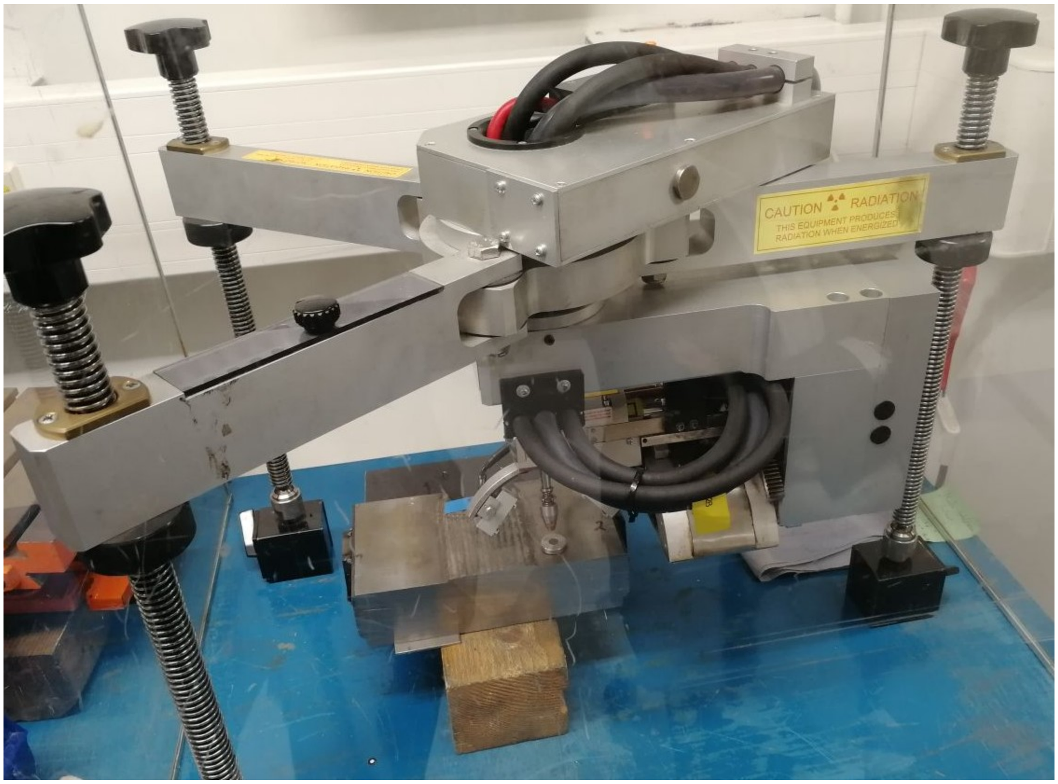


Figure 2. The ultrasonic burnishing equipment installed in NC machining centre.

2.1 Residual Stress Measurement System

2.2

The machine used for the residual stress measurements was a Stresstech Xstress G2R portable X-ray diffractometer; Stresstech also developed the software, X3000 which was used for the calculations. Figure 3 shows how the long collimator tube is pointing towards the measurement area: the darker circular area on the calibration sample.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RADIATION WHEN ENERGIZED
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Figure 3 The G2R X-ray diffractometer making a calibration from a stress-free powder sample. The collimator is pointing towards the calibration sample with a slight psi tilt.

The measurements were performed in a straight line through the centre point of the burnished areas. The measurement line was perpendicular to the short side of the burnished rectangle, and it contained five points for each burnished area with a 5 mm distance between each point. The first point (0 mm) is where the collimator tip circle is tangential to the short side of the burnished area. A total of four burnished areas were measured, two of them with aluminium as the base material and the other two with the steel material. They are referred to as aluminium area no. 7 and 9, and steel no. 7 and 8 in Figure 4.

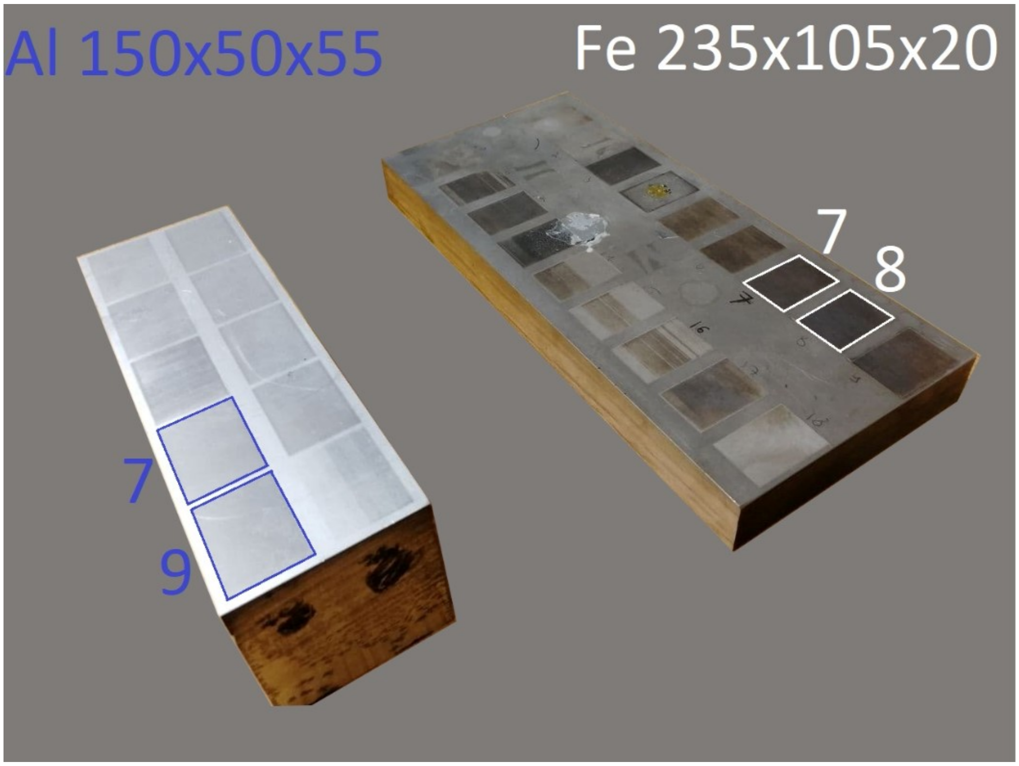
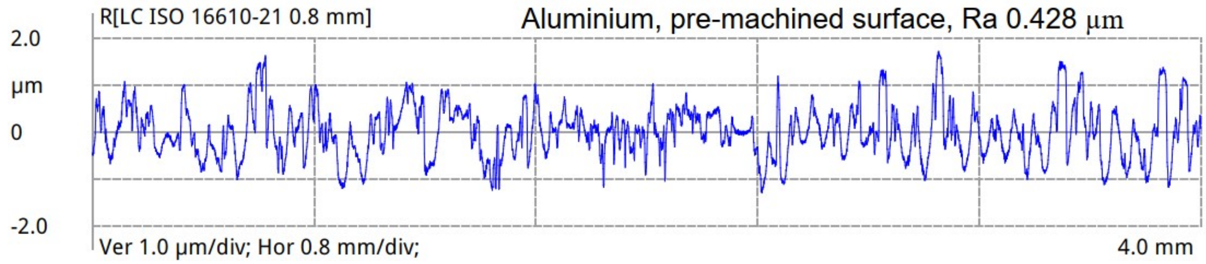
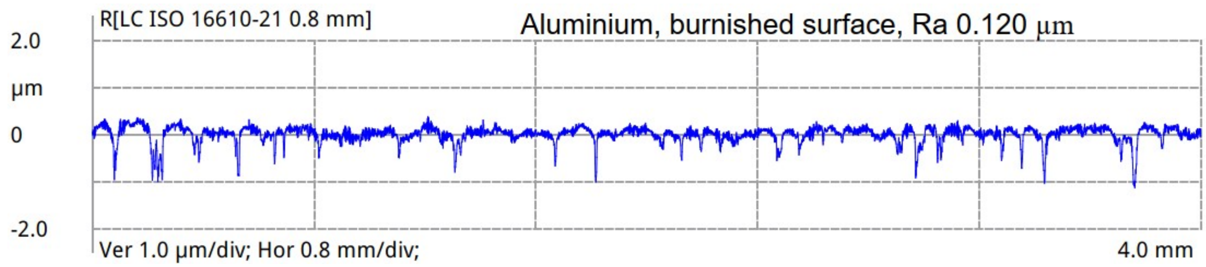

Al 150x50x55
Fe 235x105x20
7
8
7
9

Figure 4: Measured samples, where aluminium is on the left-hand side, marked in blue, while the steel sample is on the right-hand side, marked in white. The burnished areas are highlighted and numbered with corresponding colour. The dimensions of the pieces are given in mm. All the burnished areas are equally large (30 mm x 20 mm).

2.3 Surface Roughness Measuring

Surface roughness was measured to evaluate the quality of the burnished surface of the workpieces. A MarSurf PS 10 measuring device was used to measure the roughness of both the pre-machined as well as burnished surfaces. The surface roughness profiles of the pre-machined and burnished sections are shown in Fig 5. Surface roughness was measured with Taly-surf 6 profilometer. The surface roughness measurements were performed with a cutoff length of 0.8 mm. The device uses a touch probe to measure the topology of a line on the surface in Ra values.


R[LC ISO 16610-21 0.8 mm]
Aluminium, pre-machined surface, Ra 0.428 μm
2.0
μm
0
-2.0
Ver 1.0 μm/div; Hor 0.8 mm/div;
4.0 mm


R[LC ISO 16610-21 0.8 mm]
Aluminium, burnished surface, Ra 0.120 μm
2.0
μm
0
-2.0
Ver 1.0 μm/div; Hor 0.8 mm/div;
4.0 mm

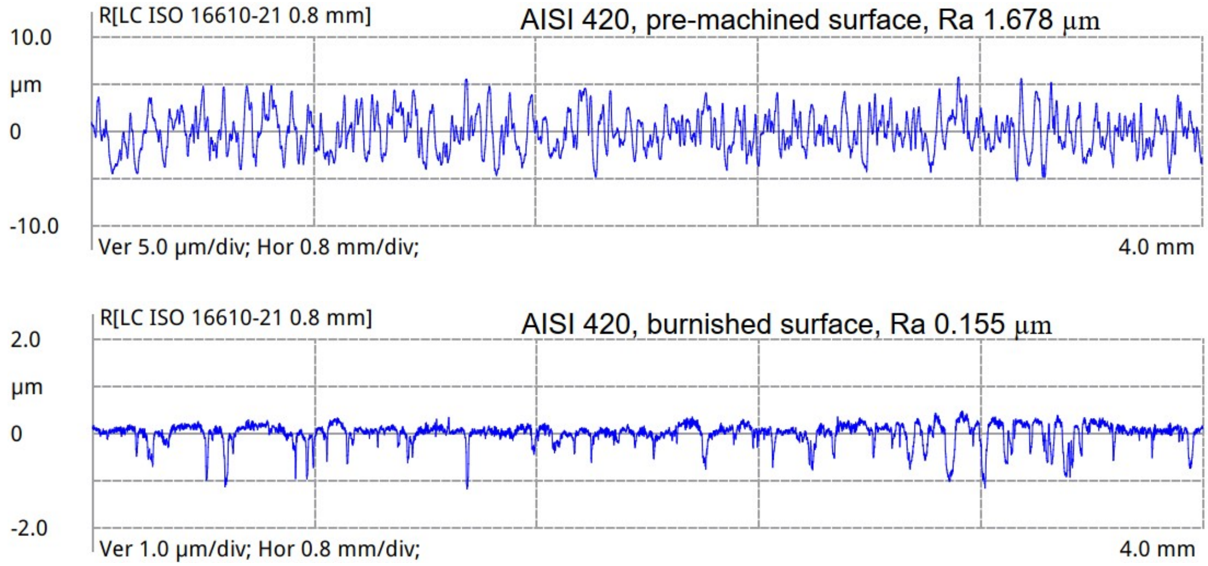


Figure 5. The surface roughness profiles before and after burnishing for Aluminium and AISI 420.

2.4 Hardness Measuring

Hardness was measured at three different points on both the finished and unfinished surfaces by the Vickers method using a Brickers 220 hardness measuring device. The workpieces were planar plates, so the shape should not cause errors in the hardness value. Each measurement was taken three times.

3 Results and Discussion

This chapter presents the results of residual stress measurements, hardness testing and surface roughness measurements.

3.1 Surface Hardness and Roughness

Table 1 presents the hardness measurements of the aluminium and AISI 420 workpieces. Each measurement was taken three times and the average value of three measurements for each specimen is shown in Table 1. A hardness of ~189HV was measured in the pre-machined zone and of ~209HV on the finished surface in the aluminium. The burnishing- induced increase in hardness caused an approximate 10% increase in hardness compared to the untouched surface. **Error! Reference source not found.** presents the hardness measurements of the AISI 420 workpiece. Hardness increased from ~459HV to ~559HV in finishing: The burnishing- induced increase in hardness caused an approximate 21% increase in hardness compared to the untouched surface in AISI 420.

Surface roughness measurements of the Aluminium workpiece are presented in Table 1. The average surface roughness in the pre-machined zone was measured at 0.446 µm and in the finished surface 0.099 µm. Ultrasonic burnishing caused the surface roughness Ra value to decline by 0.347 µm on average. **Error! Reference source not found.** presents the surface roughness of the AISI 420 workpiece. The average roughness in the premachined zone was 1.594 µm and in the finished zone 0.177 µm. The average reduction of the Ra value was 1.417 micron.

Table 1. Surface Roughness and Hardness Measurements of the Aluminium and AISI 420 workpieces

	Surface Roughness Ra (μm)			Hardness HV		
	min	max	Average	min	max	Average
Pre-machined Surface, Aluminium	0.428	0.464	0.446	187	191	189
Burnished	0.078	0.120	0.099	197	220	209
Pre-machined Surface, AISI 420	1.51	1.678	1.594	436	482	459
Burnished	0.124	0.227	0.177	491	617	554

3.2 Residual Stresses

The measurement results for the burnished areas of the aluminium sample showed that all -values for the calculated principle stresses were close to each other and the variation was slight. The principle stresses were perpendicular to the normal of the burnished planes. An additional reference measurement point was taken from a non-burnished area for both samples, the location was always as far away from the burnished areas as possible.

Aluminium sample

In aluminium area no. 7, the highest principle residual stress was 247 MPa of compression while the lowest recorded value was 233.5 MPa of compression. See Figure 6 for a visual representation of the small differences between the measured values. Similarly, the highest stress of aluminium area no. 9 was 272 MPa of compression and lowest 245.5 MPa. This can be seen in Figure 7, which contains slightly more variation in the results. The highest principle stress of the reference point in the aluminium sample was 279.2 MPa of compression.

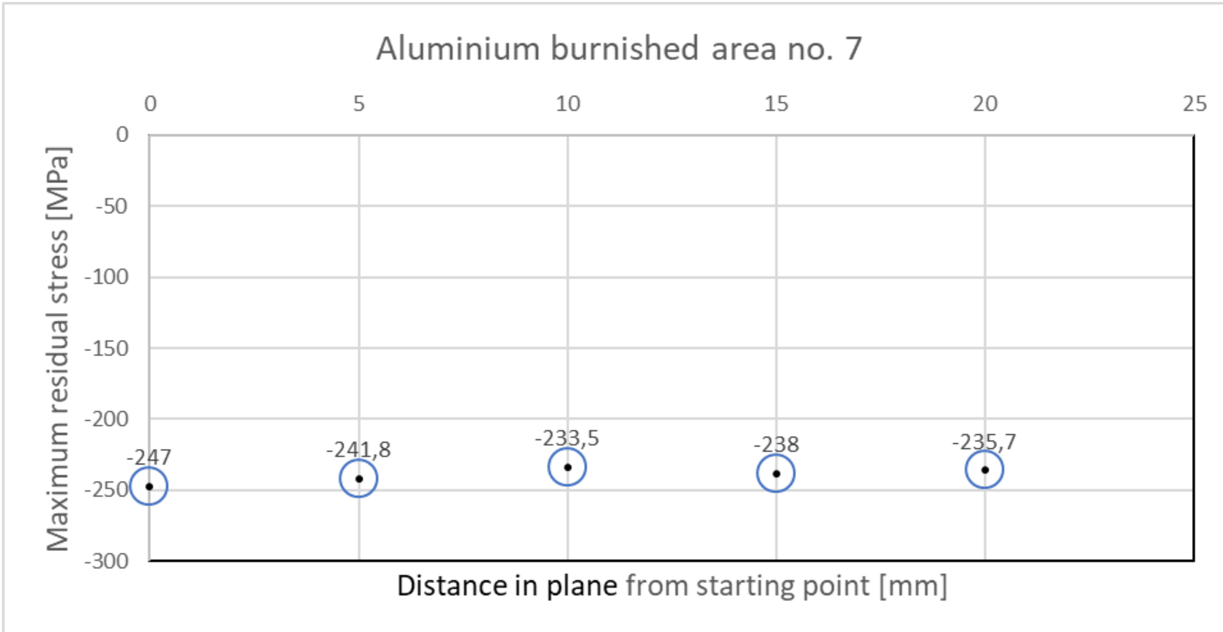


Figure 6. All five measurement points for aluminium area no. 7

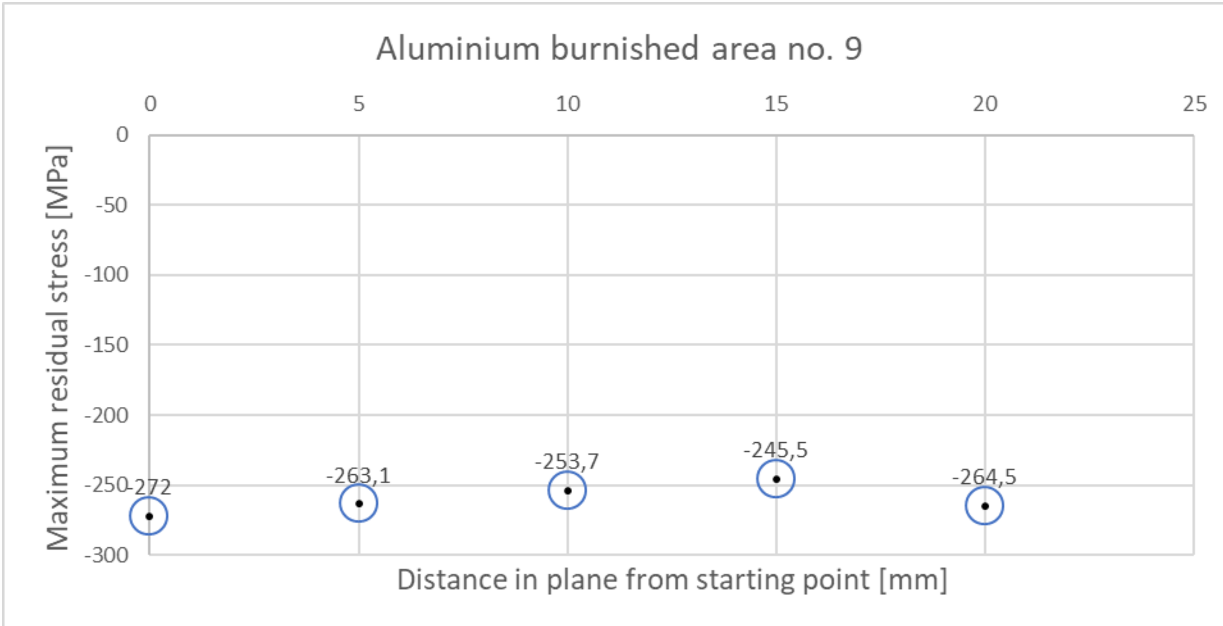


Figure 7: All five measurement points for aluminium area no. 9

2.2 Steel sample AISI 420

In turn, the highest principle stress for ferritic area no. 7 was 1743.1 MPa and the lowest 1670.9; these and other results can be seen in Figure 8. The highest principle stress of ferritic area no. 8 was measured at 1758 MPa of compression and the smallest at 1658 MPa of compression. The results for all five measurement points of ferritic area no. 8 are contained in Figure 9. The highest principle stress in the ferritic sample reference point was tension of 606.6 MPa.

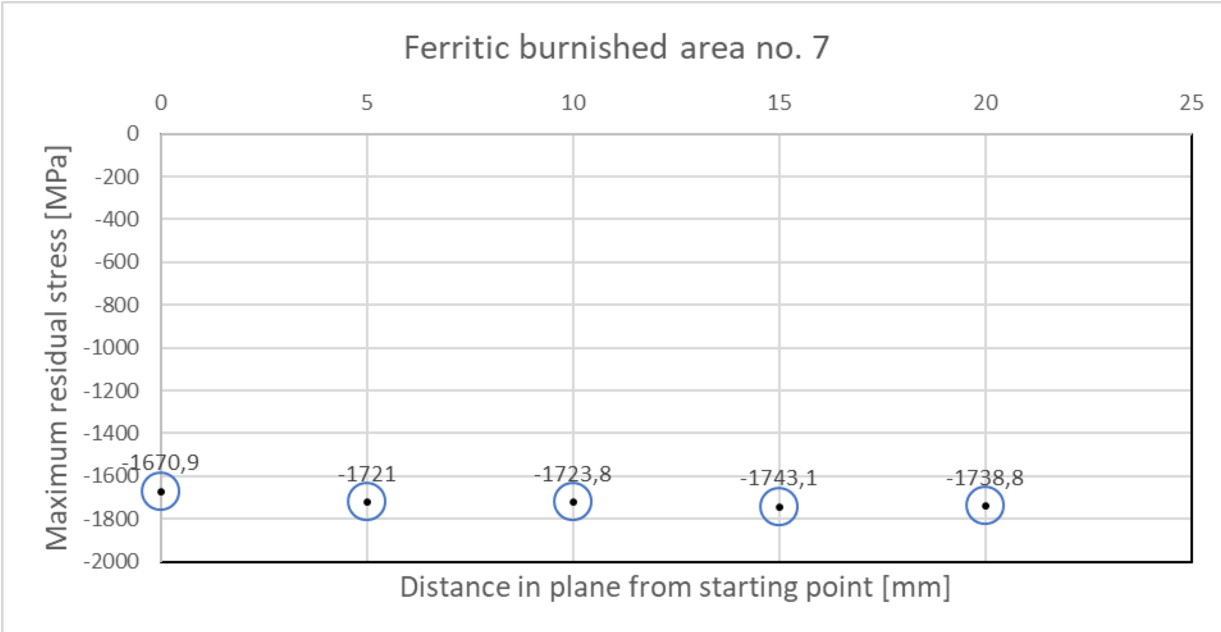


Figure 8: Five measurement points in steel sample area no. 7.

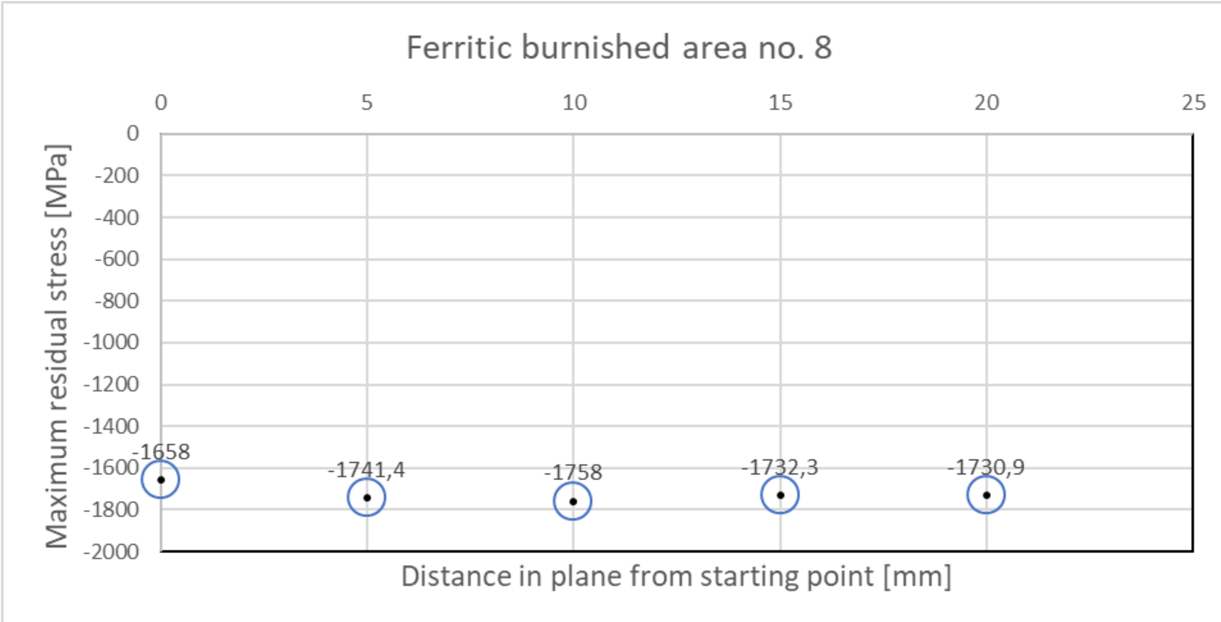


Figure 9: Five measurement points in steel sample area no. 8.

The results of the present study confirm those of earlier research: burnishing processes improve surface quality factors such as surface roughness, hardness and fatigue strength. These results are in line with the previous literature (Huuki 2013) and show that the surface hardness increasing in aluminium 10 % and AISI 420 21 % after burnishing (Table 1). Moreover surface roughness of the aluminium and AISI 420 samples improved significantly. The average surface roughness (Ra) of aluminium was 0.099 µm and 0.177 µm for AISI 420. The mean roughness indicator showed an improvement in the surface quality of around 78 % for aluminium. The surface roughness decreased by 0.3–1.4 μm depending on the starting quality of the surface. Overall, results showed that these test's results is in agreement with improvements attributed to ultrasonic burnishing of metals Huuki (2018). However, the improvement of burnishing process depends mainly on the setting parameters Cagan (2020). Looking at previous studies (Inigo

2020, Huuki 2018), the ultrasonic burnishing process parameters like spring compression adjust according to test materials in this study. As discussed in the literature review section, the burnishing method has been used in a variety of materials to improve mechanical properties as well as to decrease surface roughness and increase surface hardness. However, prior to this study, no research existed on the ultrasonic burnishing of AISI 420 and Alumec for planar plates. Moreover, this paper is the first attempt to use X-ray diffraction method to investigate how ultrasonic burnishing post-processing methods affect surface integrity in terms of residual stress values for the materials mentioned earlier.

In the steel material, both areas no. 7 and 8 (Figures 8 and 9) exhibited stresses nearly one order of magnitude larger than in both aluminium burnished areas. Material differences explain how the residual stress accumulates differently in aluminium and ferritic steel after burnishing. No significant differences were found between the reference point and the five measurement points in the burnished areas for aluminium. However, an apparent difference emerged when the performing the same comparison for ferritic steel. Here, the reference point is tension instead of compression. This can be explained by the fact that the aluminium sample was machined flat before burnishing, while the ferritic sample was burnished directly after the manufacturing of the sample. The conclusion is that the aluminium surface was already under compression and did not undergo a large change in stresses with burnishing, as it was already close to or beyond what burnishing would have achieved in such a material. Contrary to aluminium, the ferritic steel sample was under tension, and burnishing altered the stresses to compression in the target area. It was to be expected that the finished surfaces in aluminium would undergo a lesser change in compressive residual stresses than in steel (García-Granada 2017).

The results obtained by the X-ray diffraction technique are convincing for the following two reasons. Firstly, the stresses were clearly compressive in both samples, which is in line with other residual stress measuring techniques, such as deep hole drilling. Secondly, the results from the measurement points in both samples were close to each other, with the exception of the first measurement point in each burnished area. This can be explained by the first point being too close to the burnished versus non-burnished area interface, thus causing a difference compared to the other points closer to the middle of the burnished area. Nevertheless, the measurements indicate an increase of compressive stresses in the test materials, which is in line with the research done by Revankar et. Al. (2017).

While the measurement depth in X-ray diffraction is always shallow, the depth of X-ray penetration nevertheless depends on the category and angle of incidence. The depth of penetration of Cr k-α X-ray radiation in ferritic steel is extremely shallow, and the depth of the same radiation type in aluminium is only marginally deeper.

4 Conclusions

The present work investigated the influence of the ultrasonic burnishing process on the surface integrity of planar plates made of aluminium (alumec AA7075-T651) and AISI 420. The burnishing process was performed on for flat surfaces because of the lack of previous research on burnished planar shapes. The results show that the ultrasonic burnishing process improves surface quality, both in terms of surface roughness and hardness.

The average roughness of the surface decreased to 22% and 11% from their original values for aluminium and AISI 420 respectively.

This means the surface roughness in aluminium improved by nearly 5 times and nearly 10 times in AISI 420.

Residual stresses were measured by the X-ray diffraction method, and it was found that, with an optimal burnishing process, the value of compressive residual stress increased in the burnished areas. These results, again, demonstrate that the ultrasonic burnishing process improves surface quality by reducing the surface roughness and increasing the hardness of the surface. The residual stress results for aluminium (alumec AA7075-T651) showed:

1) A very slight difference in the residual stresses between the reference point and the measurement areas.

2) An accumulation of compressive residual stress until 240 MPa in area no. 7, and 260 MPa in area no. 9.

The residual stress results for AISI 420 showed:

1) A significant difference in residual stresses between the reference point and the measurement areas.

2) A general increase in the values for compressive residual stress to 1720 MPa in both area no. 7 and area no. 8.

The average surface roughness (Ra) of aluminium was 0.099 µm and 0.117 µm for AISI 420 after ultrasonic burnishing.

The relative increase in the average hardness of aluminium was 10% and 21% for AISI 420

Ultrasonic burnishing improves mechanical properties of planar parts. Particularly, this technique improves the surface quality, increases the hardness of the workpiece surface and introduces compressive residual stresses on the surface of the test pieces. As a result of the research, ultrasonic burnishing was found applicable to finishing of planar surfaces.

Measuring the burnished surface with the X-ray method provides information about how compressive the residual stresses are and could therefore validate if the burnishing process were successful or not. Compared to other measuring methods such as deep hole drilling the X-ray diffraction method is non-destructive, which is a significant advantage compared to the destructive methods. This allows a ready to be used surface to be measured after the burnishing process is completed without damage.

Future works

The residual stress measurements in the present study could be replicated with several other X-ray radiation wavelengths for broader sample variety.

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