Manufacturing of calibration samples for barkhausen noise method: case studies on temperature controlled laser and hydrogen-oxygen flame

Manufacturing of Calibration Samples for Barkhausen Noise Method: Case Studies on Temperature Controlled Laser and Hydrogen-Oxygen Flame

Suvi Santa-aho[1], Murat Deveci[2], Samuli Savolainen[2] and Minnamari Vippola[1]
1 Tampere University of Technology, Laboratory of Materials Science, Finland,
suvi.santa-aho@tut.fi, minnamari.vippola@tut.fi
2 Stresstech Oy, Vaajakoski, murat.deveci@stresstech.com,
samuli.savolainen@stresstech.com

Abstract

Non-destructive magnetic Barkhausen noise (BN) measurements are most widely used for studying the grinding burns from hardened and ground samples. The formation of the grinding burns occurs due to excess of heat generation and produces thus changes in the residual stresses and microstructure. The BN method can be used for quality control purposes because it is sensitive to changes both in stresses and microstructure. The important part of the BN inspection procedure is the verification that the sensor and the equipment are working properly. One option is to use calibration pieces to evaluate the operation of the sensor before the actual measurements. The best way is to use similar components and same measurement procedure as to be studied. The components should have artificially produced burn marks to mimic the damaged areas of grinding burns. To validate the BN measurement results properly, the BN sensor needs to be verified with both thermally damaged and thermally undamaged sample surfaces.

In this work, two different procedures to manufacture artificial burn marks were studied. A temperature controlled, robotic-assisted, laser system was used to perform temperature controlled tempering marks on carburised gear wheel teeth surfaces. Also, hydrogen-oxygen flame with robotic control was used to produce artificial burn marks on the surfaces of carburised gear wheel teeth.

The aim was to analyse the suitability of thermal damages created by these two methods by comparing the BN readings of them to each other. The new, temperature controlled, laser system was found to produce uniform quality thermal damages. While the hydrogen-oxygen process was found to be more unpredictable and it needs to be controlled extremely carefully i.e. with robotic manipulation of the flame. The speed of the hydrogen-oxygen flame affected the RMS values stronger than the other tested parameters.

Keywords: Inspection qualification, Barkhausen, Automated and robotic NDT, Defects, Laser methods, Calibration

1. Introduction

The formation of the grinding burns via the excess heat production between grinding wheel and ground sample can occur due to many reasons during grinding such as problems in cooling liquid usage (1). Grinding burns usually have changes in the residual stresses in the surface layer of the component and will also affect the microstructure of the material. Non-destructive magnetic Barkhausen noise (BN) method is sensitive to both changes in the stress state and microstructure and is thus utilised in the grinding burn detection widely. By producing thermal damages mimicking grinding burns it is possible to verify and calibrate the BN sensor readings.

Earlier, Klocke and Gorgels (2) used laser processing to create thermal damages on case hardened steels with different levels of residual stresses. Lomaev and Kharanzhevskii (3) concentrated on the laser quench layer manufacturing and measurements with BN. During laser processing, the laser beam quickly heats the surface and the surface cools rapidly in air. One benefit of the laser processing method is that the repeatability of the process is good if the laser absorption of the metal is constant. Current authors Santa-aho *et al.* have studied (4-7) the laser processing widely and found laser processing to be suitable method to produce a controlled heating of metal surfaces with utilizing temperature controlled laser processing system.

Since laser processing is already a proven technique to produce calibration blocks for BN measurements, the purpose of this study was to determinate the effectiveness of hydrogen-oxygen flame burning for calibration block manufacturing and to compare the two methods. In the flame burning method, the flame is produced by electrolysis of distilled water, which produces a hydrogen-oxygen mixture that feeds the micro flame that can reach temperatures up to 2850 °C (8). According to the knowledge of present authors, the flame burner has not been used for localized thermal damage production on metal surfaces before. It could be an alternative to costly laser systems to produce small-scale local thermal damage production. Earlier work showed (4-7) that manufacturing of even and repeatable calibration marks is not an easy task in all cases.

In this study, affordable option compared to laser, the hydrogen-oxygen flame burner was tested and evaluated for producing calibration samples with small-sized high-temperature marks, for BN equipment. Totally two cases were tested: one sample set with the temperature controlled laser system and one sample set with a robotic manipulated flame to perform tempering marks on gear wheel teeth surfaces. To make a better evaluation of the processed thermal damages, different techniques such as X-ray diffraction (XRD) for residual stress measurements and surface hardness measurements were used. In addition, the depth of the tempering effect was verified with X-ray diffraction residual stress depth profiles. For comparison, also one gear sample manufactured from the same material with actual grinding burn was studied with residual stress depth profiles.

2. Materials and methods

The studied samples were flame cut parts of a planet gear manufactured from 18CrNiMo7-6. The initial state of the gear wheel was a carburising case hardened after grinding. The gear teeth height was 83 mm. Two pieces were prepared with different processing systems. A robot controlled system, presented in Figure 1, was tested to perform tempering marks on gear wheel teeth surfaces with two different systems: temperature controlled laser system and hydrogen-oxygen flame burner.

2.1 Temperature controlled laser system

Temperature controlled laser processing was carried out with fibre-coupled diode laser Laserline LDM 400-300 with wavelength of 940 nm. The temperature controlled laser processing utilised a real-time infrared ratio quotient pyrometer control to change the diode laser parameters for keeping the surface temperature constant regardless of the surface condition (absorption changes) of the sample. Totally 10 different thermal damages to separate gear teeth within temperatures between 250 °C and 330 °C were processed. The laser head traverse speed 3 mm/s was kept constant. The laser head was kept at 90˚ in relation to the tooth flank surface. The laser mark was produced with separate laser processed lines that were done from the tip area towards the bottom area and vice versa totally 10 times with a step of 0.7 mm to produce a uniform mark with a width of 0.7 mm.

Figure 1. Robotic assembled laser system and hydrogen-oxygen flame burner system with examples of produced tempered marks with 330 ˚C laser and production speeds of 15 mm/s and 30 mm/s with the hydrogen-oxygen burner.

2.2 Hydrogen-oxygen flame burner

To create small temperature marks as artificial grinding burns on the sample surface, the equipment, Lötstar 245, was used for the creation of hydrogen-oxygen flame. The device is a micro brazing and welding unit manufactured by Mikrofügetechnik GmbH. This device is capable to process the surface with the hydrogen-oxygen flame with the temperatures up to 2850 °C (8). At first, the hydrogen-oxygen flame was tested with manual manipulation and it was noticed that it produced meaningful surface temperature changes to gain increase in the RMS value. However, the manual manipulation had challenges with the reproducibility of flame processing. Therefore, the same robot as in laser studies was programmed. Robot control enabled the process to have different and more controlled test parameters which could be varied: the speed of the flame, the width of the mark (controlled as the number of paths) and the distance of the flame from the surface of the sample. During robotic hydrogen burning process, the pressure of the system was set to 140 mbar and during the processing, it was verified to be about 94 % of the set-up value. The used nozzle's diameter was 1.2 mm producing marks with 1 mm width. The automated robotic processing system allowed to vary the process speed from 15 to 45 mm/s. The number of paths in each of the marks were varied either 2 or 4 producing thermal damages with a total width of 2 – 4 mm. Two samples, with production speeds of 15 and 30 mm/s with 2 paths and 3 mm distance between flame and surface were selected for further studies.

2.3 Barkhausen noise measurements

The Barkhausen noise measurements were carried out prior and after all the tests and for studied gear flanks. BN equipment Rollscan 300 together with MicroScan software manufactured by Stresstech Oy was utilised. The measurements were carried out with the commercial gear sensor S1-164-15-11 (#5157) which adapts the gear surface. The used magnetizing frequency was 125 Hz and used magnetizing voltage was 7 Vpp. In the analyses, the results were an average of 10 BN bursts filtered to 70-200 kHz. The average values of three measurements were used for the analyses. The used feature was the root-mean-square (RMS) value of the BN signal.

2.4 Other material characterization work for the samples

To study the treated gears with the two methods further, some of the gear tooth were water cut from the gear sections for X-ray diffraction residual stress measurements and surface hardness studies. Surface residual stresses (RS) were measured with a portable X-ray residual stress diffractometer (XRD) XStress G2 (Stresstech Oy, Finland). The measurements were carried out to 0˚ (gear flank axial direction) and 90˚ (gear flank tangential direction) degrees with 5 tilting between -45^{o} to 45^{0} angles. Exposure time was 7 seconds and measuring mode was modified χ. Used X-ray voltage was 30 kV and current 6.7 mA. For RS depth profiles, a polishing equipment Movi-Pol 5 (Struers) was utilized to remove layers off with perchloric acid, Struers A2. Surface hardness measurements were carried out with Struers Duramin A-300 device with HV1.

3. Results and discussion

The hydrogen-oxygen flame burner surface temperatures could not be measured during the production, but the surface temperatures of the temperature controlled laser marks could be used to evaluate the temperature in the surface during flame burning. The flame mark was narrower than the laser marks due to the two paths that were used. For the flame mark with 30 mm/s, there was a clear higher temperature area in the beginning of the mark in the gear tooth tip region as shown in Figure 1. To be able to clarify the effect of the surface temperature (laser) on the hardness and the process speed (flame burner) some selected samples were chosen to be analyzed. As Figure 2 presents, the unprocessed base material surface hardness was 732 HV1. The laser processing with 270 ˚C temperature decreased the surface hardness to 682 HV1 and rise in temperature to 330 ˚C decreased the surface hardness to 543 HV1, corresponding to surface hardness drop of 23 HV1 per 10ºC increase. During robotic flame burning with different speed, there was some decrease on the surface hardness value when the process speed of 15 mm/s (surface hardness of 584 HV1) was doubled to process speed to 30 mm/s (surface hardness of 610 HV1). With slower process speed, the heat interaction with the material is larger meaning that there is more time for the tempering of the structure and possible the tempering effects are wider. When comparing the two methods, it could be estimated from Figure 2 that similar decrease in the surface hardness occurs with flame burner process speeds of 15 and 30 mm/s that is formed at laser processing temperatures of 310 and 300˚C, respectively. Based on the surface hardness results, the decrease of burner process speed from 30 to 15 mm/s seems to influence only a 10˚C increase in the surface temperature.

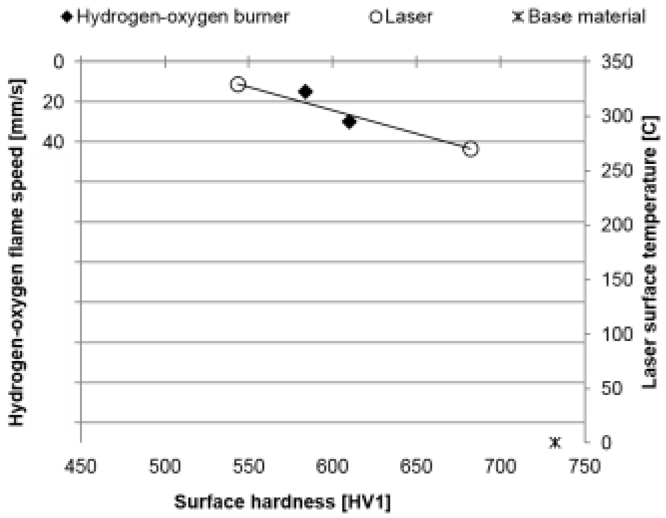

Figure 2. Change in the surface hardness in the hydrogen-oxygen burner with different process speeds and in laser process with different temperature.

Surface hardness values were compared with the BN RMS values. Figure 3 shows that the surface hardness has a linear relation with the RMS values in both studied series. The different series although have somewhat different slopes. It can be seen from Figure 4 that the flame burner samples produce also different slope but still linear relation with the RMS and residual stress. The significantly higher tensile residual stress i.e. with the process speed of 15 mm/s produces clearly less high RMS than the laser processing. This could be due to the difference of mark widths in the different processes or the effect how deep the processes are affecting the structure change. Thus, RS depth profiles were carried out to verify this.

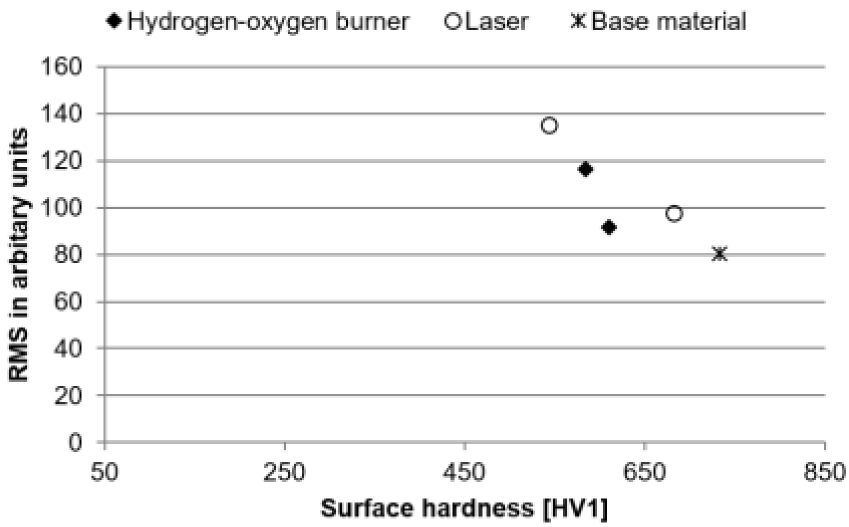

Figure 3. Change in the surface RMS value as a function of surface hardness.

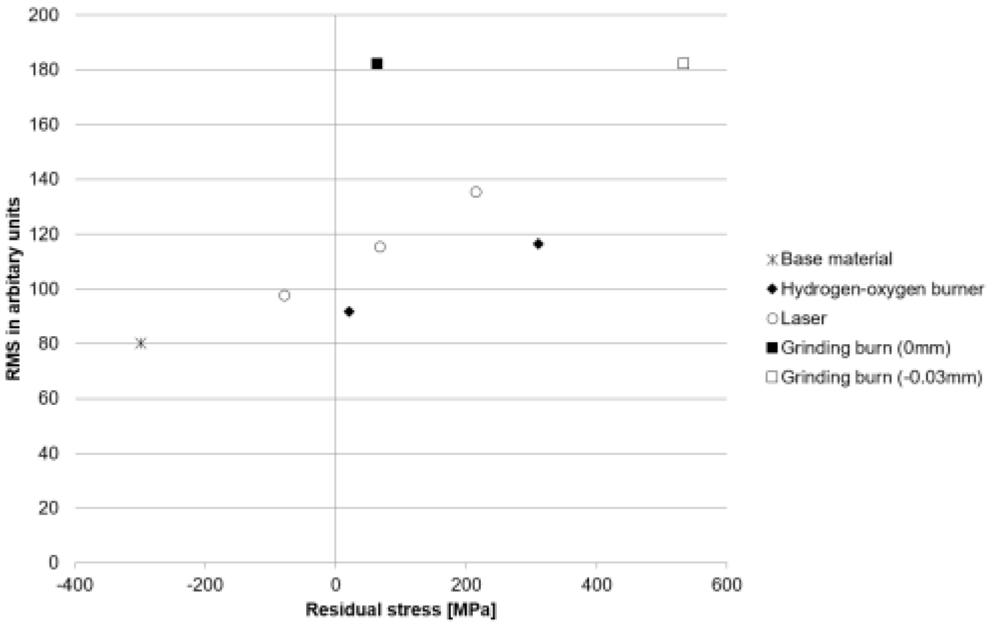

Figure 4. The relation of RMS value as a function of surface residual stress in an axial direction (0˚).

The RS depth profiles for the base material, flame burner samples with process speeds of 15 and 30 mm/s and 330 ˚C laser samples are presented in Figure 5. In addition, for comparison, a sample with grinding burn with high RMS value (RMS 182) was also studied. It is found that the base material has compressive residual stress below the surface on all studied depths while the actual grinding burn with high RMS value has a distinct tensile peak just beneath the surface with 550 MPa stress and the tensile stress decreases while going deeper below the surface. The grinding burn depth profile example studied here is similar in shape than in the study of Moorthy and Shaw (9) and therefore can be used to resample some typical grinding burn. Thus, the actual grinding burn was plotted in Figure 4 with the RMS for both surface RS value (0 mm) and with the first stress profile value with depth of 0.03 mm from the surface. It can be seen that the BN RMS value corresponds better with the 0.03 mm depth residual stress value. This is justified by the different measurement depths of the methods.

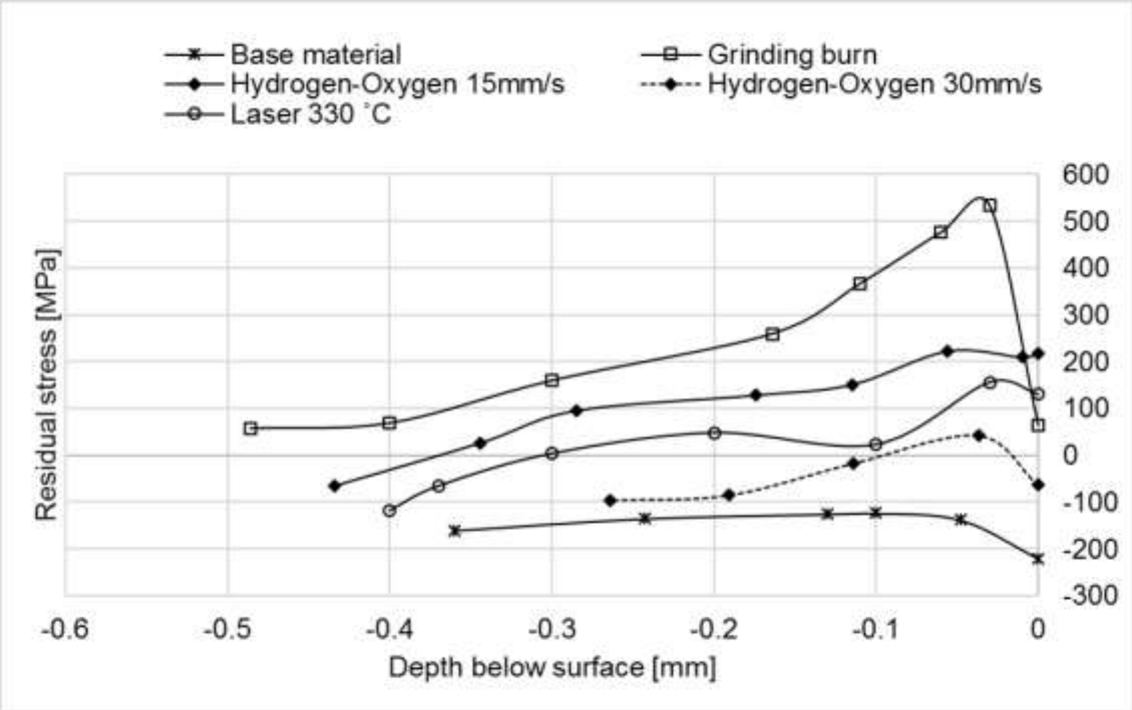

Figure 5. Axial (0˚) residual stress depth profiles: base material, hydrogen-oxygen burner (2 production speeds 15 mm/s and 30 mm/s), laser with 330 ˚C and actual grinding burn.

The shapes of the depth RS profiles for thermal damages are quite similar between the laser and flame burner: a small peak just below the surface and then decreasing trend. Hydrogen-oxygen flame with process speed of 30 mm/s produces less effect on the residual stresses than the 15 mm/s process speed. Whereas, the laser with 330 ˚C temperature is located between these two flame samples. In all cases, the effect of different treatments is still visible at 0.4 mm depth. The most notable modifications of the residual stresses occur from 0 to 0.1 mm depth from the surface where also the BN measurement range is located.

4. Conclusions

The ideal case for the BN calibration is that the operator could use similar components that are to be measured with the system and the measurement can be carried out in the same way than the real quality control measurement is done. To produce such real components with the controlled heating, the treatment systems oppose some restrictions: for laser and the flame systems, the flame or laser head needs to have unlimited access to the surface. The BN sensor calibration sample should also contain the normal sample levels of RMS, i.e. the whole sample cannot be processed with a furnace. When different levels of controlled damages are produced, the sensitivity of the sensor can be controlled. In addition, the marks can be used as making sure that the sensor works and calibration and comparison of the sensors.

In this study, the hydrogen-oxygen flame processed thermal damages were compared to temperature controlled laser processed thermal damages on gear surfaces. In addition, the depth of the tempering effect was verified with X-ray diffraction residual stress depth profiles. Both methods produced elevated RMS values which were further controlled to be linear with both the surface hardness and surface residual stresses. The RS depth profiles verified that the thermal damages produced with both methods were similar shape than the actual grinding burn. The actual grinding burn, however, did have much higher RMS value describing much higher surface temperature between the grinding wheel and the ground surface than tested here.

To select proper system to produce thermal damages mimicking grinding burns the costs of the processing unit and portability need to be evaluated. The flame burner offers a good option to laser processing if the manipulation is carried out with the robot assembly.

Acknowledgements

Jyrki Latokartano from MEI laboratory, Tampere University of Technology, is thanked for the help with the laser robot system.

References

1. S Malkin, C Guo, "Thermal analysis of grinding" *Ann. CIRP* 5 (2), pp 760–782, 2007.
2. F Klocke, C Gorgels, J Reimann, "Influence of grinding burn on the load carrying capacity of parts under rolling stress". In: Proceedings of 7th International Conference on Barkhausen Noise and Micromagnetic Testing, July 15–16, 2009, Aachen, Germany.
3. GV Lomaev, EV Kharanzhevskii, "Testing of laser-quenched layers with the help of Barkhausen noise". *Russ. J. Nondestr. Test*. 36(9), pp 631–639, 2000.
4. A Sorsa, S Santa-aho, K Leiviskä, M Vippola, T Lepistö, "A study on laser-processed grinding burn simulation and analysis based on Barkhausen noise measurement", *Insight*, 52(6), pp 293-297, 2010.
5. S Santa-aho, M Vippola, A Sorsa, J Latokartano, M Lindgren, K Leiviskä, T Lepistö, "Development of Barkhausen noise calibration blocks for reliable grinding burn detection", *J. Mater. Process. Techn.*, 212(2), pp 408-419, 2012.
6. S Santa-aho, M Vippola, A Sorsa, M Lindgren, J Latokartano, K Leiviskä, T Lepistö, "Optimized laser processing of calibration blocks for grinding burn detection with Barkhausen noise", *J. Mater. Process. Techn.*, 212(11), pp 2282-2293, 2012.
7. S Santa-aho, A Sorsa, J Latokartano, L Suominen, K Leiviskä, M Vippola, "Manufacturing of Calibration Samples for Barkhausen Noise Measurements with Temperature Controlled Laser Processing", In: Proceedings of 11th International Conference on Barkhausen Noise and Micromagnetic Testing, 2015 June 18–21, Kuşadası, Turkey.
8. "Operating Instructions Booklet of Micro Brazing and Welding Unit", MIG-O-MAT Mikrofügetechnik GmbH, Stand 1109– Lötstar 245.
9. V Moorthy, BA Shaw, "Magnetic Barkhausen Emission Measurements for Evaluation of Depth of Grinding Damage", In: Proceedings of 7th International Conference on Barkhausen Noise and Micromagnetic Testing, July 15–16, 2009, Aachen, Germany.