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Monitoring of thermal damages upon grinding of hardened steel using Barkhausen noise analysis

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Abstract Thermal damage restrict the capability of grinding in achieving the desired production rate; therefore, the present study focuses on the employment of a non-destructive Barkhausen noise (BN) technique in the assessment of thermal damages produced from grinding of hardened IS 2062 steel under dry (no lubrication) and wet (with lubrication) conditions. Optical microscopy along with microhardness measurement was utilized to reveal the microstructural and hardness alternation occurred in the ground and subsurface of sample. X- ray diffraction peak shift was measured and used for qualitative analysis of residual stress. Furthermore, surface topography was obtained by scanning electron microscope. The magnetic response from ground surface were measured in terms of Barkhausen noise (root mean square) and hysteresis loop (average permeability). The result shows very poor magnetic response from ground hardened steel due to higher carbon content. A non-linear variation is observed between peak shift and root mean square value of Barkhausen noise. However, average permeability derived from hysteresis loop shows good correlation with the peak shift with a correlation coefficient of approximately 0.8149.

1. Introduction

Grinding is more likely to be called as thermo-mechanical process rather than mechano-thermal process as energy partition typically ranges from 60 % to 85 % in the grinding process. In comparison, only about 20 % of the heat generated gets conducted into the workpiece during conventional machining processes like turning and milling [1]. High heat conduction into the workpiece during grinding process gives rise to high temperature which in turn impair the surface integrity of the ground surface in the form of surface burn, rehardening, generation of tensile residual stresses and micro cracks [2]. The occurrence of these thermal damages on ground surface restrict the capability of grinding process in achieving the desired production rate. Hence, reliable and faultless detection of thermal damage is important so as to achieve the desired production rate without sacrificing the product quality. As of now, conventional measurement technique such as metallographic inspection, X-ray diffraction (XRD) and hardness measurement were frequently utilized by the researcher to assess these thermal damages. However, these techniques being time consuming, costly, and laboratory based cannot be used for online monitoring of the thermal damages in the ground surface [3].

In last decade Barkhausen noise (BN) and hysteresis loop (HL) techniques emerged as a potential non-destructive tool to characterize surface integrity (residual stresses, microstructural and hardness changes) of the machined component [4]. The sensitivity of BN signal towards induced or applied stress is based on magneto-elastic phenomenon. The elastic stresses inside the ferromagnetic material force the domain wall to search for the direction of easiest orientation in respect to the lines of the magnetic flux. The presence of tensile stress enhances the BN signal, whereas compressive stress reduces the signal. Further, metallurgical features such as grain size, dislocation density, and plastic deformation affect the generation of BN.

These acts as a barrier in the path of domain wall movement. A ferromagnetic sample with smaller grain size produces more intense BN signal as compared to the one with larger grain size [5]. Different research groups utilized different magnetic parameters such as root mean square (RMS), peak position, permeability, coercivity, remanance, BN and HL profile for material characterization under different manufacturing processes like grinding, shot pinning, welding, and heat treatment [6-8].

The present research work focus on the assessment of thermal damage of pack carburized low carbon steel upon grinding. Experiments were performed with variation in downfeed, table feed, and lubrication conditions which introduces different level of thermal damages on the ground surface. Optical microscopy technique along with microhardness measurement was used to detect the depth of thermal damage in the ground sample. The residual stress state of the ground samples were analysed using peak position shift of XRD. Dimensional accuracy and quality of ground surface was analysed by SEM. Lastly, surface integrity of the ground sample were assessed using BN and HL technique.

2. Experimental procedure

Hardened IS 2062 steel with dimension of $100^{L}\times25^{W}\times10^{T}$ mm were taken as workpiece material in the present research work. The chemical composition of work material is reported in Table 1. The pack carburizing method was used to enhance the mechanical properties of the workpiece. In this method, samples were kept in a closed steel box where it is surrounded by a mixture of 85 % charcoal + 15 % $BaCo_3$. The steel box along with the samples was heated to a temperature of 920 °C using muffle furnace and were then kept at that temperature for 3 hours for homogenization. Thereafter, samples were taken out and quenched in water. To remove any residual stress the samples were then tempered by heating it to a temperature of 300 °C for a period of 45 min followed by furnace cooling. As-carburized IS 2062 steel samples has achieved higher hardness in the range of 55 ± 2 HRC. Grinding of pack carburized sample was carried out on H455 HMT surface grinding machine with white alumina grinding wheel. Before performing the actual experiment extensive trial run experiments were conducted to optimize the process parameter. The grinding parameters which were used to perform the final experiments are listed in Table 2.

Grinding forces were measured with the help of 3-component grinding force dynamometer (IEICOS, model-610C). Grinding temperature was measured by K-type thermocouple. The hot junction of the thermocouple was mounted at the bottom of a blind hole at a distance of 0.5 mm from the grinding surface. The reason of that hot junction made by nickel based alloys with small diameter 100 µm. When hot junction was connect at ground surface. This junction was opened owing to high pressured grinding wheel roughing over ground surface. Hence, grinding temperature was measured on basis of heat conduction and embedded thermocouple technique. The surface roughness (R_a) of the ground sample was taken perpendicular to the grinding direction at three different locations using Mitutoyo Surftest (SV-2100S4) with traverse length of 0.8 mm and cut-off length of 4.0 mm. Next, the surface morphology of the ground surface was examined using SEM (Zeiss Evo 18 Research, 20KV). In order to depict the metallurgical changes ground samples were cut perpendicular to the grinding direction and then were subsequently hot moulded in specimen mount press using phenolic resin powder. The samples were then polished using emery paper of different grit size 120, 200, 400, 600 and 1000. Thereafter, samples were polished using alumina paste on auto-disc polishing machine to achieve mirror like finish which is followed by cleaning with acetone to remove any alumina particles from the surface. Finally, the samples were etched using 2 % nital solution for about 10-15 seconds and again cleaned under running tap water before observation of cross section of ground surface under an optical microscope (Dewinter). The microhardness readings of the ground surface were taken with microhardness tester (Micro Mech Technologies, India) at 200 gf applied load and 15 sec dwell time. XRD analysis of the ground sample was performed using Rigaku X-ray diffractometer to study the nature of peak shift. The direction of peak shift of the ground sample with respect to base sample indicates the nature of residual stress. The XRD parameter used for ground sample is reported in Table 3. The BN signal and HL measurements were carried out using the commercially available Magstar system supplied by Technofour, India and is shown in Fig. 1(a). Measurement system consists of a flat-surface probe with U shape magnetising yoke to generate magnetic field inside the test sample with the help of current from the power supply. A pick-up coil (ferrite) at the centre was used to gather the signal

Table 1. Chemical composition of IS 2062 steel (%).

C	Mn	P	S	Si	Cr	Fe
0.17	0.32	0.007	0.013	0.045	0.3	Balance

Table 2. Grinding parameters.

Parameters	Settings
Grinding mode	Plunge grinding
Grinding mode	1. Dry grinding, 2. Wet grinding
Grinding wheel	Alumina (AA54K5V6)
Work material	IS 2062 steel
Wheel speed (V_s)	39.42 m/s
Table feed (V_w)	8, 12 m/min
Downfeed (a_p)	6, 12, 18, 24 µm
Dresser	Single-point diamond

Table 3. Parameters for XRD analysis.

Rediation	Voltage	Current	Step width	Scan speed
Fe-Kα	40 kV	15 mA	0.02	5 degree/min

Table 4. Parameters for BN analysis.

Magnetic frequency	Magnetic field intensity	Gain	No. of burst	Filter frequency
100 Hz	500 Oe	20 dB	6	100-300 kHz

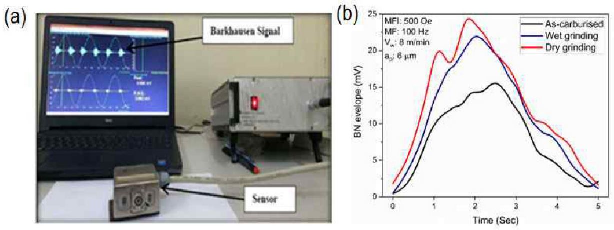

Fig. 1. (a) Barkhausen noise instrument; (b) Barkhausen noise envelope.

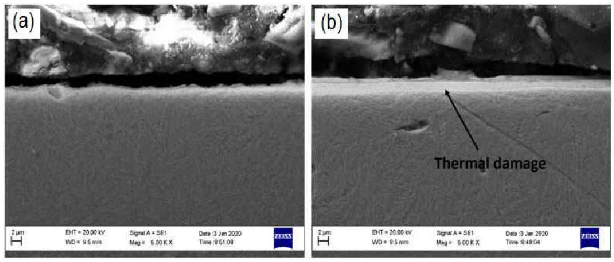

Fig. 2. Microstructure of ground surface: (a) Wet; (b) dry.

generated as the magnetic response of the work material. Fig. 1(b) clearly shows variation in BN envelope under as-carburised sample and different ground sample. Table 4 shows the detail of initial parameter considered for the BN analysis.

3. Results and discussion

3.1 Metallographic and microhardness

The higher temperature during the grinding process is supposed to change the microstructure of the ground surface. The intensity of heat generation is not only dependent on interaction forces rather it is also significantly influenced by plastic deformation mechanism associated with material removal process, table feed, and downfeed [9]. Fig. 2 shows the alteration in subsurface microstructure of the ground surface under different environmental conditions. In wet grinding, cutting fluid provides sufficient cooling and lubrication over ground surface resulted in minimum heat penetration in the ground subsurface of the workpiece. On the other hand, in the absence of cooling and lubricating media a large fraction of heat generated at higher table feed and downfeed gets penetrated into the workpiece during dry grinding and thus resulting in maximum thermal damage as observed in the Fig. 2(b). However, the extent of thermal damage and associated plastic deformation is not sufficient to cause significant change in the microstructure thereby no white layer is visible on the ground surface. Hence, microhardness was measured along the subsurface to validate the metallographic changes in the ground workpiece. A similar variation in optical microstructure

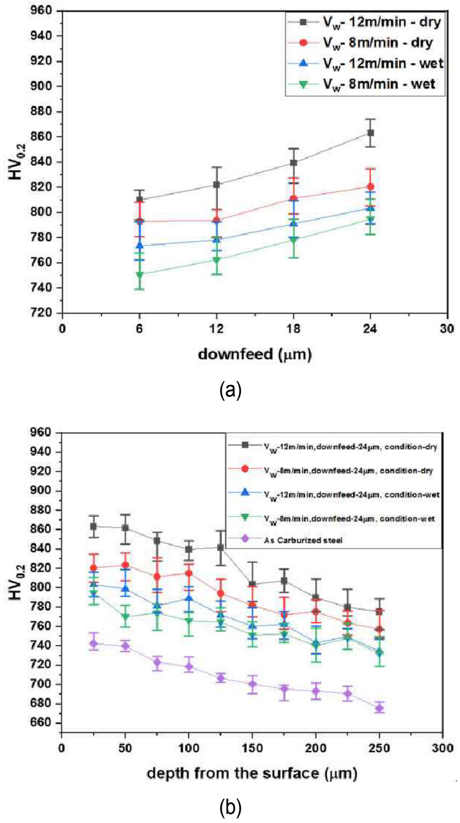

Fig. 3. (a) Microhardness variation under different environment; (b) microhardness change along the depth of the ground and carburized surface.

was observed by Sosa et al. [10] during dry grinding of ductile iron. They found drastic phase transformaton in work material at higher grinding temperature.

Fig. 3(a) displays the variation in microhardness just beneath the ground surface under different table feed, downfeed, and grinding environment. From the figure it can be seen that hardness of the ground surface monotonically increases with the increase in downfeed and table feed. This is due to the fact that increase in table feed and downfeed led to enhanced maximum uncut chip thickness and also it increases the contact length of grinding wheel with workpiece, which collectively result into significant rise in temperature leading to grain refinement and phase transformation in the subsurfaces.

In dry grinding, maximum hardness was observed in the workpiece due to absence of cutting fluid. Vasilko and Murcinkova [11] also observed that severe plastic deformation during grinding result into homogeneous structure with very fine grain size which tends to increase the microhardness value. In wet grinding due to lubrication and cooling action of cutting fluid the temperature in the grinding zone is smaller as compared to the dry grinding which thus reduces the severity of plastic deformation. Hence, higher microhardness change is observed in dry grinding as compared to that of wet grinding. The variation in microhardness as a function of depth from the ground surface and as-carburized priciple surface is depicted in Fig. 3(b). Lowest microhardness value was obtained in as-

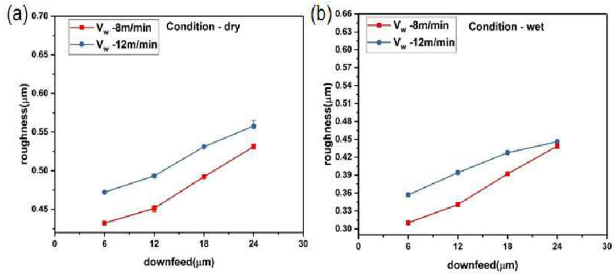

Fig. 4. Surface roughness variation of ground surfaces under different grinding conditions: (a) Dry; (b) wet.

carburized sample, whereas highest microhardness value (869 $HV_{0.2}$) was obtained under higher downfeed and table feed in maximum thermally damaged ground sample. The reason of that maximum heat penetration in the subsurface, which induced large scale plastic deformation in work material matrix. The microhardness of the as-carburized sample and ground sample under wet environment were 802 and 741 $HV_{0.2}$, respectively, which were 7.79 and 14.73 % lower than that of dry grinding. Further, it can be seen that microhardness value gradually decrease along the subsurface upto 250 μm from ground surface. This may be attributed to rapid heating and slow heat dissipation, which causes grain refinement of nascent ground surface. Similar microhardness trend was obtained in the case of as carburized sample owing to precipitation of carbides at the grain boundaries, which reprsents the unifrom of the carburizing layer over sample [12].

3.2 Surface roughness and topography

Fig. 4 displays the variation in surface roughness of ground sample under different downfeed, table feed and grinding environments. It is evident from the figure that as the downfeed increases there is increase in surface roughness of the ground surface. Also surface roughness increases with the increase in table feed. As explained earlier, any combination of grinding parameter which affects the maximum undeformed chip thickness and contact area will also have significant effect on the friction force. Higher surface roughness of ground surface was observed in dry grinding and is due to more ploughing and rubbing action rather than shearing action of the abrasive grit during wheel workpiece interaction in the absence of lubrication [13]. The grinding performed with lubrication also helps in lowering the value of surface roughness and the same can be seen from Fig. 4. In the presence of lubrication, cleaning of microchip occur which would otherwise if left on the surface get stuck to the ground surface during subsequent passes giving rise to higher surface roughness. The minimum surface roughness (0.3124 μm) were witnessed during wet grinding at lower table feed and downfeed conditions whereas the higher surface roughness (0.5776 μm) was observed under dry grinding at higher table feed and downfeed conditions.

Surface roughness and surface topography (2-D and 3-D image) are important parameter as it provides significant infor-

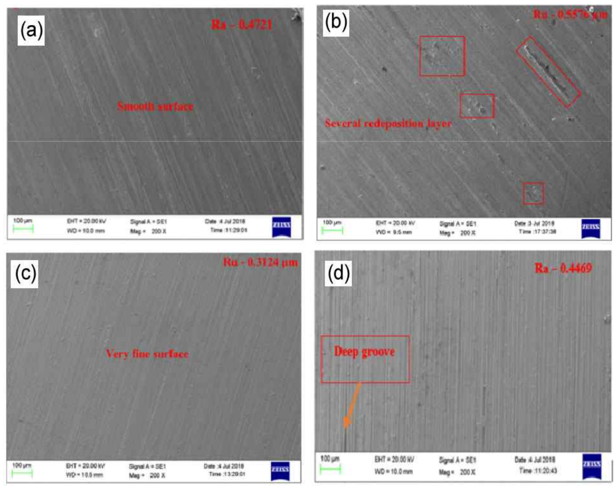

Fig. 5. Ground surface topography of hardened IS 2062 steel: (a) Dry (a_p - 6 μm); (b) dry (a_p - 24 μm); (c) wet (a_p - 6 μm); (d) wet (a_p - 24 μm).

mation about service life of the product under real working condition. The 2-D ground surface topography under different parameter conditions are represented in Fig. 5. The sliding marks can be seen on ground surface on account of frictional force during interaction of unidirectionally oriented abrasive with workpiece [14]. The very fine surface finish in terms of negligible grooves and redeposition of microchip on ground surface can be seen during wet grinding with lower downfeed because of effective lubricating layer of synthetic cutting fluid. On the other hand, higher surface deterioration with deep groove and several redeposition layers over ground surface was observed in case of dry grinding with higher downfeed. The reason of poor surface quality can be attributed to the adhesion of microchip on ground surface at elevated grinding temperature. Also some of the microchip present on the surface gets crushed during backward stroke of grinding wheel and leads to the formation of deeper groove and thus deteriorating the surface finish. Awale et al. [15] also observed the redeposition of microchip on ground surface during dry grinding of hardened AISI H13 hot die steel.

3.3 Residual stress and grinding temperature

The XRD profile of as-carburised and ground sample under different grinding parameter conditions are shown in Fig. 6. In the present work XRD peak shift of (110) plane is used for qualitative analysis of residual stress of the ground surface. The shift in peak position of XRD profiles indicates the influence of residual stress. Generally, the peak position shifts towards left hand side (lower peak position angle) due to the induction of tensile residual stress. While, compressive residual stress shifts the peak position towards right hand side (higher peak position angle) [7]. The peak shift is computed for the entire set of ground hardened steel by taking peak position of carburised hardened steel as a reference sample. A continuous peak shift towards left side of the reference sample peak

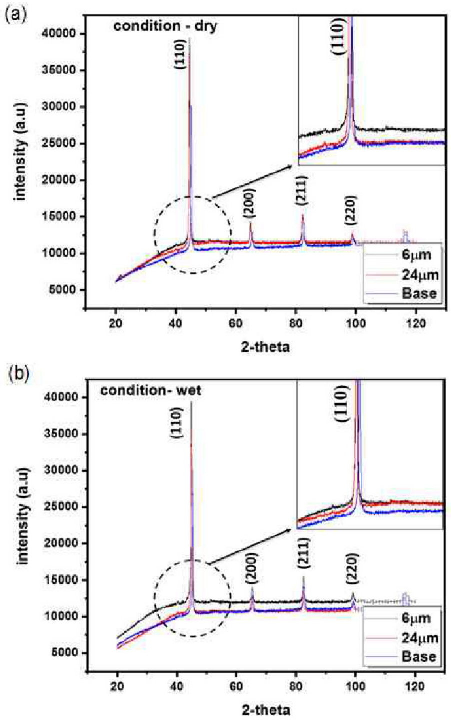

Fig. 6. XRD profile of carburized and ground surface: (a) Dry; (b) wet.

position was observed in ground sample upon dry and wet grinding indicating the presence of tensile residual stress. Normally, higher tensile residual stress leads to larger shift in peak position depicting larger thermal damage over ground surface. Fig. 6 clearly shows that maximum peak shift of (110) plane profile from carburized sample peak i.e. maximum tensile residual stress was obtained under dry grinding with downfeed of 24 µm. This is due to penetration of large amount of heat flux into the workpiece at higher downfeed, which results in localized plastic deformation of ground surface. Similar result were observed by Vashista and Paul [16] during study of thermal damage on ground AISI 1060 steel using XRD and BN (peak and RMS) techniques.

Grinding temperature is significantly enhanced by shearing, rubbing and ploughing action of abrasive grits on the workpiece [17]. Fig. 7(a) shows that grinding temperature increases with increase in downfeed and table feed irrespective of grinding environments. This is due to increase in maximum uncut thickness with increase in downfeed and table feed. In dry grinding, the higher temperature (566 °C) was observed at higher value of downfeed and table feed, whereas in wet grinding the maximum temperature observed is 376 °C under similar downfeed and table feed. A reduction by 33.56 % is observed in maximum temperature in wet grinding in comparison to dry grinding. Fig. 7(b) shows the variation of XRD peak shift of (110) plane of ground sample from reference sample with grinding temperature in the experimental domain. Maximum peak shift was observed at higher grinding temperature due to plastic deformation of matrix and presence of residual stress. A good correlation was observed between peak shift and grinding temperature with correlation coefficient of approximately 0.8947.

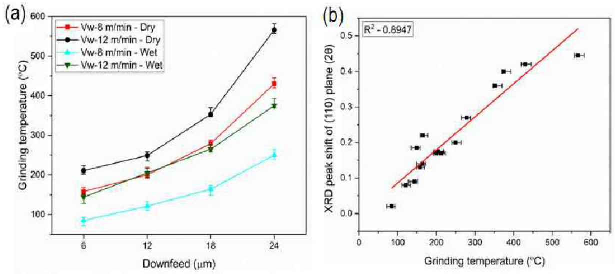

Fig. 7. (a) Grinding temperature under different environment; (b) correlation of grinding temperature with XRD peak shift of (110) plane.

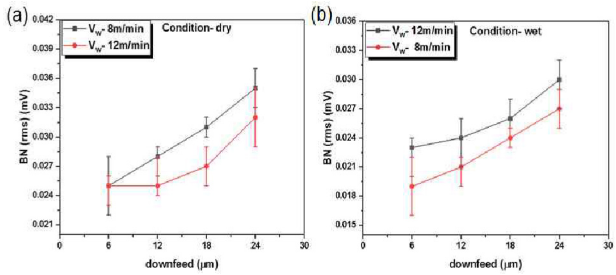

Fig. 8. RMS response under different grinding condition: (a) Dry; (b) wet.

3.4 Barkhausen noise and hysteresis loop

Thermal damage in grinding has significant influence on the micromagnetic property of the ground specimen. These micromagnetic changes can be analysed using Barkhausen noise emission technique. It has been shown that higher thermal damage induces higher order of tensile residual stress on the ground surface, which in turn aligns the magnetic domains in a direction parallel to stress direction resulting into increase in BN signal [18]. However, it is mentioned that magnetization response of hardened IS 2062 steel is smaller due to the presence of higher carbon content. Jin et al. [19] also observed that the BN (RMS) decreases due to oxidation layer and martensitic structure formation on hardened gear component during grinding. Thereby, it is important to see the sensitivity of BN signal towards thermal damage occurring on the surface of ground hardened steel. Fig. 8 demonstrate the effect of grinding parameters on BN emission. From the figure, it can be seen that BN (RMS) value increases with the increase in downfeed irrespective of table feed and environments. This is because of the fact that increase in downfeed increases the grinding zone temperature which thus increases the tensile residual stress. As already stated this increase in tensile residual stress give rise to higher BN emission. Lowest BN (RMS) value (0.015 mV) was obtained in the carburized sample. The RMS value of the ground samples at higher downfeed under dry and wet environment were 0.035 and 0.030 mV, respectively, which were 66.7 and 50 % higher than that of carburized sample.

Fig. 9 depicts the effect of grinding parameters namely

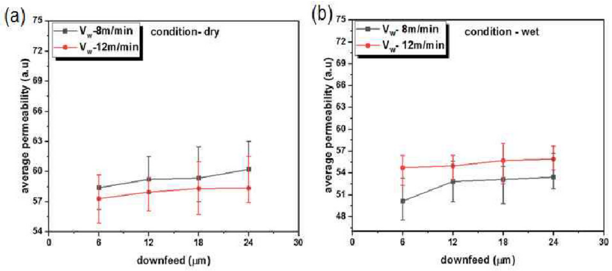

Fig. 9. HL response under different grinding condition: (a) Dry; (b) wet.

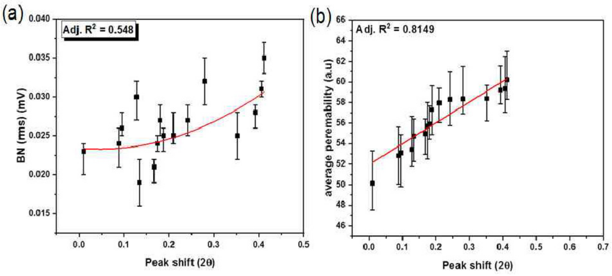

Fig. 10. Correlation of magnetic parameter with XRD peak shift: (a) BN (RMS); (b) HL (average permeability).

downfeed, table feed and grinding environment on the hysteresis loop response (average permeability). Average permeability is the ability of a ferromagnetic material to support magnetic field development, when external magnetic field was applied on ferromagnetic material. The maximum average permeability value was obtained in the dry grinding sample as compared to wet grinding and as carburized sample. This may be attributed to the increasing tensile residual stresses in the ground surface and subsurface. The average permeability value lies in the range (57.30 to 60.21 a.u.) for dry grinding, whereas for those during wet grinding it lies in the range (50.13 to 55.90 a.u.). Average permeability of carburized sample was 38.54 a.u. The HL response of dry and wet grinding at higher downfeed was 28.12 % and 22.52 % higher than that of carburized sample. Gupta et al. [20] also reported higher average permeability in welded zone as compared to heat affected zone of ferritic stainless steel SS409L because of presence of tensile residual stress in the welded zone.

Fig. 10(a) depicts the correlation between XRD peak shift due to induction of tensile residual stress with the RMS value of the BN emission. It can be observed that response of BN (RMS) with peak shift is not linear. This is due to poor magnetization of the hardened steel. Although, the variation of BN (RMS) is not linear with the peak shift a continuous increase in BN (RMS) is observed with the increase in peak shift. Fig. 10(b) represents the correlation between HL parameter (average permeability) and peak shift for the entire experimental domain. Despite of poor magnetic response due to higher hardness, a linear correlation can be observed between the peak shift and average permeability value with a correlation coefficient of approximately 0.8149. The more and more increase in peak shift corresponds to more and more induction of tensile residual stress. This tensile residual stress aligns the magnetic domains in a direction parallel to stress direction which in turn favours the magnetization process and hence improves the average permeability of the sample.

4. Conclusions

Thermal damage in grinding impairs the surface integrity of the ground surface which needs to be assessed as it effects the service life of the component under real working condition. In terms of microstructure, significant change is not observed in wet grinding whereas grain refinement is observed in the subsurface after dry grinding. This is further validated by higher microhardness of subsurface in dry grinding. Surface finish achieved in case of wet grinding is higher as compared to the dry grinding. The larger shift in XRD peak position is witnessed in case of dry grinding due to the presence of higher tensile residual stress. The magnetic parameter BN (RMS) shows poor correlation with peak shift with correlation coefficient of approximately 0.548. However, average permeability derived from hysteresis loop shows good correlation with peak shift with correlation coefficient of approximately 0.8149. The study shows that for the material showing poor magnetic response average permeability can be used to monitor residual stress in the component after grinding.

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