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Material Characterization using Barkhausen Noise Analysis Technique - A Review

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Abstract

Background/Objective: Material characterization is an essential part during manufacturing cycle of component as it assesses the surface integrity of component. Assessment of surface integrity is important since it decides the fatigue strength and service life of manufactured component. Microhardness, microstructure and residual stress are key elements of surface integrity. Modern manufacturing industries relies on laboratory based technique such as microhardness tester, optical metallographic inspection and X-ray Diffraction (XRD) techniques for measurement of key elements of surface integrity. The laboratory based techniques are not eco-friendly and as well as time consuming. **Methods/Statistical Analysis:** Barkhausen Noise (BN) analysis is a preferred and advanced technique for material characterization when an external magnetic field is applied over a ferromagnetic material, it changes the global magnetization occurs by motion of magnetic domain wall as these domain wall align these stress in the direction of applied magnetic field. A voltage pulse is generated due to motion of magnetic domain, which can be detected as signal by sensor. This included voltage pulse is known as BN signal. **Findings:** Conventional material characterization techniques such as hardness tester, optical microscopic and XRD are extensive time consuming laboratory based technique and difficult to integrate in manufacturing environment. On the other hand, BN technique is less costly, fast, eco-friendly NDT which can be easily integrated with manufacturing cycle for component. **Application:** Barkhausen Noise measurement is generally associated with hysteresis loop measurement.BN signal parameters such as Root Mean Square (RMS) value, amplitude, peak position as well as hysteresis loop properties coercively, remanence are sensitive towards change in micro-hardness, microstructure In this way, BN analysis technique can assess the surface integrity of manufactured component. In the present review paper, a critical and wide literature survey is conducted to summarize and highlight the successful attempts of BN techniques for surface integrity assessment of components, by using various manufacturing process such as machining, welding, heat treatment and grinding.

Keywords: Barkhausen Noise Measurement, Microstructure, Non Destructive Testing, Residual Stress, X-ray Diffraction

1. Introduction

Non Destructive techniques are popular method for material characterization not only in R&D sector but also in manufacturing industries. The aim of the NDT to predict strength, quality and application of tested object in service. There is a good conformity between NDT properties and service life of the manufactured product.[1] There are various NDT techniques namely XRD, Ultarasonic, Neutron Diffraction, Radiography and Barkhausen Noise (BN) method which are used for material characterization. Among these techniques BN technique is preferred and more advance. This technique based on magnetism phenomenon happens in ferromagnetic materials.[2] Ferromagnetic material's microstructure is characterized by regions, known as magnetic domain. The presence of magnetic domains in a ferromagnetic material was initial investigated by earlier scientists in the year1907. The primary experimental verification of the presence of magnetic domains was presented in 1919 by Prof H.G. Barkhausen. During magnetization, variation of the magnetic domains direction occurs in shocks, which in turn

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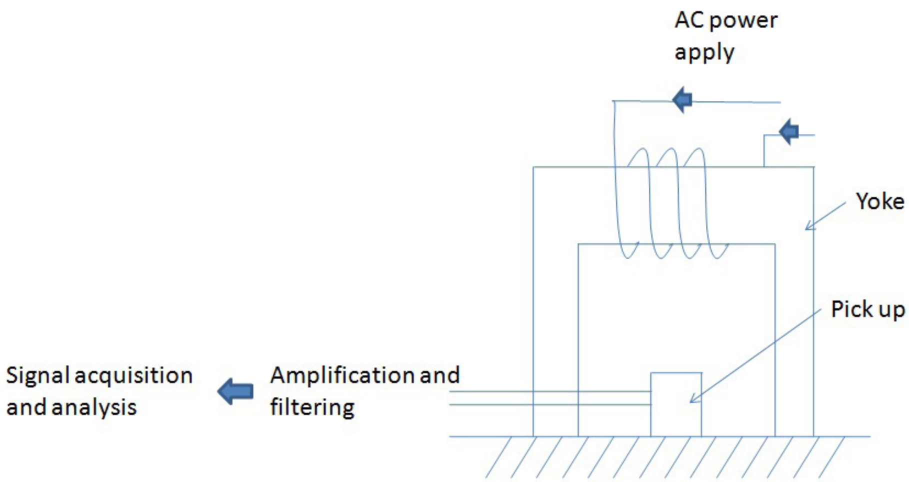

Figure 1. Experimental set up for measurement of Barkhausen Noise.

modify the global magnetization of material. This change in magnetization generates voltage shocks in the measuring coil. Professor Barkhausen identified generated voltage shocks using a measuring coil, improved and led this voltage to a loudspeaker. The induced interior magnetization by shocks in the ferromagnetic material was recorded using the loudspeaker. After that scientists represented this voltage induced signal as BN.[3] Generally an electromagnetic yoke is used to apply the external magnetic field over the specimen under study refer Figure 1. The pickup coil kept over specimen, capture the voltage pulse generated inside the material due to change in global magnetization. This voltage pulse is further amplified and filtered to generate BN signal. The acquired BN signal is analyzed using computer.

2. Major Areas of Barkhausen Noise Analysis Research

This section presents the arrangement of research papers related to material characterization with BN with three headings. The first part provides the study relates to residual stress measurement of components or structure using BN technique. The second section concentrated the microstructure analysis of components. Third part represents research regarding the hardness of components under magnetised condition.

2.1 Residual Stress Measurement

As BN signal is affected by microstructure, microhardness, grain size and residual stress.[4] Hence it can be effectively used for material characterisation. In addition, it is also applied to evaluate surface integrity of components used for various manufacturing process like grinding, fabrication, forming as well as various heat treatment process etc. The previous investigator started the research relating to the use of BN technique as non-destructive method for the assessment of the metallurgic states based on residual stress. When specimen undergoes in magnetised condition, the magnetization of the domains parallel to magnetic field increase. Furthermore the magnetization of domains perpendicular to magnetization decreases. Similarly, other researcher revealed the effect of both tensile and compressive stress and applied magnetic field on the level of BN analysis. Under the application of tensile stress, the domains with parallel magnetization to tensile stress direction raises at the cost of other domains, regularly taking over the total existing volume. On the contrary, the domains with perpendicular magnetization to compressive stress direction rise moreover in the end cancel out the other domains. When same type of change is observed in domain configurations under the influence of the stress and the magnetic field generate, the cumulative result causes elevated levels of BN. In other case, the stresses as well as the magnetic field creates contradictory the influence on wall movement, decreases BN level.[5]

The tensile residual stress is detrimental in nature due to reduce in fatigue strength and corrosion resistance. On the other hand, the compressive residual stress is beneficial for improving fatigue strength and corrosion resistance. Now these days, there are various NDT technique such as XRD, BN and Ultrasonic method etc are used to measure residual stress.[6] XRD technique is used to measure the residual stress on smaller area of the polycrystalline materials. It is depended on shift of location for different profile (i.e peak position) which is in linear relation to stress value.[7] The Energy Dispersive Analysis of X-rays EDAX is used to find out the defect area of steam generator tube used in nuclear power plant. In this method, microstructure is investigated near to a pitting defect and wall thinning because of intergranular corrosion.[8] The residual stress analysis performed by XRD, uses $\sin^2 \psi$ method.[9] From the application point of view, XRD is used to assess the residual stress due to its advancement and broad range of experience. In addition, it also facilitates frequent non-destructive surface measurement in different measuring area. Furthermore, XRD is small penetration depth of X-ray and used for the measurement of stress gradient on the components.[10] Despite the numerous advantages of XRD, there are some limitations of XRD while measuring the residual stress. When this method detect relative peak position; the outcome are undisturbed by peak splitting, irregular background, intensity variation and scatter of X-ray. In addition, XRD method is extensive and time taking process. It is also a laboratory method.[11] The BN analysis method is used for measurement of residual stress in ferromagnetic materials. As BN technique is responsive to stress, grain size, composition, hardness, along with microstructure. For this reason, it is popularly used in various industries for assessment of surface integrity of components.[12] The relation between Root Mean Square value (RMS) of the BN as well as residual stress as function had been discussed for mild steel. The reasonable changes in the RMS value of BN amplitude occurred due to high strain condition.[13] The cold rolled steel showed the increase of the BN activity under the application of stress. The jump energy distribution was angular dependence as well as dependent on the anisotropic nature of the BN activity.[14] A successfully examination for both deformation (i.e permanent and temporary) effects on BN signals was conducted. The linear and angular MBN measurements on mild steel plates undergoes changing of uni-axial elastic and plastic deformation up to 40% strain. The elastic strain effect on the BN energy is more significant than plastic strain effects.[15] In another work, the BN energy values increases with tensile stress in the elastic range. It also remains constant in the plastic deformation range up to 4% strain because of combined effect of changes of magnetic domain sizes and increases in the number of preferred domain walls. The BN technique is suitable method to detect micro yielding.[16] The variation of various contents (i.e Cr, Si) have great influence of RMS value of BN. In this contest, it was observed that silicon content in the sample decrease with decrease of RMS whereas increase of chromium causes the decrease of RMS value.[17] During the measurement of the BN of inconel-600 sample with rotary magnetic field, it was observed the limited stress amplitude of each life fraction could be determined using power of the BN. [18] Sometimes, the stress measurement is compared for mild steel using BN method and rotation of magnetisation method. Thus, the rotation of magnetisation method is more preferable than BN method due to some inherent limitation associated with BN method.[19] The BN technique is fast and reliable method used to measure surface residual stress and microstructure on welded steel plates.[20] A good correlation of the magnetic parameters and fatigue life of specimen under various loading condition, revealed that local plastic strain is an essential parameters for the prediction of specimen life. The hysteresis loop amplitude is also sensitive to cyclic plastic strain. The hysteresis loop amplitude measurement showed the bi-linear relationship with failure cyclic number leads to predict fatigue life of specimens.[21] Distribution of bending stress was studied using BN energy in the wall of steel pipe around pit with various depth of wall thickness. It was observed that the average BN_{energy} directly improves with bending stress due to increase in number and volume of preferred domains on the outside surface of the steel.[22] During the study of the alloy French steel, the difference between the Magnetic Barkhausen Effects (MBE) and the Magnetic Acoustic Emission (MAE) hysteresis loops were investigated. In this work, the Mechanical Magnetic Acoustic Emission (MMAE) intensity revealed some height-amplitude events in favour of the tensile stress because of mechanical noise of the loaded machine. The MBE and MMAE intensities were related due to peak observation for both the similar and dissimilar stress level in magnetised specimen. Both MBE and MMAE intensity rise due to more value of magnetic field.[23] The Magnetic Flux Leakage (MFL) was also used to analyze stress. The stress observed in the pipe leads to vary MFL signals because of its movement in the path of the magnetic easy axis of the specimen and vary in preferred domain wall population.[24] The BN emission technique is used to measure residual stress of ground case carburised steel. It was observed that residual stress and microstructure analysis could be evaluated from BN signal parameters.[25] The variation of residual stress occurring in the depth direction due to grinding can be assessed using BN technique.[26] The Barkhausen emission technique is used for the observation of surface morphology of the thermal grinding steel. The occurrence of various surface damage was generated in ground steel by varying coolant flow rate. For particular quarter flow rate, it was observed that a dark layer or temper burn on the surface of ground steel due to softer surface layer results weak wear resistance.[27] The amplitude of BN signal profile successfully signifies the residual stress redistribution in the near-surface and subsurface area because of controlled plastic deformation.[28] The Barkhausen Emission (BE) signal increase with increase of numerous unpinning events of Domain Walls (DWs) in low temperature annealed specimen with small grains. For small grain specimen, the BE signal increases with tension. Whereas for large-grain specimen, BE signal decrease with tensile stress due to development of new DWs leads to raise the number of unpinning events.[29] During the measurement of BN activity over particular value of plastic deformation (0-20%) in mild steel. It was noticed that MBN activity shows strong variation only in the applied stress measurement direction. The induced plastic deformation affects the BN activity obtained from dislocation and domain wall interaction resulted from multiple slip mechanism and residual stress.[30] When the effect of applied stress on BN and hysteresis loop are investigated. The maximum amplitude of BN raise and it falls down for more stress than the stress at boundary condition because of the influence of the magnetic field as well as applied stress. In addition to, the high amplitude of MBN voltage, maximum magnetic induction as well as differential susceptibility value is less for fine grain specimen and movement of domain wall. Whereas it is more in case of coarse grain specimen.[31] In modern Industries, an integrated laser process and BN method is used for calibration of the output of different gear teeth specimen. The laser temperature profile for ground surface is uniform in all laser processing direction. The laser process also influence the residual stress in two measured direction (two linear direction: before laser processing and after laser processing). The RMS value is directly proportional to residual stress and surface hardness.[32] The BN amplitude decreases in the loading direction and increases in transverse direction. In both the loading and transverse direction, prestrain increases directly with stress and BN which was implemented for evaluation of residual stress. The saturated tensile stress of the BN in the stress vs BN graph measured in the loading direction increases in terms of prestrain.[33] The amplitude of Barkhausen changed with the stress consisting of macrostress within the ferrite phase. The RMS value changed with respect to induced stress because of varies in the pulse height distribution.[34] The prestrain in austenite is tensile in nature but in ferrite prestrain is compressive. Once prestraining, austenite showed compressive microstresses whereas ferrite showed tensile microstresses. The BN increases in every measuring direction due to increase of tensile interphase microstresses and decrease of macroscopic compressive stresses. The prestrained specimens with compressive stress showed high stress sensitivity of BN.[35]

The BN measurement is used for analysis of different magnetic properties of both the hardened steel along with the soft base material core. The residual stress depth distribution on the surface layer decreases compressive and it changes gradually into tensile residual stress in depth equivalent to layer thickness.[36] The Barkhausen effect also determines the fatigue damage growth in addition to residual fatigue life of steel under application of cyclic load. The BN peak value depends on the induced voltage. When the applied stress value is lower than the fatigue limit, the BN signal remain nearly stable but when the applied stress value is higher than fatigue limit, BN signal changes.[37] The improvement of tensile residual stress decreases the movement of the walls leads to increase of Barkhausen signal amplitude. It was also observed that increase of carbon content leads to decrease amplitude of Barkhausen signal. The Barkhausen signal improves by tempering owing to the conversion of martensite and the decrease of hardness.[38] The BN response of Armco iron is compared with low carbon steel under plastic deformation state. It was found that stress at the BN measurement increase at tensile load and decreases at compressive load. When material undergoes tensile stress parallel to direction of magnetic field increase the BN analysis signal whereas in compressive stress it decrease BN signal. In addition to, formation of dislocation cell and dislocation tangles show higher plastic strain for low carbon steel.[39] The residual stresses was analysed using various NDT method such as eddy currents, BN, hysteresis loop under the application of constraints (tensile) on different steel samples. Then both result obtained from destructive and non-destructive tests are compared and used for analysis.[40] The properties hysteresis loop such as coercivity, remanence and permeability were correlated well with stress under prestrain condition.[41] The BN measurement with high amplitude signatures was associated with tensile stresses whereas BN measurement with low amplitude signatures was associated with compressive stresses. The loads were carried out to the point where one surface was yielded in tension and the opposite surface was yielded in compression. The low compressive stress yields low BN value whereas tensile stress generates high value of BN.[42] During Barkhausen measurements on crankshaft steel, it was noticed that the variation in ductility linked to the variation in BN amplitude through the grinding process. An increase in ductility raise the chip builds up in the grinding wheel ensuring more grinding temperature. The chip build up and high grinding temperature raises the danger for grinding burns and move the residual stresses towards tensile results modify the BN analysis.[43]

The effect of elastic deformation and applied stress on MBE was investigated for induction-hardened steel namely standard tempering and over tempering. For particular stress range, the output of BN shows linear relation with tension. The output of BN is more sensitive to stress in over tempering specimen than that of standard tempering specimen. In addition to this, the peak height of BN signal was larger for over tempering specimen than that of standard tempering specimen. The BN profile showed narrow hysteresis loop of material under tension stress whereas widen hysteresis loop of material was observed under compressive stress.[44] Based on the tensile and compressive stress, both peak width and position of BN signal improvement is observed in compression and at the start these decrease with tension, on the other hand the peak height and skewness decrease with compression and initially increase with tension.[45] During the measurement of residual stress of ground steel, there was no significant change in Barkhausen noise signal at the application of both tensile and compressive residual stress. The assessment of residual stresses by the BN method was carried out by means of relaxation method. The relative study during thickness measurements revealed the micro-magnetic technique is appropriate for residual stresses measurement. This method presents actual time change for residual stresses in a thin surface layer of the material.[46]

The BN signal raise in the direction of applied tensile stress whereas it falls down in direction of compressive stress due to decrease in hysteresis. The magnitude of Irreversible Differential Permeability (μ_{IDP}) in low field region increase in appliance of tensile stress and it decrease in the appliance of compressive stress. The improvement of preferred domain wall area was noted due to tensile stress whereas it decreases due to compressive stress.[47] During the assessment of surface integrity by a new approach for processing the response of BN signal over work material with poor micro-magnetic response, it was observed that linear relationship occurs between BN parameters such as count and event with residual stresses.[48] The peak value of Barkhausen signal increases with increase tensile residual stress up to yield strength of material, then it decreases. The grain elongation and surface residual stress of grounded medium carbon steel increases with increase of down feed. The full width half maximum, peak position, derived remanence and hysteresis loop area were insensitive to stress. In addition to, there was no change of phase as well as microstructure upon grinding. It represented that insignificant variation of hysteresis loop area with residual stress because of selection of different range of frequency.[49] A good correlation between BN parameters and residual stress was also obtained upon grit blasting operation on low carbon steel using aluminium grit.[50] A model applied to assess residual stress and hardness with the use of BN measurement. The predicted models are compared with an external validation data.[51] While comparing the study of BN and Metal Magnetic Memory (MMM) testing on low carbon steel, it was noticed that BN depends on time varying magnetic field (external magnetization) generated by excitation coil. The MMM was depended on earth varying magnetic field (self magnetization).The MMM is preferable over BN for its better detection capacity for characterization of specimen.[52]

2.2 Microstructure

While the observation between MBN signal with location of hysteresis loop, two types of magnetising scheme such as U-shaped electromagnet with certain air gap in specimen and solenoid were used. During magnetisation, double peak showed minimum MBN signal at coercivity point and single peak showed maximum MBN signal at coercivity point. Furthermore, it also revealed that RMS voltage increases with increase the gap between two peaks. In order to analyse the microstructure, standard mode of magnetisation was implemented with MBN because of demagnetisation factor.[53] In recent time, BN technique had successfully applied for estimating surface integrity of hard milled sample. In this application, Barkhausen events were consist of block wall movement and white layer thickness of near surface followed by heat affected zone. The white layer structure eliminates poor BN due to compressive stress and microstructure interact with block wall.[54] The variation of hardness and composition occurs while comparing the surface layer of carburised steel with induction-hardened steel using BN technique. It was observed that carburised steel revealed double overlapping peaks in the BN profile, while the induction-hardened steel showed a single peak. The induction hardened steel showed least effect on the surface layer removal. The variation on the microstructure showed minoreffect on peak position.[55]

The comparative study of the magnetic properties of steel using both BN and eddy current methods, shows that increasing the grain boundary density results decrease in permeability and normalized impedance output of eddy current test. This increment of matrensite of dual phase steel leads to increase in BN signal due to increase the dislocation density and internal stress in the ferrite phase. The Barkhausen jumps are having anon linear relation with grain size due to the higher grain boundary density. Both BN and eddy current are sensitive methods to detect and monitor microstructural changes of steels.[56] There are various methods such as BN and Acoustic Barkhausen Noise (ABN) are used to characterize different microstructure of plain carbon steel. A lower ABN activity was found in pearlite due to non-preferred domain walls in the translamellar magnetic microstructure.[57] During the study of BN analysis measurement and characterisation of pure iron carbon binary alloy, observed that value of voltage fall down with the grain size due to number of bloch walls and pinning points. The investigated RMS value is not similar in tension and compression because of the magnetostriction phenomena. The intragranular precipitation develops dispersion magnetic fields leads to increase of the number of jumps and decrease of pinning point result raise of the amplitude of the RMS signal. On the contrary, amplitude of RMS signal decreases and pinning point increases for cementite precipitate.[58] During the tempering on MBE for various ferrite steel such as 0.2% wt carbon steel,2.25 Cr-1Mo steel and 9Cr-1Mo steel. The existence of various types of carbide in the Cr-Mo steels considerably decreases the MBE when it is related with single carbides development in the carbon steel. The MBE peak height raise with improvement of tempering time. In addition, it was recognized that decrease in dislocation density and coarsening of grains results enlarge the mean free path of domain wall displacement. The reduction of peak height leads to decrease the creep strength.[59] From the relations between domain wall and the grain boundary microstructure in pure iron and silicon steel, it was noted that the linear increasing relationship exists between grain boundary of BN and the misorientation angle between two closest grains. The degree of interaction between low-angle boundaries as well as domain walls is comparatively lesser than high-angle boundaries and domain wall.[60] The surface density found in magnetic poles develops nucleation energy in polycrystalline materials. This nucleation of domains of reverse magnetization helps to investigate grain-boundary, lamellar-precipitate and a domain-wall-surface-tension contribution. These calculated parameters result in coercive force in polycrystalline materials.[61]

2.3 Microhardness

When the comparison of hardness with BN signal data obtained from the Jominy test of specimen by both conventional hardness mechanical measurements and acquisitions with a BN testing system. It was observed that the BN is a non-destructive reliable technique to ensure extensive and quick method for evaluation of hardness on steel pipe for oil and gas market.[62] The tempering induced microhardness variation were successfully identified using BN technique.[63] The application of Barkhausen signals is used to detect surface damage of ground part about 200mm thick under controlled situation. The signal changes with hardness measurements were the indication of changes in microstructure.[64] During magnetisation of steel, it was noticed the hardness decreases with increase in depth. The BN signal amplitude increase with tempering. It was noted that the linear relationship between tempering and the BN peak height. The high frequency component represented the interaction between domain wall mechanism and near surface region whereas low frequency component represented the relation between dominant mechanism of domain wall and sub surface region. The BN peak vs hardness at different depth increase with tempering. The higher the BN results lower the hardness due to movement of the domain wall with softening of the microstructure.[65] The plastic strain increase with increase in hardness leads to decrease in MAE and BN. The reverse nature of MAE and BN maintain exponential correlation to coercivity of magnetised material due to increase of dislocation densities.[66] Similarly, BN voltage signals method is used to study microstructure, micro hardness and residual stress of heat treated steel. The increase in integrated frequency spectrum value increases with increase in case depth of specimen. In addition, the maximum depth detection of micromagnetic parameters was observed in the specimen at highest microhardness and lowest relative permeability.[67] The change of potential differential in electromagnetic yoke was also employed to characterize the hardness.[68] While characterizing magnetic properties of terbium doped strontium hexaferrite specimen. It was observed that replacement of terbium ions in specimen, showed significant modification in the structural and magnetic properties of strontium hexaferrite. It was also noticed that increase of amount of terbium in sample improves the coercively value leads to hard magnetic material.[69] The Micro-magnetic method based on BN analysis is a fast, ecological and non-destructive method for measurement of ground gears. The BN analysis is a sensitive technique to identify thermal damages on specimen surface. The BN analysis provides significant advantages over nital etching method.

All the most important BN analysis articles categorization was shown in Figure 2. In this figure, there were three sections were mentioned. The first section narrates the residual stress analysis and the second part explains micro-hardness of the specimen. Furthermore, the third section represents microstructure of the sample.

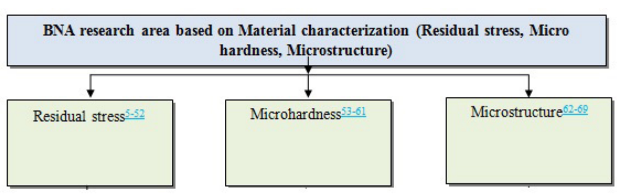

Figure 2. Major areas of Barkhausen Noise Analysis research (corresponding section numbers are in brackets).

3. Conclusion

This review paper identified the information concerned the measurement of residual stress, micro-hardness, grain size and microstructure using an advanced Barkhausen noise analysis non destructive method. Despite various studies and improvement of material characterization using BN technique concluded from numerous research papers, there is a requirement of continuous effort to analyse the depth of measurement of BN analysis which is very low. This may be improved by selecting the proper analysis parameter. The depth of measurement in BN analysis technique depends on strength of applied magnetic field, applied magnetic field frequency and frequency range of band pass filter. Therefore the depth of penetration can be increased by using higher magnetic field strength and very low frequency of applied magnetic field. In addition, the depth of measurement can be increased by selecting the proper high pass filter and low pass filter frequency.

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