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TESTING OF MACROSCOPIC HARDNESS BY ACOUSTIC RESPONSE

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Abstract

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Static measurement of macroscopic hardness (hereinafter macrohardness) of metal materials by using indentation testing is accompanied by deformation in the vicinity of the indenter. Its indenting in a material, monitoring of consequent acoustic response during plastic deformation and interconnection with the records of acoustic emission (hereinafter AE) is the aim of this submitted paper. This non-destructive testing (NDT) method concentrates on the comparison of an acoustic event and the result of the hardness measurement of steels with different hardness values and for a specimen made from steel and tungsten carbide. The aforementioned measurements were conducted concurrently at two workplaces and resulted in very good conformance of records for hard materials. The result obtained confirms the possibility of carrying out correlation between the results of measuring hardness and those obtained from the hits at the acoustic emission testing.

Keywords: measurement of metal hardness, plastic deformation, acoustic emission, deformation response

INTRODUCTION

Visualization of the movement of elastic waves in material used in the field of non-destructive testing for so-called measurements of acoustic emission (hereinafter AE) can be found since the end of twenties century when acoustic responses of mechanical operations for tested material were observed. At present it is possible to find many practical applications of this passive NDT (non-destructive testing) method in the following areas: mechanical engineering, civil engineering, geology, power engineering and biology.

The most frequent use of AE (acoustic emission) can be found primarily in mechanical engineering systems operated with various types of pressure media, furthermore in pieces of equipment and devices as well as in systems working under sustained load the operation of which is monitored in a long term manner or in those whose material changes are reported on a single basis while considering all levels of observation. The required pieces of information are obtained during cyclic loading of parts, thermal and stress loading of a piping and pressure vessels, and in the course of observing bridges as well as whole engineering units, the development of deformation and cracking processes in structural material or as the case may be corrosion degradation) (Machek, 2011; Kopec, 2008).

In examining deformation response for metal hardness measured by applying static indentation test is the main aim to determine the hardness by measuring the depth of indenting of measuring cone (Rockwell test) and its consequent correlation with the corresponding AE record. The stress pulses, the sources of elastic waves in material, are in this case generated by a stress field which is derived from the movement of linear lattice imperfections in polycrystals – dislocations. Owing to their displacements and grouping the dislocations create typical deformation response (Kříž, 2015).

Deformation Reaction – Source of Acoustic Emission

The epicentre of elastic waves arises as a result of a distortion of crystal lattice which is due to the movement of dislocations in real polycrystalline material. Very often is discussed a model of so-called distribution of dislocation loops in inverse space that are thanks to their symmetry compared to the symmetry of distribution of AE signals as a function of deformation size. If it is the case of elastic deformation then the dislocation of an AE signal is also symmetrical. However if it is the case of plastic deformation (the values of external stress applied lie within the range over the yield stress) an asymmetric distribution of signals comes into existence. This asymmetry is described just as mutual interaction (reciprocal effect) of dislocation stress domains namely in consequence of an active internal strain in material grains as a reaction to external force load. Density of moving dislocations is with regard to the distribution of dislocation loops as stated hereinbefore interconnected with plastic deformation so that it is possible to determine even coefficient of material strengthening on the basis of curve form of acoustic emission record. For this reason the AE (acoustic emission) is thus an image of dynamics of dislocation movement. It registers changes of dislocations in elastic area of loading. It brings the possibility of direct monitoring of dislocation activity in material in the course of loading (unlike transmission electron microscope) (Dostál, 2011).

Monitoring of individual lattice defects by mans of AE is conditioned by the possibility of detecting stress waves of higher frequency (over 1 MHz). These pulses propagate through body from the point of their source towards the surface where they are detected by sensors. The amplitude of free surface lies within the interval in order from 10^2 up to 10^4 nm. From the point of view of crystalline lattice it is possible to model material as a system of elements that are elastically interconnected. This approximation (the transformation of elastic bonds) is manifested by bond character during propagation of waves. In the case of an element moving in the same direction as the above mentioned direction of propagation of waves it is longitudinal movement, on the contrary if an element is moving in the direction perpendicular to the one of propagation of waves it is transversal one. In setting elements to oscillate with defined link to the movement of a wave then the total acoustic emission is determined by various types of waves and significant role plays here also so called surface waves (Rayleigh waves). These waves are a kind of transverse waves, nevertheless they are mobile only on the surface of material, and furthermore they have different magnitude of force application in imaginary wave loop (elliptic movement). By their penetrating to the depth of a cross section they die out (Ptáček, 2003; Černý, 2005).

The characteristic of waves as the case may be their velocity depends usually on material characteristics of the environment in which the wave is moving (density, Poisson's number, modulus of elasticity, etc.). In the order presented hereinbefore it is possible to evaluate also the specific velocity of waves (the fastest waves are longitudinal ones the second come transverse ones and surface waves come last). The slab waves –the Lamb's as well as line waves are not considered here as consequence of the fact that they are generated in a body whose volume is limited. Within the frequency interval from 20 kHz to 50 MHz it is possible to consider the longitudinal, transverse and surface waves to large extent being independent on frequency and they are determined by propagation velocity (material property) and their wave length.

In real a material generation of acoustic waves is of different origin. Very instructive is a deformation mechanism from the point of view of detection and processing of an AE signal and namely at the moment of an elastic wave formation. A deformation wave of undisturbed bonds having arisen is moving through its environment, gradually dying, wave energy is decreasing (primarily due to the geometric shape of wave) and with regard to attenuation effect of environment (Boháč, 2014).

In measuring macro-hardness and assessing its AE response it worth mentioning the phenomenon micro-deformation. It describes a plastic deformation within strain transformation whose range is less than one volume percent. This strain transformation is of stress origin and described in a linear deformation manner. It shows an influence of adiabatic process when resulting deformation of the whole volume is within the frame of this so-called anelasticity essentially zero. In this particular case it is the question of increase of deformation over the tensile elasticity limit when internal friction stress necessary for the start of displacement of first dislocations (edge segments) over obstacles with short reach is lower as consequential one on tensile elasticity limit thus real stress defined by first irreversible processes. In characterising anelasticity different mobility of edge and screw parts in dislocations has to be taken into consideration, though. This situation reveals itself by the time of their radical anchoring once reaching tensile yield strength i.e. the moment when the set of dislocations is irreversibly transported and measurable plastic deformation is implemented. These processes accompanying material loading as far as tensile yield stress are declared micro-plastic (Ptáček, 2003).

Deformation is typical owing to its heterogeneity and localization. Anisotropy of the whole volume of polycrystalline material applies (as the case may be anisotropy of individual grains of the material). As a consequence of the increasing external stress the quantity of grains with internal plastic deformation is also increasing. The length of dislocation displacement is decreasing and however their density is increasing. In grains as the case may be in vicinity of their boundaries array of dislocations is being developed which in neighbouring so far unstrained grains accumulates stress resulting in the development of irreversible internal stress i.e. the emergence of permanent plastic deformation. This process represents first phase of micro-plastic deformation. After attaining certain magnitude of external stress in all grains in randomly chosen cross section the plastic deformation takes place and comes into existence. The development of slip bands stops and starts the development of mechanics of macro-plastic deformation (Ludvík, 2002).

Parallel Measuring Hardness and the Detection of Acoustic Emission (AE)

For the purpose of measuring hardness steel specimen of different hardness have been chosen and a specimen made from tungsten carbide (hereinafter WC). The intention has been based on visualization of material deformation at the moment of (indenter) indenting the material being under test thereupon the interconnection of the results achieved by means of measuring steel hardness with final AE record.

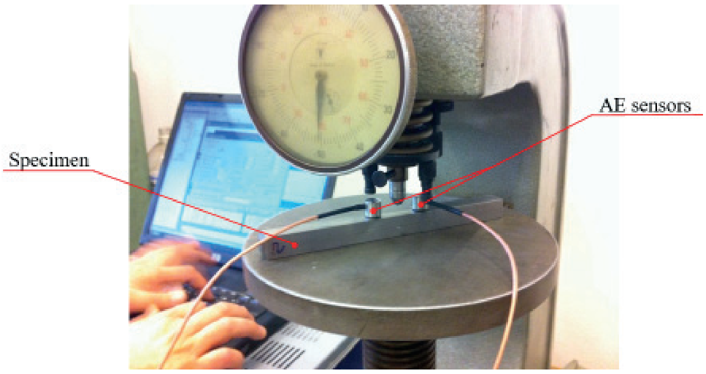
The programme of the pilot measurement was scheduled in two phases which were performed at two independent laboratories, i.e. at the laboratory of ÚTAD AF Mendel's University and at the accredited AE laboratory of the ID FME BUT (Faculty of Mechanical Engineering – Brno University of Technology) in the city of Brno.

For the initial stage of verification that was carried out at the ÚTAD were selected four specimens and two methods of hardness measurement. The first standard etalon was tested by the HRB method from Poldi group where lower hardness value was identified. The detection of AE was conducted by using XEDO Dakel device with 2 pieces of the IDK pick-ups. The pick-ups in question were fixed close to indenter tip (Fig. 1). The indenter indenting into the material being tested was repeated 10 times for statistical reasons. The metal hardness found out as well the impression of the indenter in material being tested brought about a weak response in AE records, though. Symptomatically typical AE measuring certificate for this material is not presented herein with regard to its inconclusiveness (the RMS value is low as well as the number of overshoots).

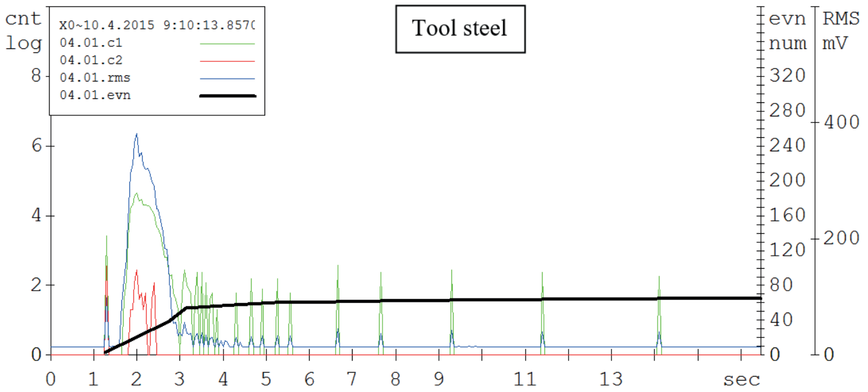
Next i.e. the second material was a specimen made from heat-treated alloy Si-Mn steel which is used for the purpose of evaluating wear tests. Its hardness was determined approx. 94 HRB. Although in the AE records the (RMS) values of acoustic energy emission increased but the number of singular events as well as that of overshoots over pre-selected levels for all measurements (10 measurement) was not even in this particular case remarkable. The events had negligible duration time and moreover their occurrence rate was also low. This record is not presented herein.

The third material put to a test was tool steel. Its hardness measured by HRC attained values approx. 64 HRC. Together with the increased hardness of material being tested and the application of different indenter geometry the acoustic emission characteristic changed significantly (Fig. 2, Fig. 3). There was an increase both in RMS level and in the number of events detected tending to rise in their frequency at the moment of the indenter having been indenting into material being tested and slow attenuation of force at applying supplementary load (Fig. 3). The acoustic emission signal for this particular specimen already has its characteristic and clearly readable shape. The shape of the AE signal in the records for all hardness measurements is apparent and it is for all of them approximately identical. Step-like character of a record corresponds to the period of material strengthening and damage of the deformation barrier by the indenter. In the last measurement there was longer time let for the purpose of detecting records of gradually coming to an end within the range of minutes and gradual release of dislocation barriers is clearly manifested.

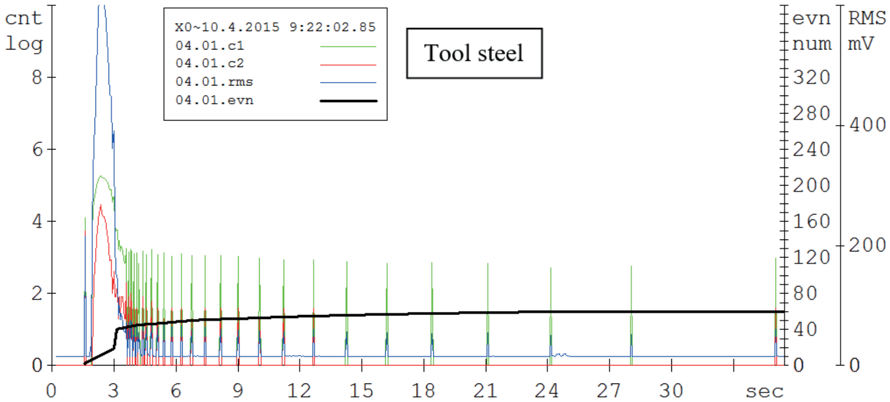
The last selected material was tungsten carbide (Fig. 4). For carbides or as the case may be ceramics there is in professional literature recommended measuring system HRA, nevertheless because it would have again represented a change of the input terms and conditions for the start forming acoustic emission signal recording the HRC conditions were accepted also for this specimen with the highest harness to be tested. The hardness of tungsten carbide (WC) was determined approximately 80 HRC. There was an increase in the number of overshoots across monitored levels and also the RMS value increased significantly in the course of whole test.



1: *Location of AE sensors on a steel specimen during measuring Rockwell hardness*
Source: author

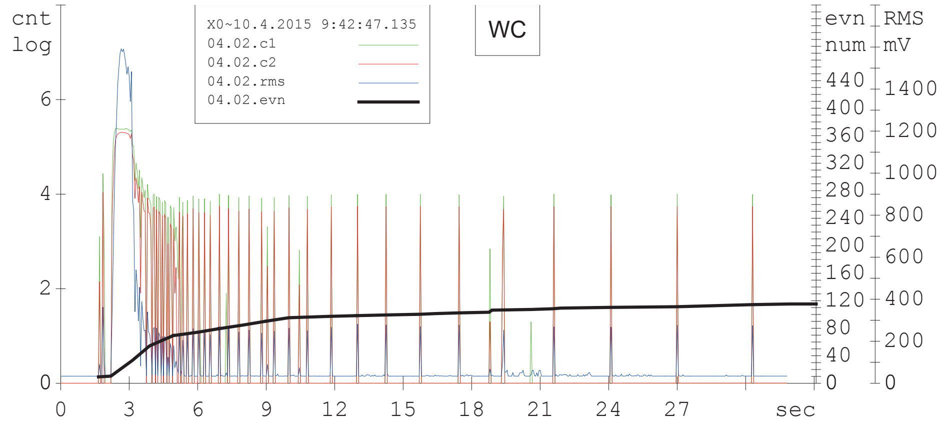


2: *Typical AE record in the spot of easier indenter penetration (value 63,1 HRC) with clear step-like fading away record of overshooting levels*
Source: author

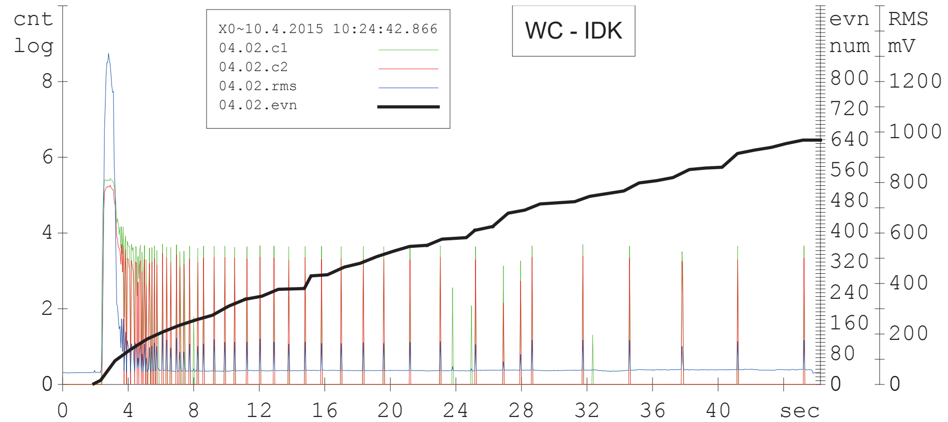


3: *Symptomatically typical appearance of the AE record in so-called place with locally increased hardness, noticeable is not only decrease of event frequency but also number of overshoots across pre-selected levels*
Source: author

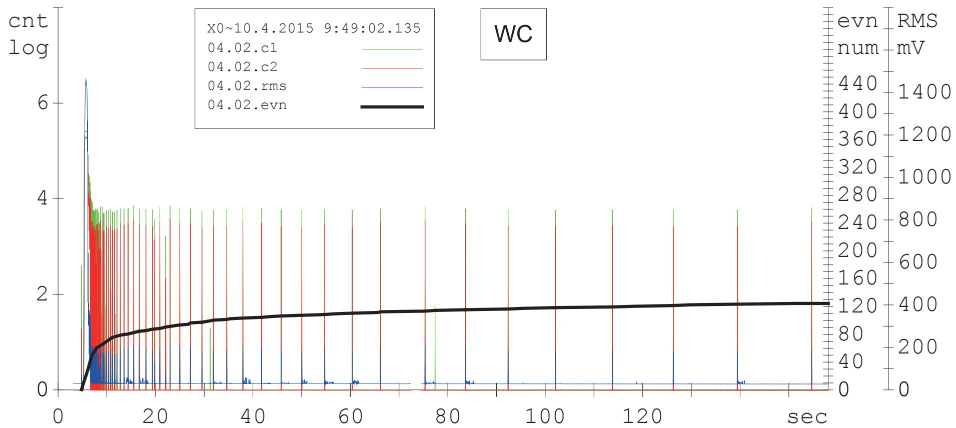
4: *Detail of pick-ups and head of the HRC indenter during tungsten carbide measurements (WC)*
Source: (ID FME BUT)



5: *Gradual barrier surmounting while the indenter indenting the material being strengthened by this process with the effect of material inhomogeneity, sensor MIDI*
Source: author



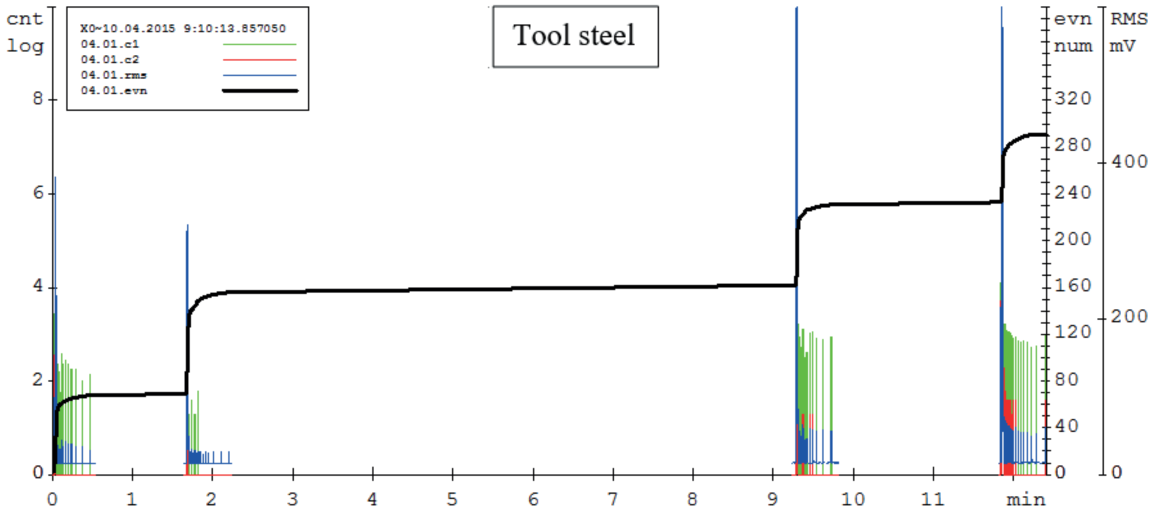
6: *Sensor IDK exhibits growth of RMS in the course of a hit (presence of a spot with weaker signals is apparent for tungsten carbide (WC))*
Source: author



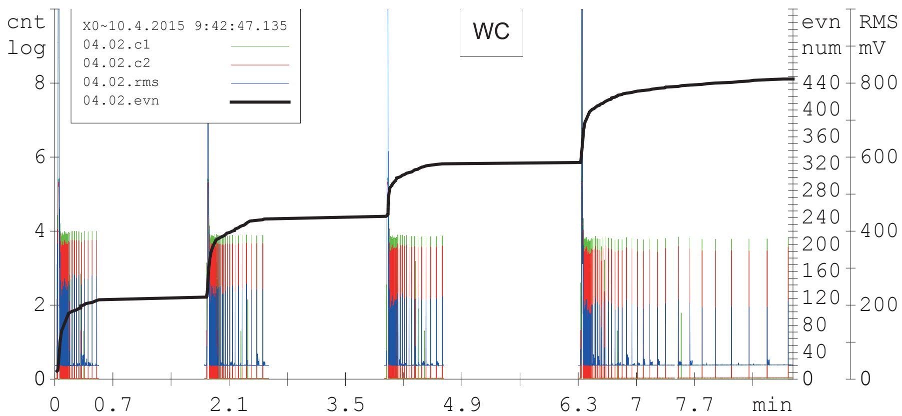
7: *Prolonged record confirms the identity of behaviour including so-called weak spots in carbide (area of bonding material)*
Source: author

After confirming correctness of the AE measured response as for micro-plastic deformation in material at the ÚTAD, the second measurement was performed at the accredited AE workplace of ID FME BUT (Faculty of Mechanical Engineering, Brno University of technology) in the city of Brno. Verification has been conducted only for hard specimens (tool steel and tungsten carbide WC); the measurement was again exercised by using HRC scale. All specimens were remeasured by means of the identical pair of sensors IDK with corundum surface from Mendel's University. At ID FME BUT (Faculty of Mechanical Engineering, Brno University of Technology) it is worth mentioning that the hardness tester used was newly calibrated. So the hardness results obtained can be taken for considerably accurate.

In addition to hereinbefore the aim was to find out time when measuring equipment detects AE sources and which are damping down. As long as time period of 140 seconds the overshoots were noticeable across both of monitored levels with characteristic RMS value. After series of validation measurements conducted with MIDI sensors (Fig. 5) a change of MIDI sensors for the IDK ones was carried out (Fig. 6) it should be pointed out that the MIDI sensors were those used at Mendel's University during the first phase of measurement. The tungsten carbide (WC) again produced higher RMS values and higher signal density in time even at longer time interval of detecting (Fig. 7). The IDK sensors qualified at the measurement of metal specimen higher sensitivity as the case may be different characteristics of individual events. However the values of the number of events as well as the RMS values remained alike to those obtained with the MIDI sensors. In the last measurement was applied longer time interval for recording running out events while the indenter was being unloaded. (Fig. 8, Fig. 9).



8: *Decay of a deformation response while the indenter is being unloaded (tool steel)*
Source: author



9: *Appearance of the record while the indenter unloaded in tungsten carbide (WC) exhibits regular groups of acoustic signals (relaxation of strain in the material of sintered carbide)*
Source: author

The Results Are Affected by the Following Items

Methodology of HRB measurements – the methodology of HRB measurement hereinbefore has not proven progressive for the following reasons: indenter shape which is a steel ball (with reference to larger surface of impression) due to the fact such initiation of microplastic deformations does not occur as it is the case with conical indenter; it implies that AE sources are diminishing (i.e. those that could be related to the value of hardness) and the scope of a test which is limited by the compressive force 980 N and right from the very beginning of the range the deformation of material caused by the indenter may negatively and in a distorted manner manifest itself. The HRB is in this way apt for measuring soft material as well as medium-hard materials. For further practical measurements and the development of a new methodology for measuring hardness by means of applying acoustic emission (AE) is the HRB inappropriate.

Methodology of HRC measurement – considering the conical shape of the indenter which is able owing to its material and geometrical shape resist to load forces at great friction occurring between material and the indenter tip, while low indenter deformation which could distort AE responses significantly – the methodology HRC has proven appropriate for correlative measurements of hardness and acoustic emission (AE) for the reason of great range of measurements of hardness up to the force 1471 N (up to 100 HRC).

Influence of the structure of tested material – influence of porosity and homogeneity on the development and frequency of a discontinuous signal at supplementary loading after indentation. In acoustic spectrum i.e. originally wave spectrum homogeneity of the martensitic matrix manifest itself the matrix is made of martensitic packets (+ remaining austenite) in comparison with inhomogeneity of tungsten carbide which is dissimilar to mechanical continuum and where the main originators of material hardness are extremely hard particles which are imbedded in bonding material. Penetration of the indenter cannot be exactly specified since it is not possible to define unambiguously from microview the direction of the movement of the cone in martensite and the possibility of bonding material deformation.

Influence of a sensor – for the purpose of measurement of microdeformation response at the measurement of hardness of metals by means of the HRC it proved to be more suitable to make use of conventional sensors Dakel IDK - 09 with corundum surface. The sensors of MIDI type exhibited lower sensitivity in the course of measurement. In passing over the influence of bonding material it is obvious that corundum surface of the sensor IDK - 09 is in the course of measurement of hardness of very hard materials by virtue of its capacity of resistance more related than stainless steel surface of the MIDI sensor.

DISCUSSION

It is evident that the correlation between material hardness and acoustic emission response is influence by the hardness and structure of tested material. The harder material the stronger, more readable a more regular is acoustic emission response. The main assessed and evaluated variables were the following: signal energy – RMS which was proportional to hardness i.e. the higher signal energy the higher hardness and another important indicator – the number of overshoots and total cumulative quantum of events.

Together with increasing material hardness and thereby causing rise of indentation resistance, which results in increase of discontinuous signals of AE with very regular attenuation. This trend according to measurements performed corresponds the value of measured material hardness regardless of current precision of measuring device and in accordance with occurrence of these events (as the case may be frequency) there would be possibility, however for statistically more significant measurements, to determine hardness scale depending on the value of these discontinuous signals.

Correlated value between hardness and acoustic emission response is also initiation amplitude RMS in the moment of indenter indentation into a body which is increasing in dependence on increasing material hardness and is rising even in the course of discontinuous signal during indenter being supplementary loaded while the indenter is moving in the structure of measured material. Discussed the influence of structure homogeneity possible porosity or presence of soft inclusions is a theme for distinctiveness of measurements from microview. This aspect may be quite unambiguously eliminated considering rising number of hardness measurements when statistical evaluation will necessarily prevail.

Correlative question is also the recommendation of time relation of measurement, the evaluation of signal shapes from the point of view of presence of elastic deformation – anelasticity which is likely the function of the structure of measured material and the internal stress. It is certain that from this point of view there will be difference between measurement of hardness by using acoustic emission (AE) for materials of different technological origin – casting, metallurgical half-finished product, forged piece and a product of powder and pseudo-powder metallurgy and consequently its heat treatment. Detailed analysis of the signal shape, overshoot rate across individual levels, RMS rise as well as overall shape of hits is feasible after attaining statistically significant set of measurements by using defined methodology for acoustic emission measurements (AE).

CONCLUSION

The result as stated hereinbefore presents the interconnection of both areas (the area of destructive and nondestructive) material testing based on presentation of theoretical pieces of knowledge from the field of measuring hardness as the case may be material deformation and detail definition of conditions for recording wave response of the material being tested in the course deformation while subject to test and applying the methodology for measurements defined by international standard – indenter penetration within the scope of so-called Rockwell test.

There is a description of the principle of initiation of acoustic waves at the movement of dislocations during plastic deformation which follows after the development of elastic deformation at the moment of the indenter indentation and process of their detection from the surface of the measured material by using professional sensors of acoustic emission (AE).

Theoretical part supplemented by a pilot measurement that for the reason of objectiveness was conducted at two independent workplaces (Mendel University in Brno – Department of Technology and Automobile Transport and Brno University of Technology – Institute of Engineering Design, accredited workplace Czech Society for Nondestructive Testing). All measurements performed unambiguously exhibit the possibility of progressive using acoustic emission (AE) for measuring hardness (so far conditioned by professional definition of input antecedences of measurement). After making provisions for above stated input edge conditions it is more than realistic verification of material hardness primarily for harder material systems (over 60 HRC) in engineering practice and that is to state regardless of accuracy (i.e. calibration) of measuring equipment for the determination of macro-hardness.

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