Character of Acoustic Emission signal generated during Plastic Deformation

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Abstract
The paper brings present findings based on experimental results. During plastic deformation the signal of acoustic emission (AE) has special character. That can be called as white noise with low energy. That is why it is necessary to carefully eliminate all disturbing electromagnetic as well as vibration sources. The potential solution is utilization of suitable sensor or working frequencies. The experiment consisted of individual amplitudes measurements and subsequently analyzed the influence of surface layers monitoring. Experimental samples for AE were made from steel and magnesium alloy. It can be concluded that the surface layer has a great influence in the form of shear bands that are responsible for AE signal. In the case of magnesium alloy, considerably stronger amplitudes were detected compared to other materials. This AE activity is caused by the presence fragile β phase in the structure of Mg alloys. The paper also discusses the influence of grain size on AE signal.

Keywords: AE resonant transducer, amplitude analysis, white noise signal, surface layer, dislocation pile ups, fragile β phase

1. Introduction

In the 1950s years it was reported by Kaiser that upon tensile loading of a tin bar, a great deal of audible noise was evident [1]. In his interpretation as the source of this sound was the plastic deformation (twinning) and he called this signal acoustic emission (AE). While the use of this method has been given to great importance in fracture mechanic, corrosion cracking or machine health monitoring, the monitoring of plastic deformation was the subject of minor interest. Signal is in the principle generated by sudden changes in the structure of material. AE during plastic deformation is based on occurrence of signal induced by sudden structural changes. Such typical changes may be for example mass movement of dislocations or twinning [2-5]. Characteristic of the signal in the formed materials depends apart from material properties (hardness, breaking strength, toughness...) also on testing conditions (deformation speed, temperature, friction...). Great potentialities AE are in the description of this process as well as in the indication and recovering of possible discontinuities and abnormalities in situ. Examples of the application for forming sheet metals have been published [6-9]. The results of this application can be used for evaluation of the level of lubrication (deep drawing). The described experimental technique has been applied to other forming technologies, for example for forging [10].

The criterion for detectability AE is according to work [11] the relationship (1)

\[ naV \geq 0.035 \text{ m}^2\text{s}^{-1} \]  

where \( a \) is the radius to which the loop expanded before arrest at pinning point, \( V \) is the radial velocity, \( n \) is number of dislocations involving in the cooperation motion. When the value \( a = 10^{-7} \) the product \( nV \) will be greater than \( 3 \times 10^5 \text{ m/s} \). This is an unlikely value regarding to estimates published for example in [12].
The aim of the paper is to summarize the issues relating to the AE during plastic deformation. Further to specify the limits and conditions under which a detectable signal is generated and to carry out the discussion about the application possibilities of this method in technical practice.

2. Experimental

It is very difficult to detect AE signal, during plastic deformation of fine grain metal material with high level of deformation, using commonly manufactured experimental equipment. These materials can include low carbon steels (for example containing 0.2% C). Wide band or resonant commonly manufactured sensors are not able, even with the amplification the signal in electronic chain, detect homogenous plastic deformation. The experimental procedure based on using accelerometers working on their “sharp” own resonant frequency was proposed in [13]. As it turned out, very useful is to use the accelerometer Brüel & Kjaer 4335 working on its own resonant frequency 65 kHz. Output from sensor was led to input of 2 stage selective amplifier working on frequency 65 kHz. After amplification the signal was sorted into two groups. One counter Tesla counted up all the pulses greater than 150 mV+ in + polarity on its input. Second counter Tesla counted up all the pulses greater than 300 mV+ in + polarity on its input. Outputs from both counters were in digital form. In order to register the outputs from counters, on measuring tape recorder Bell & Howell, the digital signal from counters was converted into analog form using D/A converter. For the record of loading was used output from load cell, which is the part of tensile test machine Instron 10t. The all experimental assembly is pictured on Fig.1.

![Experimental assembly for monitoring AE during tensile test of low carbon steel](image)

Description:
1. Tensile test machine Instron 10t
2. Load cell
3. Test specimen
4. Teflon fixture
5. Accelerometer Brüel & Kjaer 4335
6. Selective amplifier 65 kHz
7. Counter Tesla (2X)
8. D/A converter
9. Measuring tape recorder Bell & Howell
The measuring assembly was further improved. First aim was to extend the possibility and accuracy of amplitude analysis and second to extend the space for data archiving. The new system EMIS_01 enables the sorting of signal into seven amplitude windows. Practically unlimited on-line time measurement guaranteed connection with notebook. The advantage of system is sampling in short time interval without the lost of total background. The output from sensor, after amplification and frequency filtration, was led to preamplifier and then to data acquisition unit EMIS_01. In this unit carried out further amplification and distribution into seven amplitude windows. Digital processing was performed after analog processing in this unit. Counts rate at one second interval and time arrival for events are outputs, which are recorded on notebook. The system enables recording seven analog inputs such as temperature, pressure, displacement, strain etc. During monitoring plastic deformation was recorded output from load cell. The all experimental assembly of upgraded system is shown in Fig.2.

Two materials have been selected for experimental investigation. First low carbon steel with composition 0,20% C, 1,05 % Mn, 0,30 % Si, 0,035 % P, 0,038% S, 0,19 %S and second Mg alloy AM60 with composition 0,09% Zn, 6,00% Al, 0,03% Si, 0,001% Cu, 0,29% Mn, 0,003% Fe, 0,001 %Ni, 0,008 Be. Both materials were treated differently. Low carbon steel was hot forged, Mg alloy AM 60 was in cast condition without any following treatment.
3. Results and Discussion

Typical record of one of tensile tests from low carbon steel is shown on Fig. 3a and 3b.

The dependence mechanical stress and counts rate on time at the constant crossbeam speed is shown in the both figures. Counts rate of all pulses which are crossing adjusted level 150 mV⁺.
in + polarity on counter input is recorded in Fig. 3a. In this case, all amplitudes including those with very weak amplitudes on transducer output are registered. Other situation is evaluated in Fig. 3b. The counter counts of all pulses which are crossing adjusted level 300 mV+ in +polarity. The pulses with amplitude under 300 mV+ were not registered, just strong signals. The comparison both figures confirms the well – known fact, that during homogenous plastic deformation, low carbon steel produces very week signal. The character of this signal is similarly near to white noise. The counts rates on Fig. 3a achieve values over 20 000 counts/s, unlike pulses with amplitude higher than 300 mV+ on Fig. 3b don’t achieve value 750 counts/s either before failure.

Detection of white noise signal with accessible experimental equipment in our circumstances is practically impossible. Thanks modified experimental equipment, working on „sharp” resonant frequency of accelerometer Brüel & Kjaer 4335 and with new design mounting fixture, the background noise was depressed and sensitivity of detection was increased. Now it was possible to detect the movement dislocation bands in this test specimen. The sensitivity of detection was estimated on approx. 95 – 100 dB.

The next factor, which has very strong effect on AE signal are processes in surface layer or in its vicinity. In a series of publications, Kramer and others have emphasized the importance of the surface layer on the plastic deformation of metals [14-19]. During plastic deformation a surface layer is formed which serves as a barrier to dislocation movement. Dislocation pile-ups increase the dislocation density near the surface. Removing the surface layer and the associated pile up of dislocations permits recovery of certain mechanical properties. By removal of surface layer the changes were observed in work hardening coefficients, in stress corrosion cracking and in fatigue live. Sudden rising of counts rate near the yield point on Fig.3a should be induced from the movement of a lot dislocation bands. These bands form the file up barrier under the surface. Dislocation density rises in surface layer, but this process does not run continuously, at increasing loading the drops in counts rate occur (see Fig.3a) and simultaneously higher values of counts rate of greater amplitudes are recorded on Fig.3b. Occurrences of counts rate greater amplitude in Fig.3b and drops in record of counts rate lower amplitudes on Fig.3a are in good correlation. The tensile test in the end is influenced by deformation instability due to in changes cross section of the specimen. Greater values of counts rate before breaking the specimen on Fig.3b are probably the result of micro cracking and cracking processes.

AE was applied to monitoring tensile tests of Mg alloys AM60. During tensile tests of these Mg alloys, ordinal difference in comparison with the low carbon steel was detected. Plastic deformation of Mg alloys in cast stage is accompanied by an energetic very strong signal AE (see Fig.4). This phenomenon allows use the lower sensitivity sensors and lower level of amplification signal being detected in comparison with low carbon steels. The reason is probably the different condition of material from which both test specimens are manufactured. Low carbon steel was hot forged hence a significant change of microstructure was done. Dendritic structure transformed itself into grain structure and during forging the size of grains was reduced to range some units of micrometers. Particle grain structure is probably one reason of great difference in counts rate between low carbon hot forged steel and Mg alloy AM60 in cast condition. This conclusion is confirmed by the some published studies [20]. Strain rate is next parameter, which has great influence on the level of emitted AE signal [21]. Reduction of strain rate causes a significant reduction of emitted AE signal. The crossbeam speed had approximately the same value therefore this parameter could not affect the comparison.

Both specimens confirmed the fact that the maximum of counts rate is somewhere near the yield point, after this point the value this parameter falls. This behavior is documented also for
pure metal with FCC grid [22-26]. This reduction of AE activity is contributed to the influence of secondary induced barriers to the movement of mobile dislocations.

Note: AE – Counts rate 1 was evaluated for all amplitudes greater than 30µV_p on sensor output
AE – Counts rate 3 was evaluated for all amplitudes between 120µV_p and 240µV_p on sensor output

Fig.4

The significant activity of strong energy signal AE after yield point is shown on Fig.4. In addition to the described effect of grain sizes there is also the influence of secondary phases (see Fig.5).

Fig.5 Microstructure of Mg alloy AM60

Secondary phases distinctly separated on the borders of grains are characterized by great fragility. Morphology of these phases is significantly altered under deformation during tensile test. It is considered that cracking of fragile phase β in alloy AM60 significant contributes to
high value of counts rate and also to low differences in amplitude distribution of AE signal. The changes in morphology phase $\beta$ should be, with the great probability, the main factor causing the constant value of counts rate after overcoming yield point. Compared to the steel being tested we do not see drop of the signal in this area. The difference in mechanical properties exists obviously between these two stages. The steel being tested acquires tensile strength approx. 275 MPa, while Mg alloy AM60 acquires approx. 160 MPa. At the same time the forge-ability of Mg alloy is inconsiderable in comparison to the steel test specimen.

4. Conclusions

The results of tensile tests, simultaneously monitored by AE confirmed influence of grain size and forming stage on AE-signal level. Homogeneous fine grain structure generates AE signal on low energetic level during plastic deformation, which is similar to white noise. Such signal is possible to detect, using resonant sensors (accelerometer) working on its “sharp” resonant frequency. Accelerometer’s output is processed in selective preamplifier and then the signal from its output is led to counter input. All electronic chain is adjusted on resonant frequency of transducer.

Ordinary higher values of counts rate were monitored from beginning of tensile test by coarse grained Mg alloys. The pulses amplitude achieves maximal values near the yield point. It was confirmed that great differences exist in the character AE signal between coarse grained materials and ultrafine grained materials (UFG). The signal from UFG materials has not burst character in contrast to coarse grained materials. For both group of materials the AE signal during plastic deformation is irreversible [1]. The significant influence of surface layer on this effect was proved in [27]. After removal of surface layer, similar AE to original test was observed during reloading [27]. The aim of this work is to identify limit of detectability by UFG materials. Great plastic deformation during forming causes great increasing of hardness and strength. From this reason the hardening during subsequent tensile test is not apparent. The fragile phase $\beta$ is the main source AE signal generated from Mg alloy AM60 after its yield point. The proportion between the signal from dislocation bands and signal from cracking phase $\beta$ could be probably evaluated from the amplitude distribution of AE signal.

The sensitivity AE method on structure stage and on forming stage can be used for design of simple technological tests. The experience from tests will serve for source analysis during hydrotest and for preparing method for on line monitoring exposed machinery parts.

Acknowledgments

This paper was created in the project No. CZ.1.05/2.1.00/01.0040 "Regional Materials Science and Technology Centre" within the frame of the operation programme "Research and Development for Innovations" financed by the Structural Funds and from the state budget of the Czech Republic.
References