Study of Plastic Deformation of Metals Using Acoustic Emission

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Abstract. In the paper experience with monitoring of acoustic emission (AE) during plastic deformation of low-carbon steels, aluminum alloys, magnesium alloys and copper is summarized. Methods for scanning and processing of signals are evaluated and compared according to their different character (a continuous signal compared to a discontinuous one occurring in a material with defects). A continuous processing method, the signal in which is assorted to seven amplitude windows, is compared to a common discontinuous signal processing method, individual hits in which are recorded. From the measured results is evident that characteristic parameters of the signal are dependent on the structure of the material, character of surface layers, residual stress and the way of loading. All the mentioned features are of a direct influence on deformation processes dynamics, therefore on the amplitude and frequency of the detected AE signal. An obvious change occurs for cracks origination and propagation. To design technological tests it is necessary to take in account all the above mentioned influences. In the paper a process of monitoring of relaxation processes efficiency after forming of copper using AE is described. In conclusion, other possibilities to monitor deformation processes using the AE method are discussed.

Keywords: Thermocouple Fe-Ko, excess energy, AE resonant transducer, amplitude analysis, white noise signal, surface layer, dislocation pile ups, fragile β phase

1 Introduction

As AE are determined elastic waves, which are released during sudden changes of induced stress in material. These changes are caused by plastic deformation in metals, crack formation and propagation, phase transformation, changes in internal stresses etc. First was this phenomenon observed by Kaiser upon tensile loading of tin bar [1]. The source of audible noise was intended plastic deformation (twinning). The released elastic waves are essential generated as excess energy, which is not consumed during own (proper) process. The excess energy should be, besides elastic waves, emanated as temperature. Some experiments were done in 70th years in our institute on CT specimens. The many thermocouples (Fe-Cu) were fastened in defined steps along to fatigue crack propagation. There was recorded small temperature rising, which was slowly sinking after propagated crack was moving away. Surprising result was indication of elastic waves as pulses with high frequency, similarly as by detection using piezoelectric sensors. It must be proved if sources of these pulses are temperature or electromagnetic interference.

In the 1950s years it was reported by Kaiser upon tensile loading of tin bar, a great deal of audible noise was evident [1]. In his interpretation as the source of this sound was intended plastic deformation (twinning) and he called this signal as 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. The excess energy, which transform into elastic waves or temperature, depends in great deal on the character of support energy to all physical processes. In the case if a great amount of energy by high speed is supported, the level of excess energy will be very high. The AE signal depends from this reason for example on stiffness of testing machine [2]. The signal is in 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 movement of dislocation piles or twinning [3-6].

Characteristic of the signal in the formed materials depends among others on material properties (hardness, breaking strength, toughness...) also on testing conditions (strain rate, temperature, friction...). Great possibilities of AE are in the description of process and also in indication and recovering of possible discontinuities and abnormalities in situ. There are published several examples of the application for forming sheet metals [7-10]. The results of this application can be used for evaluation of the level of lubrication (deep drawing). Described experimental technique has been also applied to other forming technologies, for example for forging [11].

The criterion for AE detectability is according to work [12] given by relationship (1)

$$naV \geq 0.035 \text{ m}^2\text{s}^{-1} \qquad (1)$$

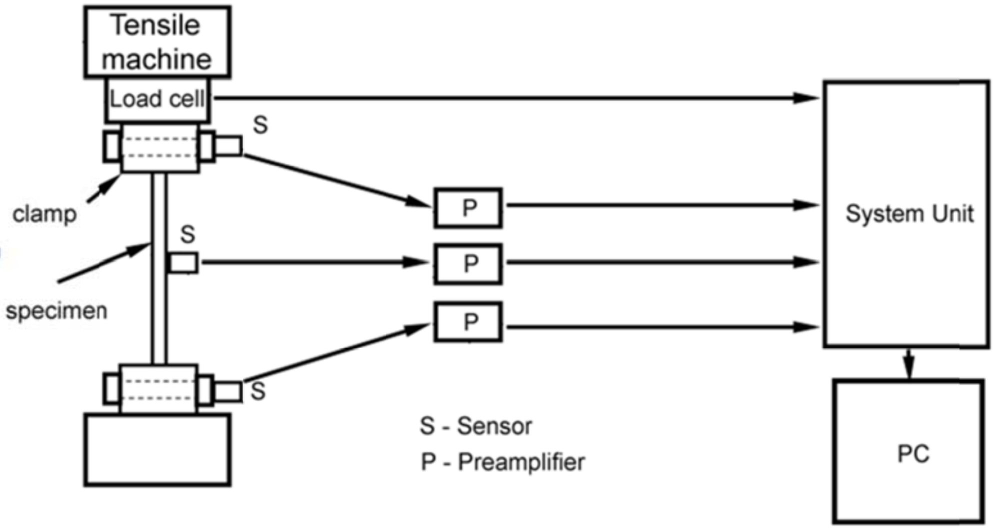
where a is the radius to which the loop expanded before arrest at pinning point, V is the radial velocity, n is number of dislocations involving the cooperation motion. When the value $a = 10^{-7}$ product nV will be greater than 3×10^5 m/s. This is the unlikely value relative to estimates published for example in [13].

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

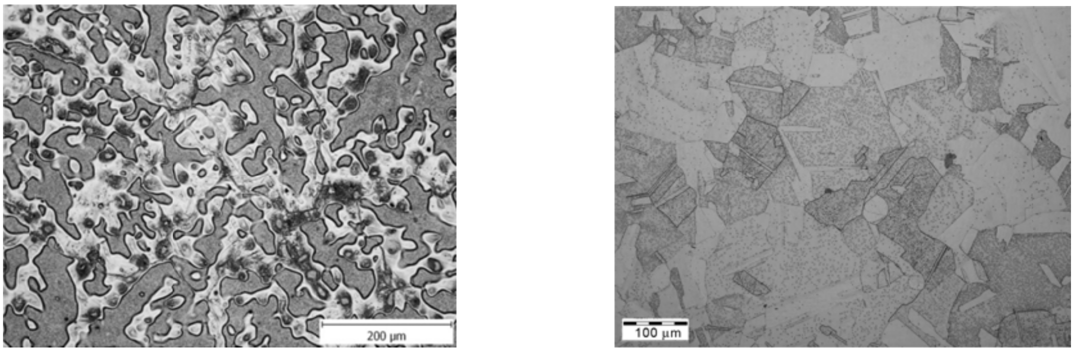
It is very difficult to detect AE signal, during plastic deformation of fine grained metal material with high level of deformation, using commonly produced experimental equipment. These materials can include low carbon steels (for example containing 0.2% C). Wide band or resonant commonly produced sensors are not able even the amplification the signal in electronic chain, to detect homogenous plastic deformation. The experimental procedure based on using accelerometers working on their “sharp” own resonant frequency was designed [14]. 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 mVp^+ polarity on it inputs. Second counter Tesla counted up all the pulses greater than 300 mVp^+ polarity on it inputs. Outputs from both counters were in digital form. In order to register the outputs from counters, on measuring tape recorder Bell &Howell, 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. In order to improve and to extend the possibility of measuring system the system was upgraded. This was done by upgrading additional components necessary for increasing the accuracy of amplitude analysis and for extending the space for data archiving. New system EMIS_01 enables the sorting the signal into seven amplitude windows. Practically unlimited on-line time measurement was guaranteed by direct connection with notebook. The advantage of system is sampling in short time interval without the loss 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 was carried out further amplification and distribution into seven amplitude windows. Digital processing is 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. System enables recording seven analog inputs such as temperature, pressure, displacement, strain etc. During monitoring of plastic deformation the output from load cell was recorded. Whole experimental assembly is drawn on Pic.1.

Detection of white noise signal with accessible experimental equipment in our circumstances is practically impossible. Thanks to modified experimental equipment, working on „sharp" resonant frequency of accelerometer Brüel&Kjaer 4335 and with newly designed friction, background noise was depressed and sensitivity of detection was increased. It was possible now to detect the movement of shear bands at this test specimen. The sensitivity of detection was estimated on approx. 95 – 100 dB.



Pic.1 Experimental assembly for monitoring AE during tensile test of Mg alloy (upgraded system)

Two materials have been selected for experimental investigation. First an Mg-Al-Zn 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 and second commercially pure Cu (99,97%). Alloy AM 60 was in as cast state without any following treatment. On the other side copper was in initial state defined by previous manufacturing history of forming and final heat treatment. Microstructures of both are depicted in Pic. 2a, b. The experiment was aimed on the mutual comparison of both materials. Main interest was paid on investigation of different phenomenon that is responsible for individual behavior of material.

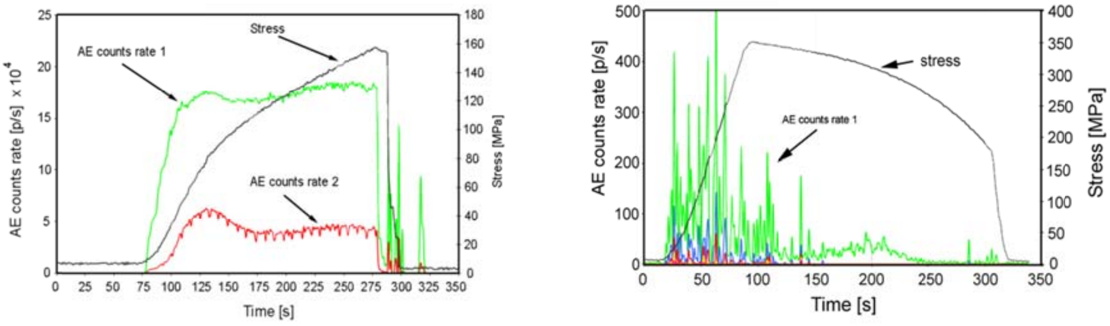


(a) (b)

Pic.2 Microstructure of investigated materials: (a) AM60 alloy (b) copper

3 Results and Discussion

AE was applied to monitoring the tensile tests of Mg alloys AM60. During tensile tests of these Mg alloys the ordinal difference in comparison with the copper was recorded. The dependence between mechanical stress and counts rate on time at the constant crossbeam speed is drawn on the Figure 3. Counts rate of all pulses which are crossing adjusted level 150 mVp^+ polarity on counter input is recorded on Pic. 3 (green curve - counts rate 1). In this case, there are registered all amplitudes including those with very week amplitudes on transducer output. Other situation is evaluated by counts rate 2 (red curve). The pulses with amplitude under 300 mVp^+ were not registered, there were registered the strong signals only. The mutual comparison between both curves confirms the well – known fact that during homogenous plastic deformation of Mg alloys a very strong signal is generated. The counts rate on Pic. 3a achieves values over 200 000 counts/s, unlike pulses with amplitude higher than 300 mV_+ on Pic. 3a do not achieve value 75000 counts/s in early states of plastic deformation. There can be clearly seen steady state behavior of the curve in spite of the fact that plastic deformation is still continued (stress is rising). As a potential reason for this behavior is the factor of microstructure arrangement.



(a) (b)

Pic.3 Dependence of stress and AE behavior for (a) AM60 alloy (**b**) Cu

Plastic deformation of Mg alloys in cast state is accompanied by an energetic very strong signal AE (see Pic.3). The significant activity of strong energy signal AE after yield point is shown on this figure. In addition to the described effect of grain size the presence of secondary phases was established. Secondary phases clearly segregated in the Mg matrix are characterized by great brittleness. It can be recognized that in microstructure of AM60 there is a lot of places where intermetallic phases are localized (see Pic.2a). As a consequence, during any plastic deformation will be these places weakest regions in view of homogenous plastic deformation as well as cohesion strength. During plastic deformation (tensile test) will be intermediate phases broken into smaller aggregates which will influence next deformation behavior of alloy. Morphology of these phases is significantly amended under deformation. It is considered, that cracking of brittle phase β in alloy AM60 contributes significantly to high value of counts rate and also to low differences in amplitude distribution of AE signal. The changes in morphology phase β should be, with the great probability, main factor causing constant value of counts rate after overcoming yield point.

The AE signal is obvious already form the point where plastic deformation starts. On the other hand AE maximum is placed into the area of stress-strain curve slope change. This finding is very probably connected with the fact of the occurrence of another deformation mechanism. This is supposed by lighter growth of stress in next stages of tensile test. Very probably is (at least in early stages of plastic deformation) the plastic deformation caused by twins present in microstructure (the lack of suitable slip planes).

This phenomenon allows using the lower sensitivity sensors and lower level of amplification signal being detected in comparison with copper. The reason is probably different microstructure arrangements. Copper was heat treated after rolling (manufacturing procedure), when a significant change of microstructure was done. The dendritic structure transformed itself into grain structure with many twins (sees Pic. 2b). Particle grain structure is probably one reason of great difference in counts rate between copper and Mg alloy AM60. On the contrary to previous case during tensile test of Cu the highest activity of AE was detected in early stages of deformation (up to sample necking). As can be compared counts rate between both cases cannot be compared. AM 60 alloy embodied considerably higher rate (by factor 100) than Cu (maximum is approx. 500 counts/s). Next difference is in subsequent decreasing of AE activity for copper. While in the case of AM60 the certain decrease was detected in the case of Cu significant decrement is evident there. As a potential explanation the change of deformation mechanism can be considered. It is known that deformation twinning mechanism prevails in low temperature and low to moderate strains mode when is combined with conventional slip.

Other factor which must be taken into account is the influence of surface layers. This 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 [15-20]. 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 with it the pile up 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 life.

These conclusions are confirmed by several published studies [21]. Strain rate is next parameter, which has great influence on the level of emitted AE signal [22]. Reduction of strain rate causes a significant reduction of emitted AE signal. The crossbeam speed had approximately the same value, therefore cannot be comparison by this parameter affected. This behavior is documented by pure metal with fcc lattice [23-27]. This reduction of AE activity was probably caused by influence of secondary induced barriers to the movement of mobile dislocations. Sudden rising of counts rate near the yield point should be induced by the movement of dislocation bands. These bands form the pile up barrier under the surface. Dislocation density rises in surface layer, but this process does not run continuously, by continuing loading the drops in counts rate occur (see Pic.3a) and simultaneously higher values of counts rate of greater amplitudes are recorded on Pic.3b. Occurrence of counts rate greater amplitude on Pic.3b and drops in record of counts rate lower amplitudes on Pic.3a is in good correlation. The tensile test at the end is influenced trough deformation instability by cross section changes. Greater values of counts rate before breaking the specimen on Pic.3b are likely due to the response on micro cracking and cracking processes.

4 Conclusions

Plastic deformation processes of metallic materials have significant influence on forming and fracture behaviors of metallic products. AE is method, which should bring new approaches to material quality evaluation. During the tensile tests, simultaneously monitored by AE, signal is influenced from surface layer, residual stresses, grain size, secondary phases etc. From statistical evaluation of great amount of experiments can be then designed technological tests and evaluation procedures for production processes.

The results of tensile tests simultaneously monitored by AE, confirmed influence of grain size and forming stage on AE-signal level. Homogeneous fine grained structure generates AE signal on low energetic level during plastic deformation that 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 pulse amplitude achieves maximal values near the yield point. The fact was confirmed, that great differences exist in the character AE signal between coarse grained materials and ultra-fine grained materials (UFG). The signal from UFG materials has not burst character in contrast to coarse grained materials. For both groups of materials is AE signal during plastic deformation irreversible [1]. The significant influence of surface layer on this effect was proved e.g. in [28]. After removal of surface layer, similar AE to original test was observed during reloading [28]. Great plastic deformation during forming causes great increasing of hardness and strength. From this reason the hardening during subsequent tensile test is not emphatic. The brittle phase β is the main source of AE signal generated from Mg alloy AM60 after its yield point. The proportion between the signal from dislocation bands and signal from cracking phase β should be probably evaluated from amplitude distribution of AE signal.

The sensitivity of AE method on structure stage and on forming stage can be used for design of simple technological tests. Relaxation processes efficiency after forming of copper using AE can be evaluated from the first part (elastic state) of tensile test. After relaxation process is the AE activity in this part of tensile test significant lower. The experiences from tests will serve for source analysis during hydrotest and for preparing method for on line monitoring exposed machinery parts.

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