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Acoustic Emission from transformation of the textures of TRIP steel

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Abstract
Acoustic Emission signals were recorded and are presented during fast cooling processes in different steel materials using Gleeble 3800 thermomechanical simulator. After rapid heating up to 950 degrees, TRIP steel and other steel specimens have been cooled down. They had undergone phase transformation from austenite to pearlite, bainite or martensite. Our technique made it possible to record Acoustic Emission signals from transformation. We use the traditional AE parameters like rate of hits, energy duration from one side. Localization of AE events could help in filtering electrical noises. Also localization proved the validity of AE events. Finally AE events during cooling process were devoted to phase transformation from residual austenite to ferrite. The body-centered-cube residual austenite transition to face-centered ferrite structural constituent can be the cause for low temperature AE events observed only in TRIP steel.

Keywords: Acoustic Emission, Gleeble simulator, phase transition of steel,

1. Introduction

Different loading can be applied to materials generating acoustic emission. Recently stresses have been applied to evoke AE events, better to say AE events have been used to investigate material structural changes or to find flaws in materials. During early history of AE research, the godfather of the contemporary AE investigations J. Kaiser demonstrated that AE event can be measured during tensile test, thus it can be used effectively for material research [1]. Such measurements are carried out in many places partly for teaching purposes partly for material testing in laboratories even today and we also do such measurements [2].

Much less work has been done in the area of investigation of the AE during phase transformations. It is clear that allotropic transformations of steel at high cooling rates, the transition from austenite to bainite or martensite will cause internal stresses in the material through the distortion of the crystal lattice. Both the transformations itself can emit AE impulses or due to internal stresses there is a possibility in the material for formation of dislocations and movement of these during plastic forming leading to emission of acoustic signal (i.e. for AE). Therefore we believe that AE measurements can be used for monitoring and interpreting the response of the material, which is induced by the changing of the microstructure during cooling. Few papers have demonstrated the possibility of this route [3,4,5,6].

However, it is not so easy to produce recordable AE due to temperature changes. If the temperature changes slowly, then internal stresses can be smoothed by phonons. Or simply we may have AE events too rare to distinguish them from background noises.

2. Experimental conditions

2.1 Experimental aims

Our laboratory started to examine the acoustic properties of TRIP steel because of a steel manufacturing company's request. These tests were necessary because of the growing applications of this type of steels. We call "TRIP" those steels which contain three types of structural constituents, such as ferrite, residual austenite with high carbon content, and carbon-poor bainite in their microstructure. This unique structure makes possible that the steel can be highly deformable and due to the secondary plastic forming (e.g.: pressing of sheets) the residual austenite transforms to martensite. It results enhanced strength and ductility due to the three-phase (ferritic-bainitic-martensitic) microstructure.

The main objective of these tests was that gain acoustic information about the phase transitions in the texture. To get these results we used a dynamic thermal-mechanical testing device, called Gleeble, and we observed the acoustic signals which emitted by the different deformation progresses on the test pieces. We performed this observation by our standard 32 channeled acoustic emission system.

2.2 Devices used in experiments

2.2.1 Gleeble system[7]

The College of Dunaújváros has a Gleeble 3800 thermomechanical simulator, which is a high-tech solution for physical simulation and thermal-mechanical material testing. The system has a lot of application areas, the most important to us are the next:

- Hot/warm tensile test
- Hot/warm compression test
- Thermal/mechanical fatigue
- Thermal cycling/heat treatment

In all of our experiments we used the programmable heating and cooling abilities of the system, which can fine-tuning the heat-treatment process. The device reaches this temperature-control by a direct resistance heating combined with water-cooled copper grips, and the control signal of the process derived from a thermocouple, which is welded to the surface of the test specimen.

Figure 1. Gleeble 3800 thermomechanical simulator

The system has a strongly modular setup. It has a mechanical system: a servo hydraulic system, what is a part of a high-accuracy mechanical control loop with optional displacement transducers for the compression and tensile tests. It has also an electrical heating system with conductivity grips which make the system capable of high cooling rates too. With the sealed working chamber and high-power vacuum pumps the system can produce extremely low pressure around the specimens, preventing this way the corrosion because of the high temperature.

Figure 2. Working chamber

The operations of the different systems have been coordinated by a digital system, which provides all the digital signals – from the different built-in analog sensors – which are necessary to control the programmed thermal and mechanical variables simultaneously during the test, through the digital closed-loop thermal and mechanical systems.

2.2.1 AE measuring system

The heart of our acoustic emission system is an contemporary, 32 channel, digital device type AED40/32 Sensophone manufactured by Hungarian company Geréb & Co. Technical Development Ltd. [8]

Figure 3. Sensophone

During testing we connect to the Sensophone AE sensors through the amplifier units. the device fully satisfies the current AE standards. Today, Sensophone is one of the most modern

AE devices. It has 32 AE input channel which make possible to observe really extended structures. Of course it has more analog and digital I/O interfaces to receive load signals, or emit alarm signals for example. Its hardware and software capable of precise source localization along line, or surface and it can record the standard acoustic emission parameters like amplitude, rise time, duration rate, sum of hits counts (i.e. number of oscillation or zero crossing during the hit and so on. It supports the automatic measurements of threshold, dead time, coupling, speed of sound, and attenuation.

3. Results of experiments

3.1 Fighting with disturbances

One of the first tasks to be solved working with heating devices and in general was to eliminate disturbances, false effects. We are interested only in AE events. However, the heating system of Gleeble emits high frequency electromagnetic disturbances as well as there are similar disturbances from other sources. The second false source of events may arrive from mechanical couplings.

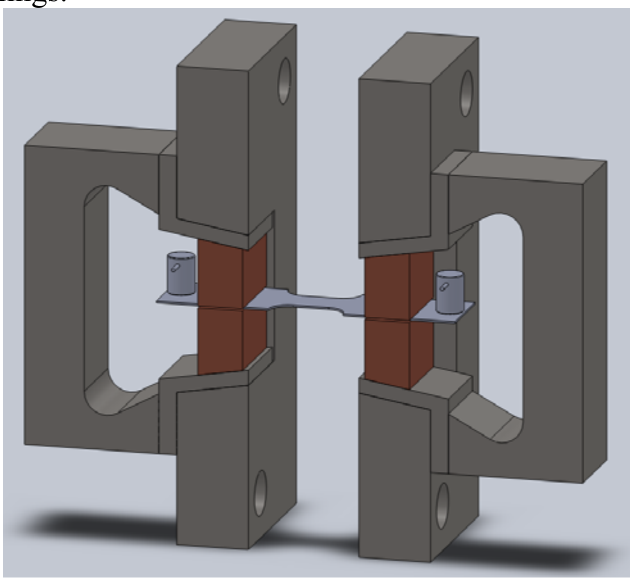


Figure 4. Specimen in the cooled jaws of Gleeble with two AE sensors

There are traditional methods to filter out false hits and events in AE tests. Those are the threshold, waiting time (dead time) etc. We believe we found a unique way in our case to eliminate electrical noises. We have a one-dimensional case from the point of view of localization of the source location of AE events. That means in case of time delay between the arriving hits detected by the system the localization can be made using the delay time. All electromagnetic noises arrives at the same time (since they velocity near to the light velocity) to both sensors. Thus we developed a software to eliminate those pairs of hits, which have the same (i.e. zero in comparison) time delay in the two sensors. This method works very well, and if the ROI is at the middle of the specimen, then the only modification needed is to place the two sensors asymmetrically.

Mechanical coupling caused severe problems. The first problem came from the jaws, but this is easy to eliminate using localization procedure. The length of the specimen changes with the temperature due to the thermal expansion and if it not balanced then this can lead to a bending of the material. This can be balanced by automated program of the Gleeble simulator. That keeps the force constant in tension. We programmed constant 50 N in tension during the whole measurement. However, the control process itself can modify the position of the hydraulic piston only, until the deviation from the prescribed force value is eliminated. Saying the truth we are not absolutely convinced that we could eliminate until now all those problems. Some fluctuation still remained when the heating process stops or the cooling starts, which may be due to change of temperature not absolutely balanced by the program. However, they do not disturb to our conclusions.

3.2 Measurement during single heat load and cooling

3.2.1. Description of the measurement

Experiments were carried out using Gleeble simulator applying a medium velocity in heating process with 10^{o}C/s up to 950^{o}C, then the specimen was hold at this temperature for 2 minutes (soaking time). A rapid cooling took place with cooling rate 10^{o}C/s until approximately 400^{o}C, when the controlled cooling process, which is cooled by constant water flow and a controlled by an additional heating process to achieve the constant cooling rate was stopped and an exponential “free-cooling” – without any control achieved by heating – took place. This temperature changes can be followed on Figure 5.

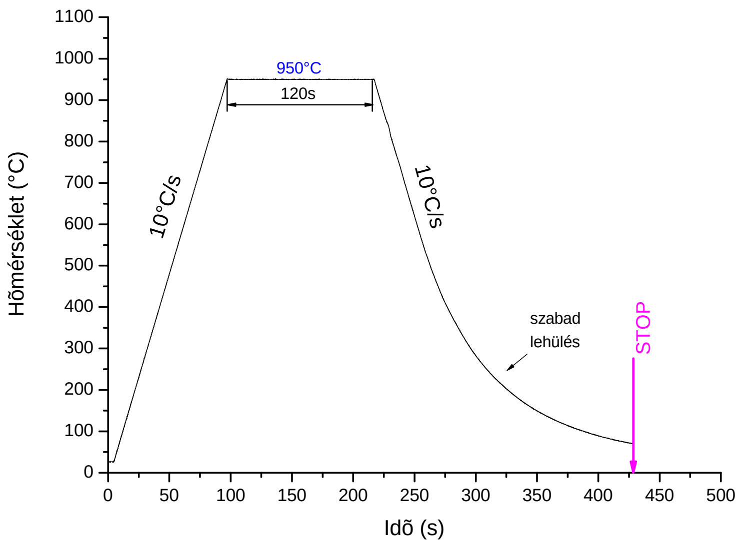


Figure 5. The temperature changes in single heating-cooling experiment

During the whole process AE hits and events were recorded using AED40 with two AE sensors of 150 kHz shown on Figure 4.

3.2.2. Rate of hits and sum of hits

Typical results are shown on figure 6 for TRIP steel and for Cr-Mo steel.

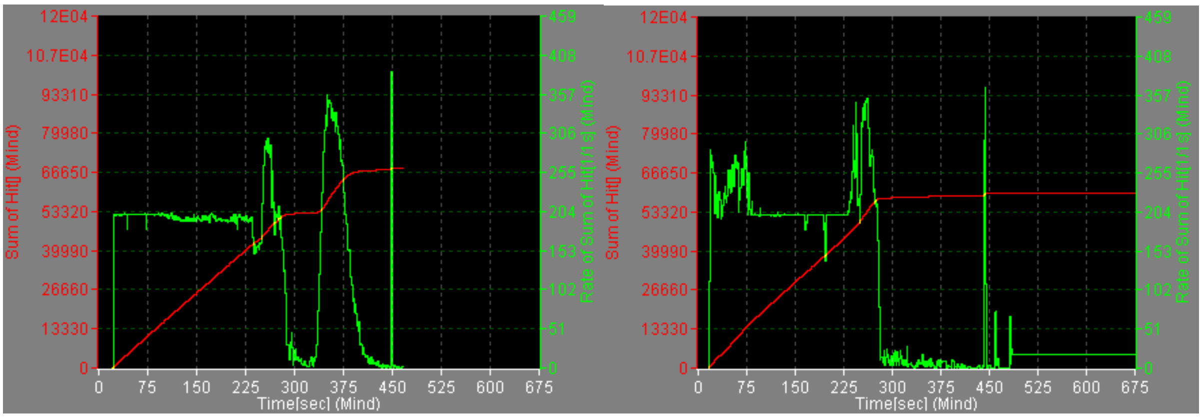


Figure 6. Comparison of rate of hits (geen) and sum of hits (red curves) for TRIP and Cr-Mo steels during singal heeting and cooling process

During heating up process the rate of hits sometimes were relatively higher. Then during soaking time it is constant at the level about 200 hits/sec. Since that higher rate sometimes appears sometime it is missing, we cannot exclude, that it may come partly from mechanical stresses. At the beginning of forced cooling we got back again relatively high AE rate till 350 hits/sec, but it drops down very quickly and becomes very still for Cr-Mo steel. But for TRIP steel another high rate of heat appears (as we shall see later) at relatively low temperatures as well. And this can be devoted to phase transformation of the residual austenite in TRIP steel.

3.2.3. Localization of AE events

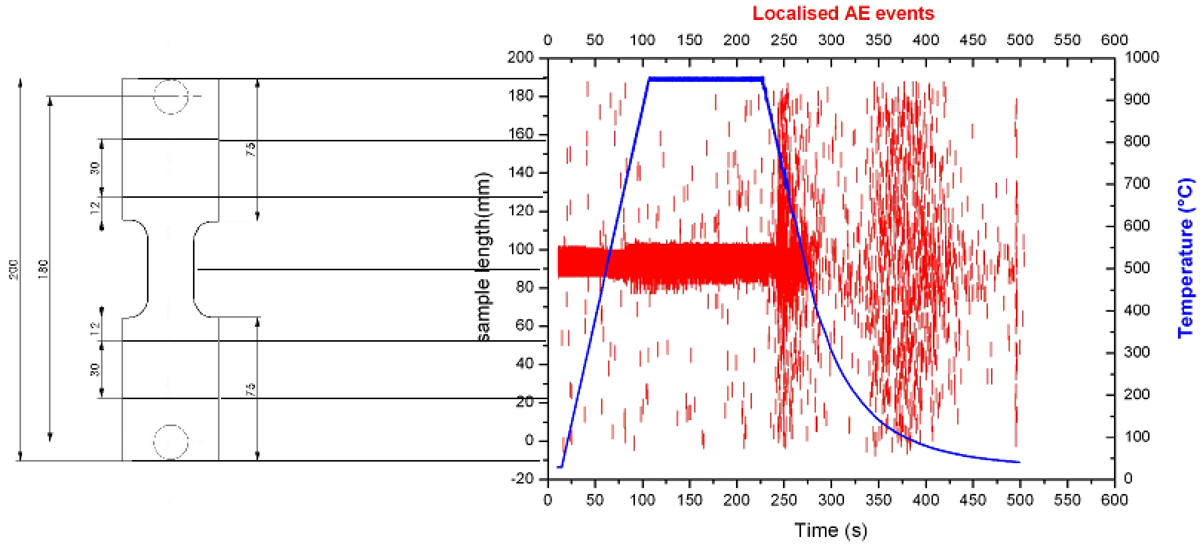


Figure 7. Localization of AE events along the specimen during heating and cooling in TRIP steel

The localized events are shown on fig. 7. Most of the events are concentrated in the middle of the specimen. However, not all events are due to some electrical noises.. (Electrical noises are concentrated in the vicinity of the centre in +-2mm range. It is clearly seen, that the area, where we have most of the events is much wider. They are really AE events in the middle of the specimen during heating, and during soaking time. A few events were localized outskirt as well, which is also a proof of real AE events

More interesting are the localized AE events during cooling process. The real growth in the rate of AE events has been observed much later than the cooling process had been started. That growth appears only when the temperature in the middle point sink below 800 degrees. However, AE events were localized not only in the vicinity of the middle of the specimen, like during heating up process, but in the whole specimen. Those are really due to temperature effect. The rate of AE events drops suddenly at about400 degree Centigrade, where the intensive linear cooling (with 10 degree/sec) ends and temperature fall becomes exponential. After a relatively silent period a new peak, a new rise of the rate of AE events was observed, but only in TRIP steels!

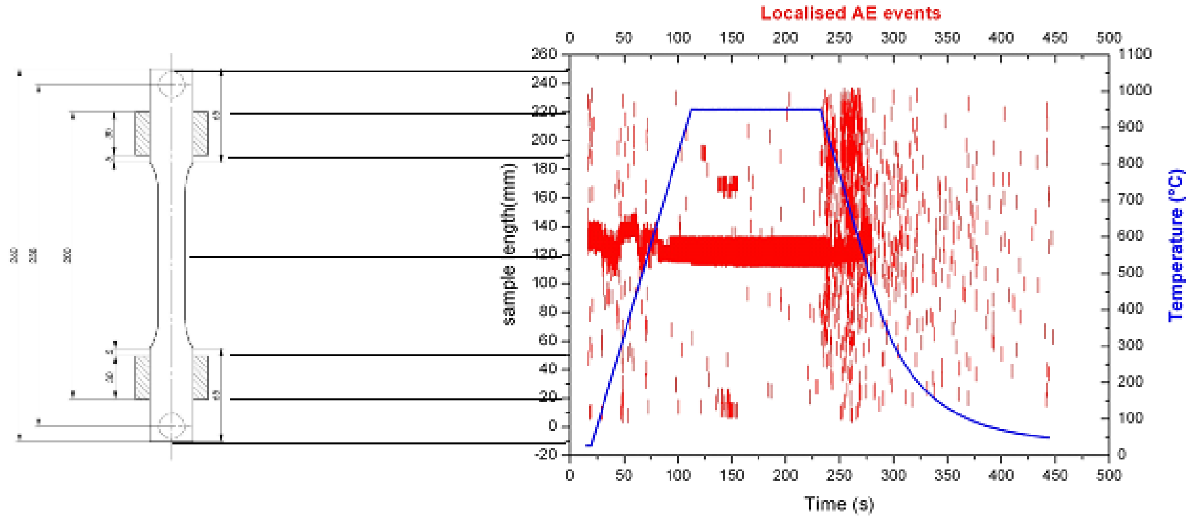


Figure 8. Localization of AE events on a Cr-Mo steel during heating up an cooling down

A really very wide and intensive second AE period starts at about150 degree till 50 degrees (see fig. 7). This is the characteristics only for TRIP steel. We did not observed that in the other steels (for example at Cr-Mo steel, see fig.8). However, the AE events in both steel exhibit two distinct periods at the beginning of the cooling as well. To show this, we zoomed in the beginning of cooling on figs. 9 and 10.

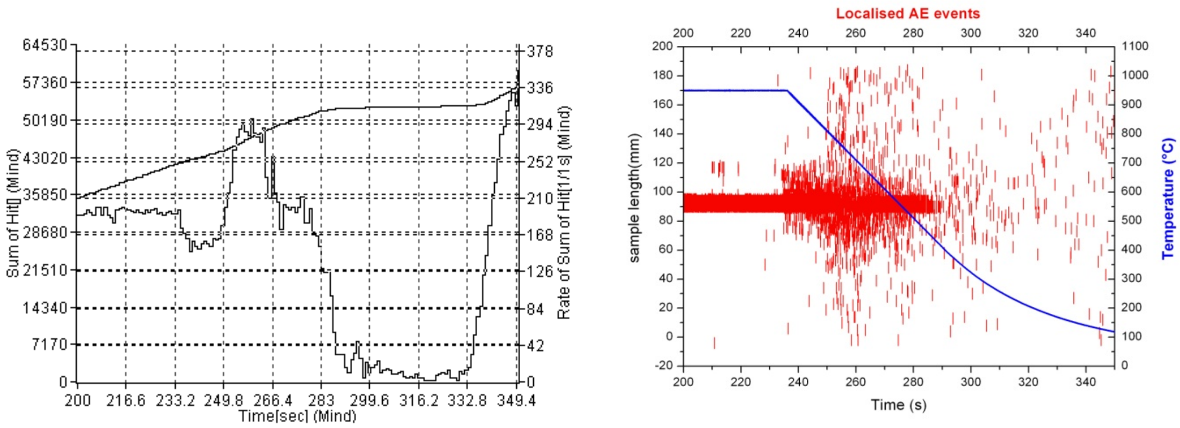


Figure 9 AE events and their localization at the beginning of the cooling in TRIP steel

There are some AE events at the very beginning of the cooling (see fig 10), which may be due to mechanical forces or to their delayed control. But when it seems to terminate another peak appears in the rate of hits, with rather distributed localization at about 700 degree of Centigrade and it continues until approximately 450 degrees, where Cr-Mo steel becomes still. In the TRIP steel at the beginning of cooling we have negative effect on fig.9 (but sometime positive effect like in fig.10). This was explained by the mechanical effects (cf.

friction or bending). But the second period of AE effect with distributed localization along the specimen can be also seen starting from 700 degrees.

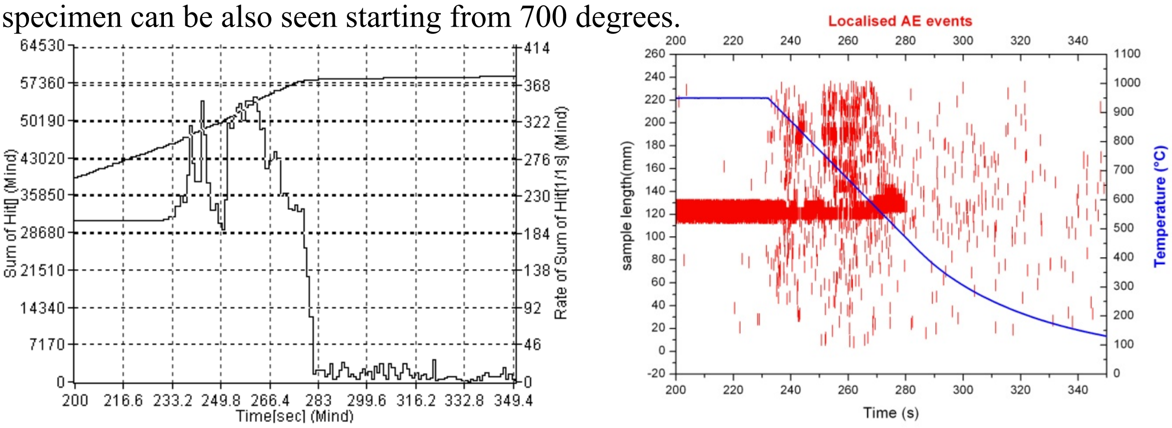


Figure 10. AE events (rate and localization in Cr-Mo steel at the beginning of cooling

3.2.4. Amplitude of events

The amplitudes of the AE events exhibit very interesting pictures (figs.11 and 12). Clearly parallel layers can be followed on figures. A possible explanation is, that amplitudes from sources of different distances are attenuated differently, thus if their variation in the time is the same but their amplitudes are different due to attenuation.

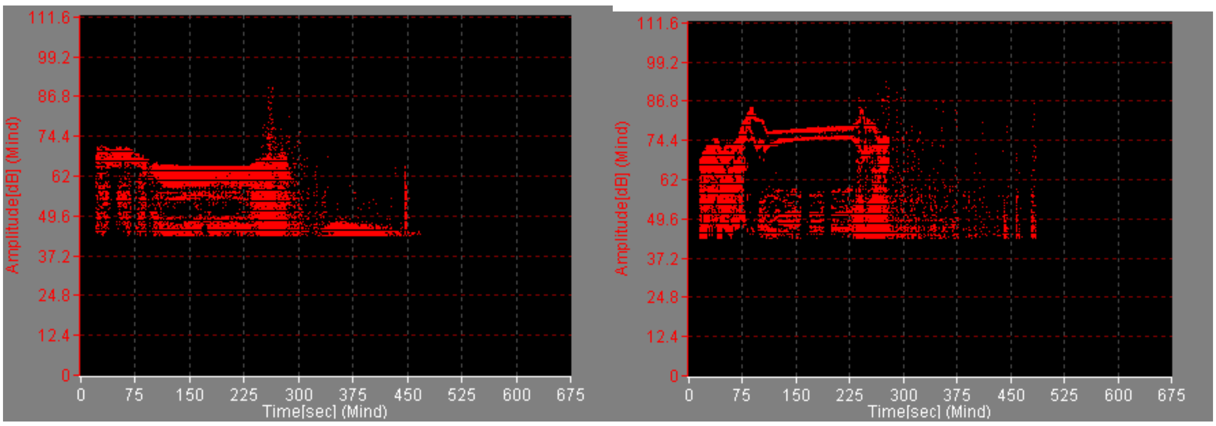


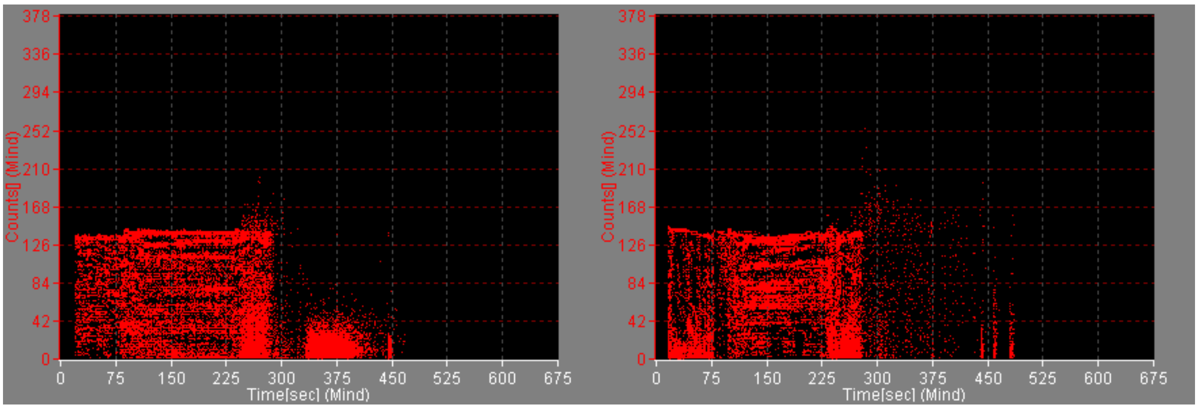
Fig 11 and 12 Changes of amplitudes of AE events during heating up and cooling down in TRIP and in Cr-Mo steels

Therefore the important message from figs 11 and 12 is only the global behaviour. First of all, in the case of TRIP steel the amplitudes are higher during the heating up and they fall to a lower level when soaking time takes place, while in case of Cr-Mo steel the amplitudes simple follows the changes in temperature.

Much more important are the amplitudes of AE events in TRIP steel during secondary coooling phase. They are clearly small (less than 50 dB), much smaller then any other AE events. This clearly points to their origin (mechanical AE can be excluded).

2.3.5 Counts versus time

We present the counts versus time pictures (figs 13 and 14) for the same case, since they are also very interesting. They exhibit also parallel lines in time. Since above we have argued that this is due to different localization of AE sources, here we believe the reason is the same: higher counts are registered from further sources, since they duration is longer either.



Figures 13 and 14. Counts (characterising number of oscillatiuon within the AE event) for TRIP and Cr-Mo steels correspondingly

2.3.6. Amplitudes in 3D

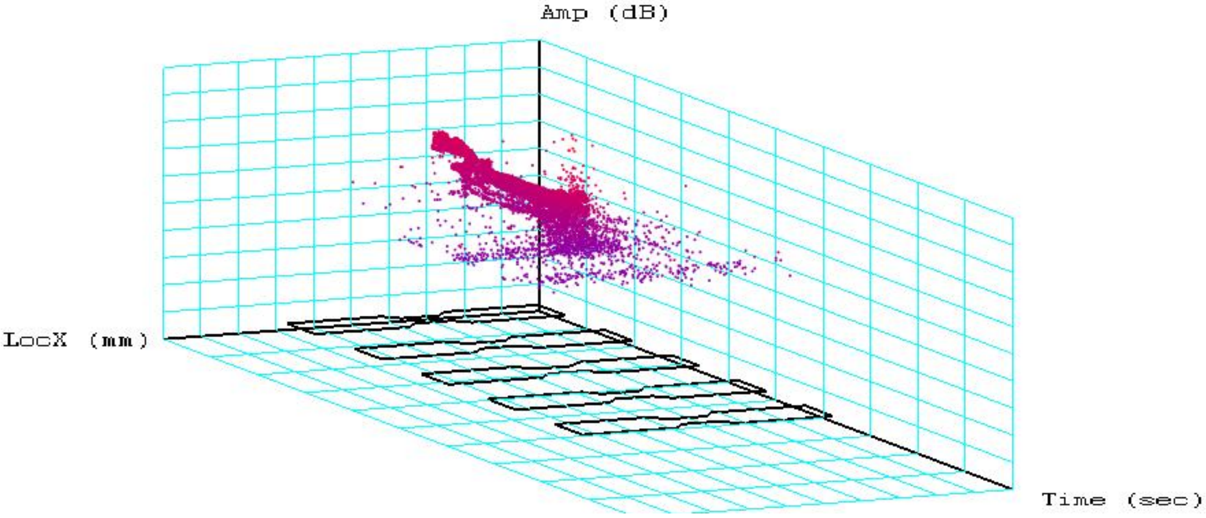


Figure 15 3D representation of AE events showing their distribution in time and space in TRIP steel

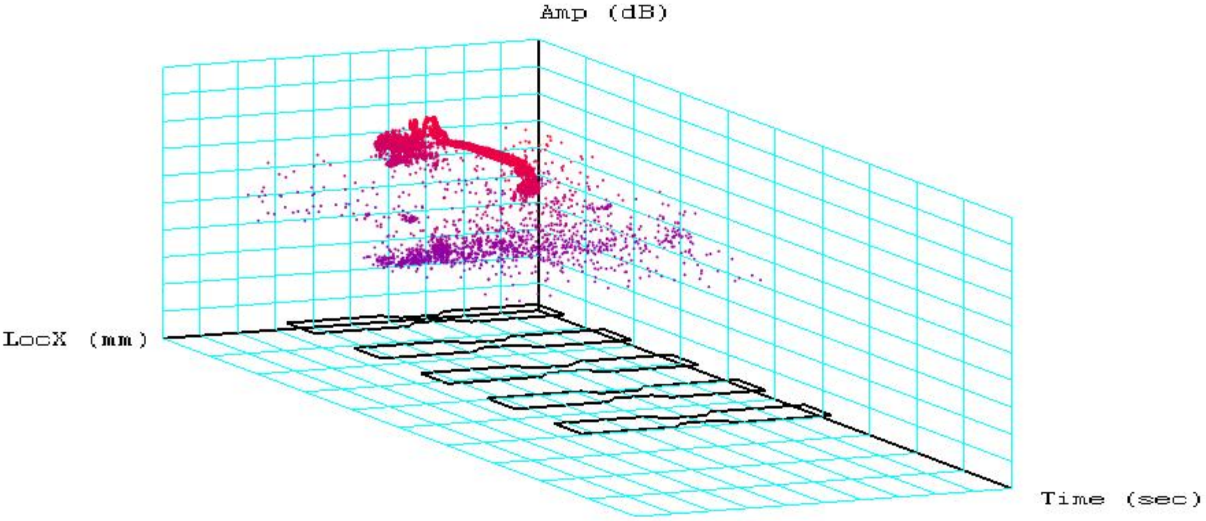


Figure 16 3D representation of AE events showing their distribution in time and space in Cr-Mo steel

In fact this is a new method and new algorith developed by our group. It is a combination of amplitude ditribution and the localisation picture. It shows the change of amplitude in time and their distribution on specimen (the specimen form is shown on the bottom plane). From figs 15 and 16 one can slearly see, that while the AE events during heating up and soaking time are concentrated in the middle of specimen, where it is the hotest, the AE event during cooling are distributed all along the specimen.

4. Discussion

4.1 Using acoustic emission during heating and cooling

It was even questionably at the beginning if we can measure AE events on Gleeble simulator at all, during heating and cooling. Besides machine and electrical noises, heating supply emits electromagnetic spikes. AE sensors do not withstand high temperatures. We tried also to use acoustic waveguides. However, the window of Gleeble system should be closed and no strait access to the specimen. Finally, we put our sensors behind the jaws of the system. In spite the stresses from jaws AE signals passed that barrier and reached the sensors.

Disturbances were thoroughly filtered. Unfortunately threshold does not help here too much. Electrical disturbances may be higher in amplitude than AE events. This is generally true, but it is even more valid in case of secondary cooling effect in TRIP steel, where amplitudes are low. Filtering by threshold would filter out effect that we want to see. The best method to eliminate electrical noises came from the fact, that they will cause hits at the same time in both sensors, thus time delay between them is zero and consequently AE event would be localized on the halfway between the two sensors. One can select the position of the sensors considering this fact.

4.2 Discussing possible cause of AE emissions

It is evident from the analysis of the figures above that AE events filtered by our method are caused by temperature effects, most probably by phase transformations in the steel during cooling. In hypoeutectic steels the austenite cools slowly, it often transforms into a mixture of ferrite and cementite as the carbon diffuses to the boundaries of crystals. Depending on alloy composition and rate of cooling, pearlite and ferrite may form. If the rate of cooling is faster, the alloy may experience a large lattice distortion known as bainitic and martensitic transformation in which it transforms into a BCT-structure instead of ferritic-pearlitic structure. In industry, this is a very important case, when the carbon cannot diffuse due to the cooling speed or other technological parameters and influence of alloying elements, that results in the formation of harder structural constituent. The rate of cooling determines the relative proportions of martensite, bainite, ferrite, and pearlite, and therefore determines the strength- and toughness properties of the resulting steel, such as hardness, tensile strength, contraction and rupture elongation.

Heating steel above ~900 °C causes the decomposition of the structural constituents to austenite. It is called austenitisation. After soaking time we started to cool down. Until 727 °C there were not very strong AE events except those, which had been classified as mechanical effects. Cooling down relatively rapidly diffusion of the carbon could not follow the changes. In such cases different layers (typically bainite and martensite) can be formed in the material overlapping each others, thus stresses may be formed which generate AE events Due to the forced cooling and its speed transformation cannot be ended at 723 °C (like in the case of equilibrium) but lasted until 400 °C. Finally or at certain degrees process has been stopped, near where forced cooling has been stopped either. When the temperature of free-cooled steel reached 105°C, then the remaining body-centered cube form residual austenic phase started to turn to face-centered cube ferrite, bainite or martensite depending on cooling rate. This is the cause of the second peak in rate of AE events (cf. fig.6 and 7.) How formation of different phases are distorted can be followed qualitatively using fig 17, which has been borrowed from [9]

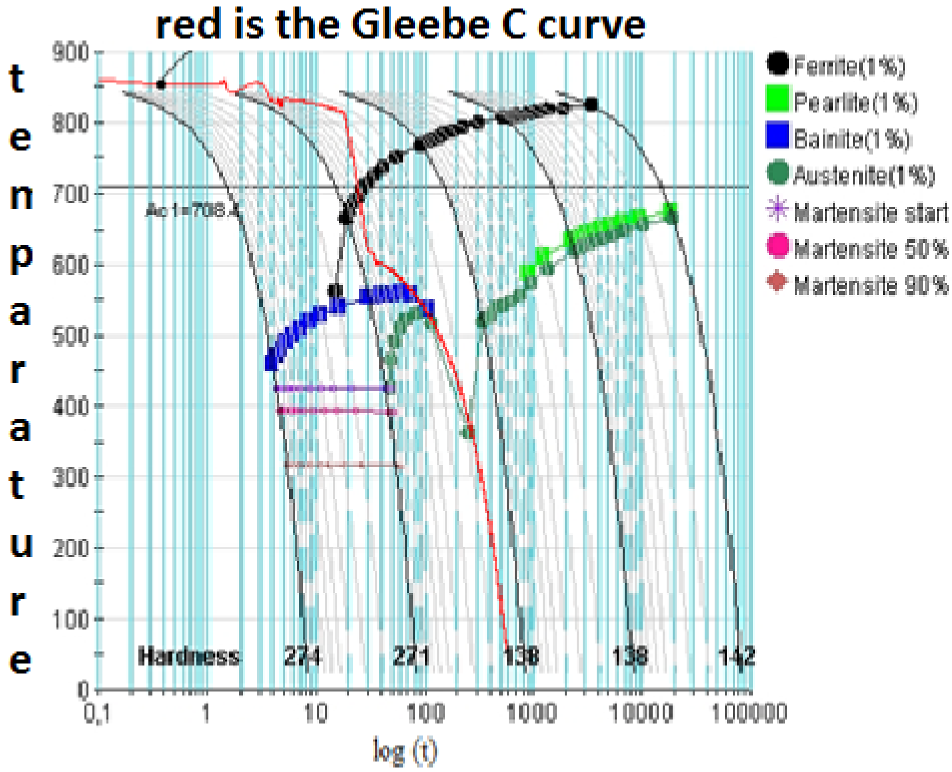


Fig 17. Calculated phase transition curves for fast cooling in Gleeble simulator (from [9])

We believe, this is a proof that AE measurements can be used in the future to follow the phase transformation in steel during cooling process.

5. Summary

We carried out series of acoustic emission measurements on Gleeble simulator to investigate the possibility to detect and localize AE events during heating up and cooling down with the aim to investigate the possibility to monitor structural changes during heat treatment. The first question was if it is possible at all to carry out such measurements, since the AE sensors are usually not heat resistant, the transients on Gleeble can be too fast to follow and there are electrical and mechanical disturbances due to circumstances of the experiment. General problems were solved and discussed in another publication [2]; specific problems concerning electrical noises could be eliminated using the zero time delay, the threshold level, and localization procedure of AE.

The other question was if the AE events were due to heat and mainly due to phase transformations in the steel. Our experiments showed that there were AE sources along the specimen, well localized which could be devoted only to temperature gradient in the material.

The most convincing results of these experiments came from registered AE events during cooling process and from the comparison of TRIP steel with similar measurements made on

Cr-Mo steel. First of all there was an increase of AE events during cooling, which were found to be in correlation with those temperature limits, which are usual for well known phase transformations in steel. The difference between the AE events during cooling in TRIP steel and Cr-Mo steel convinced us that in TRIP steel underwent a phase transformation below 150 degree of Centigrade, under which the residual austenite formed to bainite or martensite, that is well seen in AE event, thus AE could be used for monitoring such transition.

6. Acknowledgements

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