Possibility of On-Line Monitoring of Laser Cutting of Deep-Drawn Sheet Parts by Measuring Acoustic Emission

Janez GRUM, Tomaž KEK, Janez M. SLABE
University of Ljubljana, Faculty of Mechanical Engineering, Ljubljana, Slovenia

Abstract. The paper treats the results obtained in simultaneous measurements of acoustic emission with PZT AE sensors and of strain with resistance measuring rosettes carried out during and immediately after laser cutting-out of a deep-drawn sheet product, i.e. mud-guard. The presence of a field of residual stresses produced by deep-drawing is characteristic of deep-drawn products. In the course of laser trimming and cutting-out the residual stresses get released, which affects the deformation of the deep-drawn mud-guard concerned. The strain was measured at two measuring points chosen with the resistance measuring rosettes. To describe the changes in the material, acoustic emission was measured at the same points. The two phenomena were then analyzed. A goal of the study presented in this paper was primarily to analyze the sources of acoustic emission present during and immediately after laser cutting. It was found that the main source of acoustic emission during laser cutting was the cutting gas jet. The acoustic emission occurring immediately after cutting of the mud-guard is related to the phenomena in the heat-affected zone of the laser cut and partly to the release of the residual stresses present in the deep-drawn sheet product. The amplitude and the energy of the acoustic emission signals recorded during the cutting process and immediately after cutting, the number of AE hits detected by individual sensor in a unit of time and their cumulative value indicate a significant connection with the phenomena in the material, which may enable optimization of the laser-cutting technology, including the selection of the cutting conditions.

1. Introduction

1.1 Acoustic Emission (AE)

Acoustic emission is generally defined as a acoustic wave motion, i.e., vibration of material particles, generated by energy release at local events in a material. For acoustic emission the abbreviation "AE" (see standard EN 1330-9) is frequently used. A prerequisite for the AE generation is a mechanical or thermal influence exerted on the object by the environment. AE sources can be very different. Roughly they can be grouped into sources of discrete AE, with which the AE activity stops after a certain time, and sources of continuous AE [1, 2].
AE measurement can be efficiently applied to control of various production processes such as classical machining processes. With these processes AE measurement is applied for on-line control of cutting-tool wear and, indirectly for on-line control of product-surface quality. In contrary just a few studies on the control of various welding and particularly laser processes using AE measurement can be found in technical literature [4-6]. Even less data are available on the application of AE measurement for on-line control of these processes in industry.

In laser processes there is no mechanical contact between the workpiece and the laser beam (tool). The workpiece surface is simply irradiated by laser light. But several phenomena occur, due to interaction between laser light and material, which induce AE. Such phenomena are the material melting and solidification, thermal deformations of the material, deformations due to residual-stress releasing, occurrence of micro cracks in a material, evaporation of the workpiece material and an absorbent, etc. These numerous sources of the AE can give with an efficient on-line and/or off-line analysis of recorded AE signals generated by these sources very useful information for the evaluation of process quality. Accurate determination of sources of recorded AE signals is a very demanding and difficult task. Beside mentioned sources of the AE other sources of AE must be considered with the laser processes. In these processes flow of cooling and/or shielding and/or assistant (with added particles of the filler material) and/or cutting gas represent very dominating AE source [5].

1.2 Strains and Residual Stresses

In a deep drawing process a plate is formed with deep-drawing tools, i.e. by mutual movement of the punch and the die, the plate being held by a blankholder. At the end of the process, when the plate is pressed between the parts of the deep-drawing tool, the stress field in the plate is balanced with the external forces acting on the plate by the tool. When the tool opens, the internal stress field is no longer balanced; therefore, a new balance will be established in the material of the deep-drawn part with the relevant residual-stress field. Particularly with larger deep-drawn parts, after deep drawing, products are trimmed separately or individual segments are cut out. Consequently, in laser cutting-out and trimming the existing residual-stress field in the deep-drawn product will vary due to the part deformation and the establishment of a new balanced residual-stress field.
The strains resulting from residual-stress releasing can be measured, during the cutting process, with resistance measuring rosettes. The measuring rosette must be placed on the deep-drawn part surface prior to laser cutting. Placing of the measuring rosette on a suitable chosen measuring point on the deep-drawn part surface will provide useful information on strain generation in the deep-drawn part during the laser cutting process.

2. Experimental Procedure

2.1 Description of a Deep-drawn Mud-guard

Deep-drawn mud-guards are made of steel sheet (1.0338 W.Nr.) of 1.5 mm in thickness. This steel is frequently used in the automobile industry to produce body parts. Sheet shows isotropic mechanical properties prior to deep-drawing process. A simplified picture of a deep-drawn part, from which the left and right mud-guards are cut out, is shown in Fig. 1. The figure also shows the two measuring points MP 1 and MP 2 at which AE sensors and resistance measuring rosettes were located. The two measuring points were located on the right mud-guard and were chosen at the locations where relatively strong longitudinal and transverse residual stresses, i.e. relatively strong deformations due to residual-stress releasing during laser cutting, could be expected.

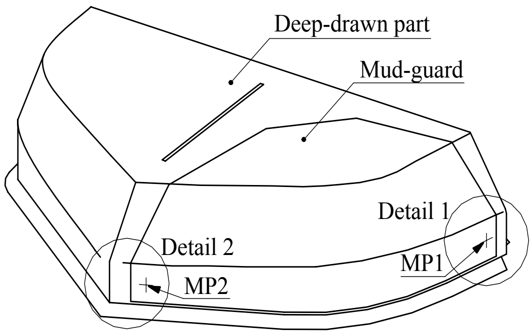


Fig. 1: Deep-drawn part; definition of measuring points.

2.2 Laser Cutting Conditions

Laser cutting of the deep-drawn part was carried out with an industrial CO_2 laser Spectra Physics 820. The laser beam showed the Gaussian distribution of power (TEM_{00}). The cutting gas used was oxygen. The laser-beam output power and the cutting speed were chosen with reference to the complexity of he shape at the location of cutting the deep-drawn part. The laser-beam power *P* at individual cutting-path sections was varied between 400 W and 900 W and cutting speed *v* between 700 and 2500 mm/min. The laser-beam outlet diameter was 2,2 mm and the cutting-gas pressure 0,2 MPa. During laser cutting the deep/drawn part was clamped at a fixed machining table. Only the 5-axis laser head was moving. The mud-guards were cut out in two different ways (mode 1 and mode 2) shown in Fig. 2. Two different modes were chosen due to optimisation of the laser-cutting technology of the deep-drawn part.

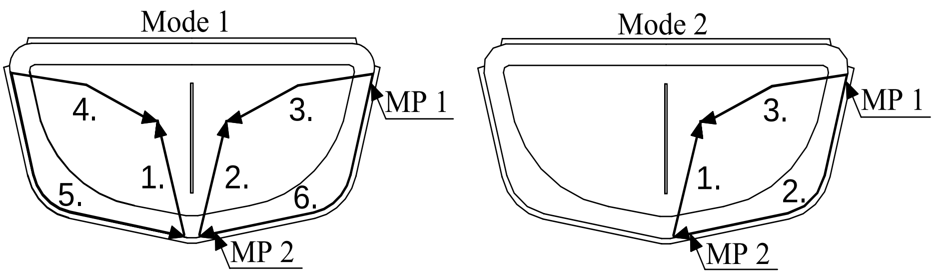
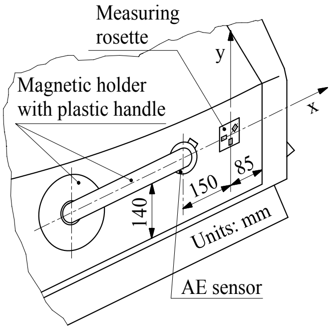


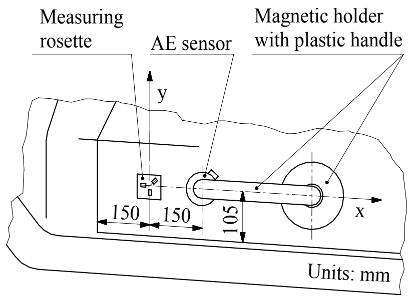
Fig. 2: Modes of cutting mud-guards out of deep-drawn part.

2.3 Measurement of Acoustic Emission and Deformation

AE was measured during laser cutting and immediately after cutting-out of the mud-guard. For AE measurement, a measuring system Vallen AMSY4, product of Vallen-Systeme [7] was used. The measuring system included a base unit AMSY4-MC2, two signal pre-amplifiers AEP4, two piezoelectric AE sensors VS150-M with a frequency range of 100-450 kHz, and adequate software. The position of the piezoelectric AE sensors at the MP 1 and 2 is shown in Fig. 3. The threshold of AE signal sensing was set at 40 dB. The mud-guard deformation was measured with a resistance measuring rosette CEA-06-062UL-120, product of Vishay Measurement Group.



a) Detail 1 - Measuring point 1 (MP1)



b) Detail 2 - Measuring point 2 (MP2)

Fig. 3: Location of AE sensors and resistance measuring rosettes at deep-drawn part (details of Fig. 1).

3. Experimental Results

3.1 AE Sources During and After the Laser Cutting Process

The mud-guard used in the study was made from a steel plate using the deep-drawing process. Large dimensions and comparatively complex shape of the mud-guard favour the application of laser cutting to cut out the mud-guard from the deep-drawn part. The aim of the study is to optimise the procedure of cutting-out of the mud-guard related to a sequence cuts and to optimise the laser cutting process. The study includes acoustic-emission measurement using PZT sensors in order to provide better cutting conditions to achieve as high as possible cut quality and as low as possible strain of the plate part. Further in the present paper, a part of a more extensive investigation including measurements of acoustic emission is described.

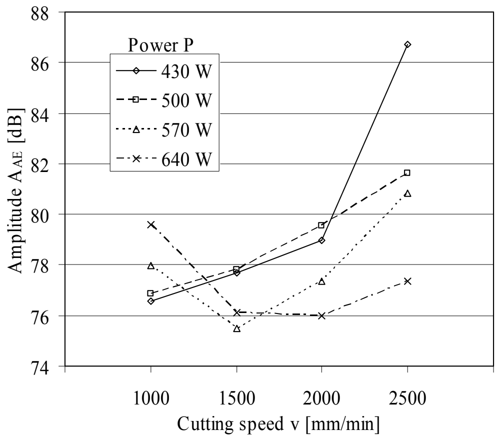


Fig. 4: Maximum amplitude A_{AE} of acoustic emission in laser cutting as a function of cutting speed *v* and laser-beam power *P*.

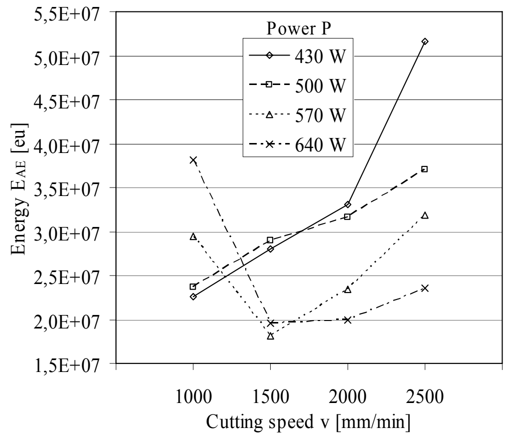


Fig. 5: Energy E_{AE} of acoustic emission in laser cutting as a function of cutting speed *v* and laser-beam power *P*.

The study of acoustic emission during and after laser cutting showed that by using PZT sensors very intense AE can be sensed in the material. It shows as a continuous signal. The preliminary measurements carried out in laser cutting of a flat non-strained steel plate without deep drawing (1.0338 W.Nr.) showed that only the maximum measured amplitude A_{AE} of AE signals was significantly dependent on the laser-cutting parameters. In laser cutting, cutting speed *v* and laser-beam power *P* were varied. These two laser-cutting parameters were chosen because in practice, with a adjusted focus of an optical system at the plate surface, only these parameters are frequently varied when optimum cutting conditions for a steel plate are searched for. In the analysis a level of significance α of 0.05 was considered because it fulfils requirements set regarding the reliability of a statement. Between the maximum amplitude A_{AE} and the energy E_{AE} of continuous AE signals in laser cutting of the flat non-strained steel plate there is an increasing linear dependence having a correlation coefficient R^2 of 0.74. In disagreement with the maximum amplitude A_{AE} with the energy E_{AE} of the measured AE signals, the results of an analysis of variance, however, do no indicate a significant influence of the cutting parameters, i.e. of the cutting speed v and laser-beam power P. The maximum amplitude A_{AE} as a function of the cutting speed v and laser-beam power P in laser cutting is shown in Fig. 4. Fig. 5 shows a relation between the energy E_{AE} of the AE captured and the laser-cutting parameters given.

The study of the processes in the material included also AE measurements during laser cutting-out of the mud-guard from the deep-drawn part. Fig. 6 shows A_{AE} as a function of time t in laser cutting-out of the mud-guard from the deep-drawn product. It shows a stepwise distribution of the amplitude values A_{AE} in an AE signal in dependence of the moment of observation of the phenomena in the material, i.e. from time t. The zones of a relatively constant value A_{AE} coincide with carrying-out of the individual laser cuts at the mud-guard. The intermediate zones represent the periods when there was no laser-cutting process going on and the laser head was freely travelling from the end of the preliminary cut to the beginning of a new cut. For comparison's sake, Fig. 7 shows also the amplitude values A_{AE} of acoustic emission as a function of time t when the laser head is travelling along a cutting trajectory and a cutting gas is flowing but the laser beam is not turned on, i.e. there is a gas flow but no cutting. A similar shape of A_{AE} variation as in Fig. 6 can be observed in Fig. 7. In the latter case the zones with a relatively constant value A_{AE} coincide with the movement of the laser head along the trajectories of the individual cuts with no laser beam turned-on, which means that the incidence of the cutting gas on the smooth plate produces no notch since laser cutting is not going on.

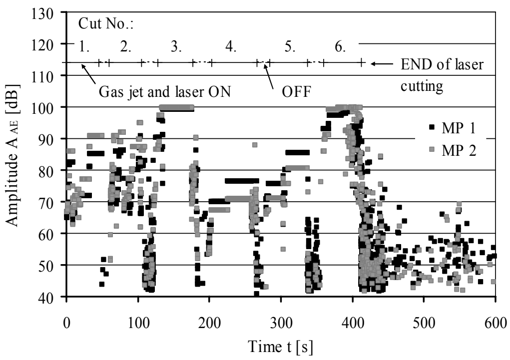


Fig. 6: Maximum amplitude A_{AE} of AE signals captured in certain time period during laser cutting.

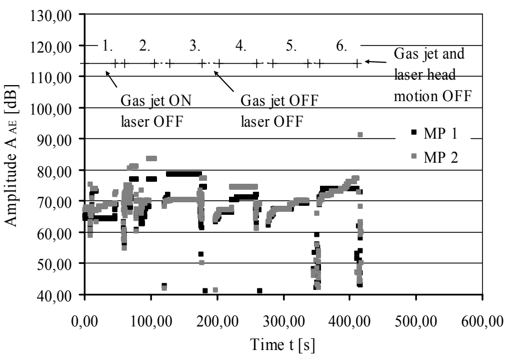


Fig. 7: Maximum amplitude A_{AE} of AE signals captured in certain time period during laser-head travel with just cutting-gas jet - no cutting.

An average value of the maximum amplitude values of the continuous AE signals measured during the execution of the individual laser cuts shown in Fig. 6 amounts to 83 db. An average value of the maximum amplitude value A_{AE} of the AE signals measured during the cutting-gas flow but without cutting was by 15 % lower (Fig. 7). From Fig. 6 it also follows that after the conclusion of laser cutting a relatively intense AE in the form of discrete signals can be measured. From Fig. 7 it follows that after the laser-head movement has been finished and the cutting gas stopped flowing, no discrete AE signals were sensed. The discrete AE signals after the conclusion of laser cutting resulted from phenomena in the heat-affected zone of the laser cut and partially from the strain occurring in the plate and caused by residual-stress relieving. These AE signals are, in opposition to the AE signals

generated by the cutting-gas jet, mainly of discrete character, their duration ranging between some 10 μs and some 10 ms. The average amplitude of the discrete AE signals after laser cutting is lower and amounts to around 53 dB. The range of the maximum amplitudes of the discrete AE signals is large and varies between 40 dB and 100 dB.
From the results obtained it can be inferred that it is possible, primarily with reference to the duration and partly also to the maximum amplitude, to efficiently distinguish the AE signals due to the cutting-gas jet from the discrete signals due to various events in the material obtained when no cutting gas is flowing.
The large range of duration of the discrete AE signals and also the relatively large range of the maximum amplitudes indicate a great variety of the events in the mud-guard material. The discrete AE signals with a relatively high maximum amplitude (i.e. above 70 dB), are attributed to the generation and propagation of micro-cracks and other similar events at the micro-level [2]. The location of the occurrence/propagation of micro cracks is usually limited to the heat-affected zone of the laser cut. The events of this type may occur also during the material deformation due to residual-stress releasing in the deep-drawn part. This applies in case when in the material are defects such as hard and brittle metal inclusions, which can break during elastic or plastic deformation of the material. The discrete signals due to the events related to the material deformation such as moving dislocations, slippage, twinning, friction between grain boundaries, and similar [2] have lower amplitude (i.e. below 70 db).
The phenomena concerned produce the occurrence of discrete signals and are present also during laser cutting when the cutting gas is flowing, but they are hard to be distinguished in a continuous signal.

3.2 Correlation Between Acoustic Emission and Strain

This sub-heading will deal simultaneously with the results of AE measurement and strain measurement during and immediately after laser cutting-out of the mud-guard. In that manner both modes of cutting-out of the mud-guard will be discussed (Fig. 2).
The results obtained with each mode of cutting-out the mud-guard are shown as two types of diagrams. The first type of diagram, shown in Figs. 8 and 10, represents the AE signal energy E_{AE} and the mud-guard strain ε_y in the y direction (Figs. 3a and 3b) in dependence of time *t*. The second type of diagram, shown in Figs. 9 and 11, represents the number of AE hits n_{AE} of a sensor per unit of time and the mud-guard strain ε_y in the y direction in dependence of time *t*. The diagrams in Figs. 8 and 9 refer to mode 1 of cutting-out and Figs. 10 and 11 to mode 2. In the individual diagram the duration of the individual cut is shown as a full line parallel to the abscissa with the number of cut. Free laser-head travel between the individual cuts is indicated by a dashed line.
Before the treatment of the correlation between AE and strain, the strain measured with both modes of cutting-out the mud-guard will be discussed.

a) Mud-guard deformations with cutting mode 1
The diagrams in Figs. 8 and 9 show that with cutting-out mode 1 typical strains were measured only during cut 2, cut 3, and cut 6, i.e. in the course of cutting out the right mud-guard, at which the measuring rosettes were mounted (Fig. 1). The influence of cutting-out the left mud-guard on strains of the right mud-guard is minimum. The strongest strains of the right mud-guard occurred during cut 6 at the MP 1 located at the beginning of cut 6.

b) Mud-guard deformations with cutting mode 2
As distinguished from mode 1, mode 2 was applied only to cut out the right mud-guard from the deep-drawn part. The right mud-guard strain occurring in the course of the second

mode of cutting-out is shown in the diagrams in Figs. 10 and 11. In this case too the strongest strains were measured during the last, i.e. cut 3, and at MP 1.

c) Correlation between acoustic emission and mud-guard strain with cutting-out modes 1 and 2

The diagrams in Figs. 8 through 11 make it possible to see that the mud-guard strain was measured only during the cutting-out process whereas after finishing the individual cuts no important strain in the mud-guard was measured. Contrarily, there is AE occurring also during free laser-head travels and after cutting-out of the mud-guard. This difference is attributed to the fact that it is possible with measuring rosettes to measure only local strains at the measuring point where the measuring rosette is mounted, whereas with AE measurement the events are sensed also at distance. In generally with AE measuring events occurring no matter where in the material of the deep-drawn part can be sensed. When assessing the relation between strain and the characteristics of the acoustic emission captured it should be taken into account that macro strain of the plate is measured only at a certain measuring point and not at the mud-guard as a whole and that AE can be generated also by other sources such as the initiation and propagation of micro cracks at a laser cut, etc.

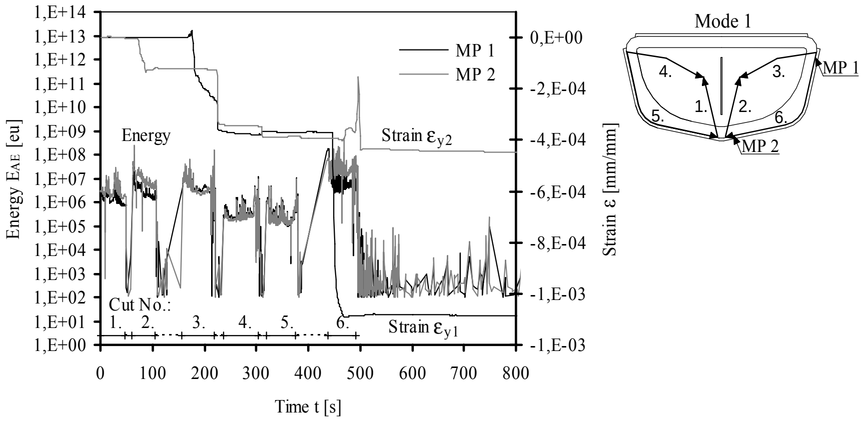


Fig. 8: Energy E_{AE} and strain ε_y of right mud-guard as a function of time *t*; cutting mode 1.

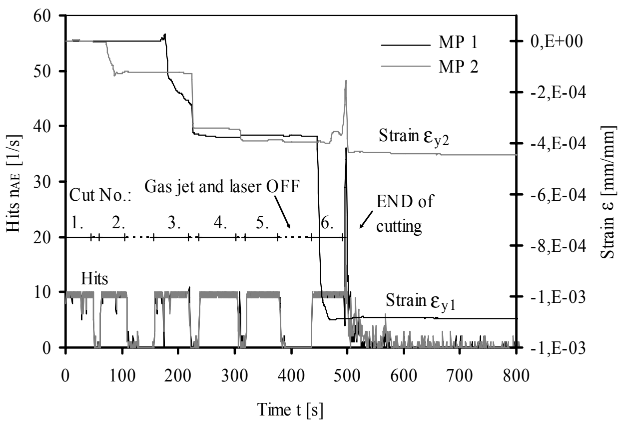


Fig. 9: Number of AE hits n_{AE} and strain ε_y of right mud-guard as a function of time *t*; cutting mode 1.

The different energy levels of the AE energy E_{AE} with the individual laser cuts can result from the different distances between the cutting area and the measuring point. The influences stated are related to AE attenuation with the increasing distance from the source. The attenuation of the AE signal is particularly noticeable with cutting-out mode 1 if the measured signals with cuts 1, 4 and 5 are compared with the signals obtained with cuts 2, 3 and 6 found at the right half of the deep-drawn product where there are measuring points MP 1 and MP 2. The energy E_{AE} varied also due to different laser-cutting parameters varied during the individual cuts. The energy E_{AE} measured was influenced also by the shape of the deep-drawn part and the cut length. The measured energy E_{AE} clearly reflected a jump in the mud-guard strain. These quick jumps in strain reflected in rapid and short-term increases of the energy E_{AE}.

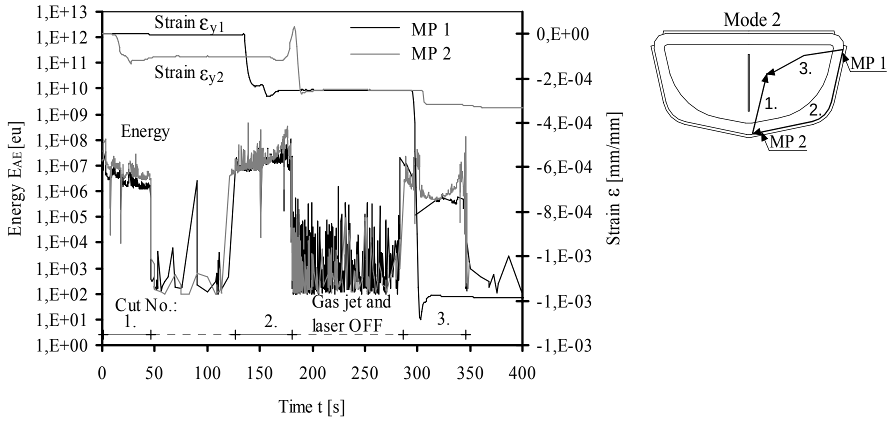


Fig. 10: Energy E_{AE} and strain ε_y of right mud-guard as a function of time *t*; cutting mode 2.

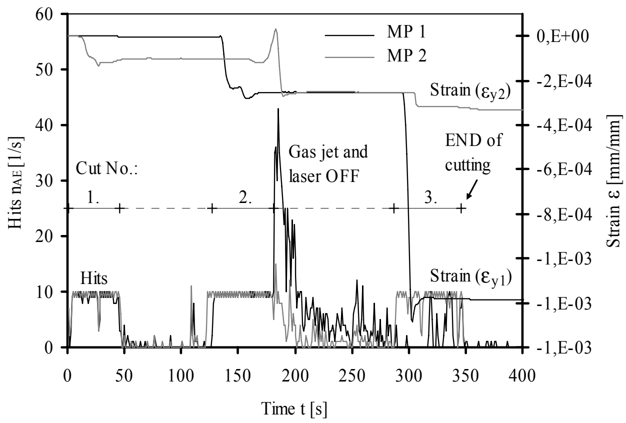


Fig. 11: Number of AE hits n_{AE} and strain ε_y of right mud-guard as a function of time *t*; cutting mode 2.

The diagram in Fig. 9 makes it possible to see very well the moment when the mud-guard became separated from the deep-drawn part. At this very moment the number of AE hits of sensors per unit of time n_{AE} increases strongly. This parameter of the AE signal can serve, with cutting-out mode 1, as a good indicator of the end of cutting-out mud-guard. With cutting-out mode 2, however, the greatest number n_{AE} occurs after the end of cut 2, whereas the strongest strains are found in the course of cut 3. A reason for a leap-frogging increase of the value n_{AE} in mode 2 is the combination of cuts 1 and 2 and the resulting leap-frogging change of strain in the mud-guard similar as with cutting-out mode 1.

4. Conclusions

The investigation presented is considered a basic step towards the control and optimization of laser cutting-out process for deep-drawn parts by means of AE measurement.

It was found that the main AE source during laser cutting was the cutting-gas jet. The latter generates continuous AE signals. The laser-cutting process exerts the strongest influence on the maximum amplitude A_{AE}. The acoustic emission present after the laser-cutting process is related to the phenomena in the heat-affected zone at the micro level and to strain at the macro level due to residual-stress relieving in the deep-drawn part. The phenomena concerned occur also during laser cutting, but from the viewpoint of AE measurement they are mainly masked by the continuous signals due to the cutting-gas flow. It turned out that the leap-frogging changes of strain of the mud-guard could be sensed. The leap-frogging change of strain is related to a leap-frogging change of the number of hits per unit of time n_{AE} and a clear change of energy E_{AE}.

From the results obtained it may be inferred that the control of the laser-cutting process by AE measurement provides useful additional information on the process itself and events in the workpiece material. It should be mentioned that applicable data on events in the material can be obtained only with an exacting analysis of the AE signals captured.

5. Reference

[1] Dreyfuss R.H., Bailey S.J. et al: Annual Book of ASTM Standards, Section 3: Metals Test Methods and Analytical Procedures, Vol. 03.03: Nondestructive Testing, ASTM International, Baltimore, 2003.

[2] Vallen H.: AE Testing Fundamentals, Equipment, Applications, NDT.net, Vol. 7, No. 9, 2002 (http://www.ndt.net/article/v07n09/05/05.htm).

[3] Grabec I., Govekar E., Susič E., Antolovič B.: Monitoring manufacturing processes by utilizing empirical modeling, Ultrasonics, Vol. 36, No. 1/5, 1998, 263-271.

[4] Grad L., Grum J., Polajnar I., Slabe J.M.: Feasibility study of acoustic signals for on-line monitoring in short circuit gas metal arc welding, International journal of machine tools & manufacture, Vol. 44, No. 5, 2004, 555-561.

[5] R. D. Rawlings, W. M. Steen: Acoustic Emission Monitoring of Surface Hardening by Laser, Optics and Lasers in Engineering, Vol. 2, No. 3, 1981, 173-188.

[6] Steen W.M.: Laser Material Processing, Springer-Verlag, London, 1996.

[7] http://www.vallen.de/products/amsy4.htm