ACOUSTIC EMISSION AS AN INDICATOR OF LASER-CUTTING QUALITY

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ABSTRACT
The paper presents results of an analysis of acoustic emission (AE) signals captured in the course of laser cutting of a steel sheet, and the analysis of the signals characteristic of particular phenomena occurring after the cutting process. In the course of cutting, continuous signals, which are related to the quality achieved of the laser cut, are measured. After laser cutting characteristic AE bursts in the specimen material, which are results of a thermal influence, can be detected. A relation between the AE bursts and dross formation at the lower edge of the cut is shown. The presence of dross is an important indicator of poor quality of laser cutting. The investigation on laser cutting was conducted on an unalloyed steel DC04 sheet and on austenitic stainless steel X5CrNi18-10 sheet of 1,5 mm in thickness. These grades of steel sheet are frequently used in the production of body components in the automotive industry. In this case laser cutting and welding are often used to give a final shape to functional components. The same physical mechanism in the cut formation at both steels, however, resulted in a considerable different cut quality, which was indicated by the AE signals captured after the cutting process. Further on, an application of AE measurement during laser cutting of a larger deep-drawn product, where the magnitude of residual stresses and, consequently, because of cutting, relaxation and distortion of the cut part are important, is shown.

Keywords: Acoustic emission, laser cutting, burst emission, PZT sensor, dross

1. INTRODUCTION

Laser cutting belongs to thermal cutting processes, in which the material separation is accomplished by local heating with the heat transformed from laser light to the point of melting or evaporation. In the process usually an auxiliary gas, i.e. oxygen, is used, which exothermally reacts with iron and alloying elements and makes material cutting easier. The continuous travel of the laser beam or a workpiece provides a laser cut of the shape desired. The sheet thus formed may be cut into 3D products.
Laser cutting of unalloyed and stainless steels using oxygen is a well-established cutting process in industrial applications and capable of satisfying requirements of numerous users in terms of production costs and quality [1]. In laser cutting of stainless steel with oxygen, however, the dross formation at the lower edge can hardly be avoided, which results in poorer quality of the cut made. The cutting mechanism is the same as in cutting of unalloyed steel,

but during cutting stainless steel oxygen will exothermicaly react both with iron and chromium, and other alloying elements in steel. The oxidation process, however, is less efficient than in cutting of unalloyed steel. In cutting of unalloyed steel the exothermic reaction, having its source of additional heat in the cutting zone, contributes to the formation of iron oxides, which have lower viscosity and lower adhesion to the cut edge of the sheet material, which reduces the risk of dross formation at the lower edge [1]. Higher chromium content in austenitic stainless steel, in comparison to unalloyed steel, exerts a major influence on laser cutting. The occurrence of chromium oxides at the melt surface in the cutting front hinders the oxidation of the remaining melt. In spite of tearing of the chromium oxides quite some unoxidised melt persists in the cutting zone. The unoxidised melt exhibits good adhesion to the substrate, which prevents complete blowing-out of the melt from the laser front by the oxygen jet. This will result in the dross formation at the lower edge of the laser cut. Surface tension of the chromium oxides is also higher than that of the melt in laser cutting of unalloyed steel, which additionally contributes to the increased dross formation [1].

The melt solidification on the cut face and in the dross, and subsequent cooling, upon the termination of the cutting process, results in various phenomena occurring in the material, which can be sensed as AE bursts. The AE bursts are caused by cracking of the oxide layer due to the difference in the coefficient of thermal expansion of the oxide layer and that of the sheet material [3]. The AE bursts are produced also by crack and microcrack initiation and propagation. Microcrack initiation or propagation shows in momentary energy releases at the microscopic level, which results in elastic waves in the material. A metallographic analysis of the laser-cut surface will confirm that the point of initiation and propagation of microcracks is usually limited to the dross and to the lower edge of the laser cut.

The occurrence of acoustic signals can be attributed to phase changes, i.e. martensite formation after rapid cooling of austenite. Distinctive acoustic emission may be expected in twinning deformation, which may accompany the martensite transformation occurring [2]. The AE burst signals with lower amplitude values of a voltage signal may result from the events related to the microplastic deformation of the material, the nucleation and sliding of dislocations [6]. Acoustic emission may result also from bonding defects during dross cooling, porosity and microcavities in the solidified material. An evaluation should also consider reflection of the AE signals from the specimen walls or other obstacles [7].

2. EXPERIMENTAL PROCEDURE

Laser cutting of sheets was carried out with an industrial CO_2 laser Spectra Physics 820. Its laser beam had a TEM_{00} power distribution. The lens used had a focal distance of 127 mm. During cutting the laser focal point was positioned 0,5 mm below the upper sheet surface. The cutting gas used was oxygen with an overpressure of 0,2 MPa. The laser nozzle used had a conical shape and an output diameter of 2,2 mm. The distance between the nozzle and the sheet surface was 1,5 mm. The respective laser-cut sheets with a thickness δ of 1,5 mm were made of unalloyed deep-drawing steel DC04 (EN 10027-1) and of austenitic stainless deep-drawing steel X5CrNi18-10 (EN 10027-1). These steel grades are frequently used in the production of body components in the automotive industry. During laser cutting a sheet was positioned on soft-rubber supports arranged in segments so as to prevent any noises due to sheet rubbing against the workbench of the laser system. Under different laser-cutting conditions, parallel cuts Lc = 300 mm in length and with spacing of 20 mm were made. For

cutting, laser-beam powers of 430, 500, 570 and 640 W and cutting speeds of 1000, 1500, 2000 and 2500 mm/min were used.
For the detection of acoustic emission a contact PZT sensor VS150-M, a product of Vallen Systeme GmbH, was used. The sensor makes it possible to measure ultrasonic waves in a frequency range between 100 and 450 kHz. A good acoustic coupling of the sensor with the sheet surface is accomplished by an intermediate deposit of silicon grease between the sensor and the sheet at the point of their contact. The sensor is connected to an AE measuring device AMSY4 (Vallen Systeme GmbH), via a pre-amplifier AEP4. An AE voltage signal is amplified, filtered and transformed into a digital signal by means of modification elements in an acoustic signal pre-processor ASIPP. The digital signal is fed to a unit determining signal parameters. ASIPP also enables signal squaring and transient recording of the digital form of the AE time signal. From the unit for parameter determination the signal is fed to a digital signal processor DSP. The latter permits temporary data storage and calculates floating threshold. The DSP unit is connected to a personal computer AMSY4-PC, which makes it possible to analyse the measured AE signals in modules VISUAL AE and VISUAL TR.

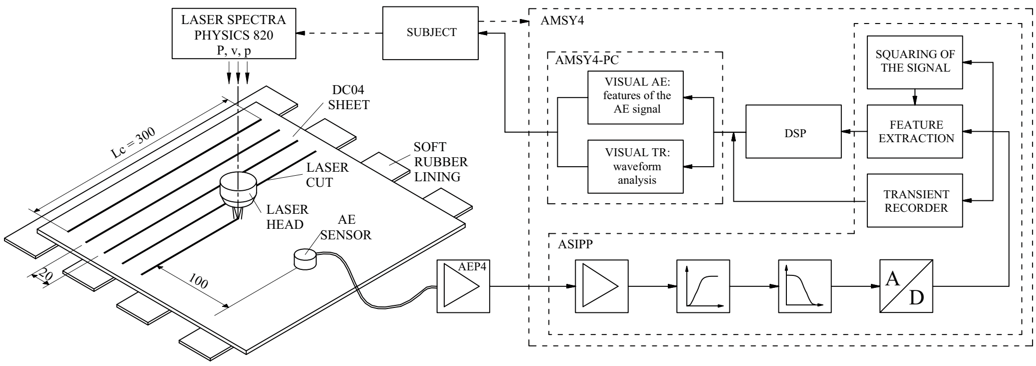


Fig. 1. AE capture during and after laser cutting of flat sheet.

3. EXPERIMENTAL RESULTS

During the laser cutting process a turbulent flow of the cutting gas produces continuous AE signals. In a continuous signal changes, of the signal amplitude and frequency can be detected. The continuous AE signals for the control of the cutting process are limited to duration of 0.1 s. The highest amplitudes during the signal duration are shown in Fig. 2 with a point. In case of cutting with a power 430 W and speed 1000 mm/min, signals with a relatively uniform amplitude value in the continuous signal can be measured. A lower energy input at the interaction zone caused by an increased cutting speed will result in a lower melt temperature and, consequently, in increased melt viscosity. The portion of the oxidized melt will decrease too. When the melt flows out from the cutting front, droplets will form at the lower cut edge. When the forces due to gas flow cannot exceed the adhesion forces of the melt to the sheet surface, the melt leftover will solidify in the form of droplets at the lower cut edge, i.e. dross will form. The solidification of the molten material persisting at the lower cut edge and cracking of the oxide layer will produce AE bursts in the continuous signal. Distinctive AE bursts increase the amplitude value in the continuous signal, which is shown

in Fig. 2b. More information on the influence of the laser cutting conditions on continuous AE signals is given in Ref. [4].
When cutting is stopped, acoustic emission in the form of bursts with appertaining signal duration can still be captured. The signal duration is a time interval between the first and last transition of the absolute signal voltage value across the amplitude threshold set, i.e. 0,1 mV (40 db). The individual points at Fig. 2, after the termination of cutting, represent the amplitude values of the AE bursts. A comparison of the signal amplitudes in Figs. 2a and 2b indicates a characteristic difference among the captured continuous AE signals as well as in the AE activity after laser cutting under different conditions. The AE activity, n_{AE}, defines the number of signals detected per unit of time (1 second). The increased AE activity is related to the size of the dross formed at the lower cut edge and is, consequently, an important indicator of laser-cut quality. The analysis of the number of AE bursts after the termination of the laser cutting process will be treated next.

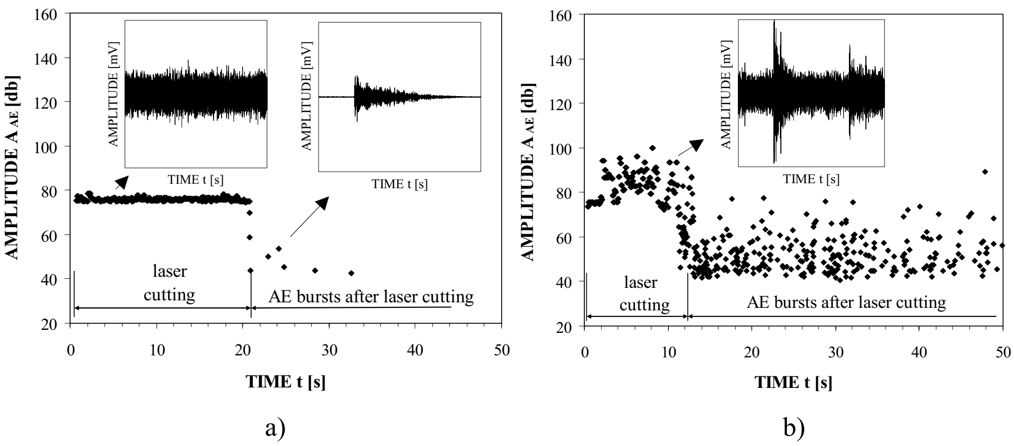


Fig. 2. Acoustic emission during and after laser cutting of DC04 steel sheet under two laser cutting conditions: a) P = 430 W, v = 1000 mm/min and b) P = 430 W, v = 2500 mm/min.

3.1. LASER CUTTING OF UNALLOYED STEEL DC04

The presence of dross at the lower cut edge is shown by AE bursts after the termination of laser cutting. Figure 3 shows amplitude distribution of AE burst signals immediately after the termination of cutting of the flat sheet in the duration of 30 s. The number of the bursts exceeding the chosen signal amplitude levels $A_{AE,N}$, i.e. 40 db, 50 db, ..., 90 db, is marked NA_{AE}. The number of the bursts NA_{AE} at the signal amplitude level of 40 db is thus equal to the total number of the bursts $N_{AE,30s}$ in a time period of 30 s immediately after the termination of laser cutting. It was found that the mutual dependence of the number of bursts NA_{AE} and the signal amplitude levels $A_{AE,N}$ can be described with an exponential function. A greater distance of an exponential trend line from the origin of the coordinate system in the diagrams in Fig. 3 shows the higher AE activity. Higher AE activity is related to the dross formation at the lower laser-cut edge.
A statistical analysis of the height and width of the individual characteristic portions of the dross measured at the metallographic specimens shows a strong dissipation of the dimensions measured. Consequently, it was decided to evaluate the dross size at the lower cut edge with the grades ranging between 0 (perfect – no dross) and 5 (poor – large dross). Figure 4 shows

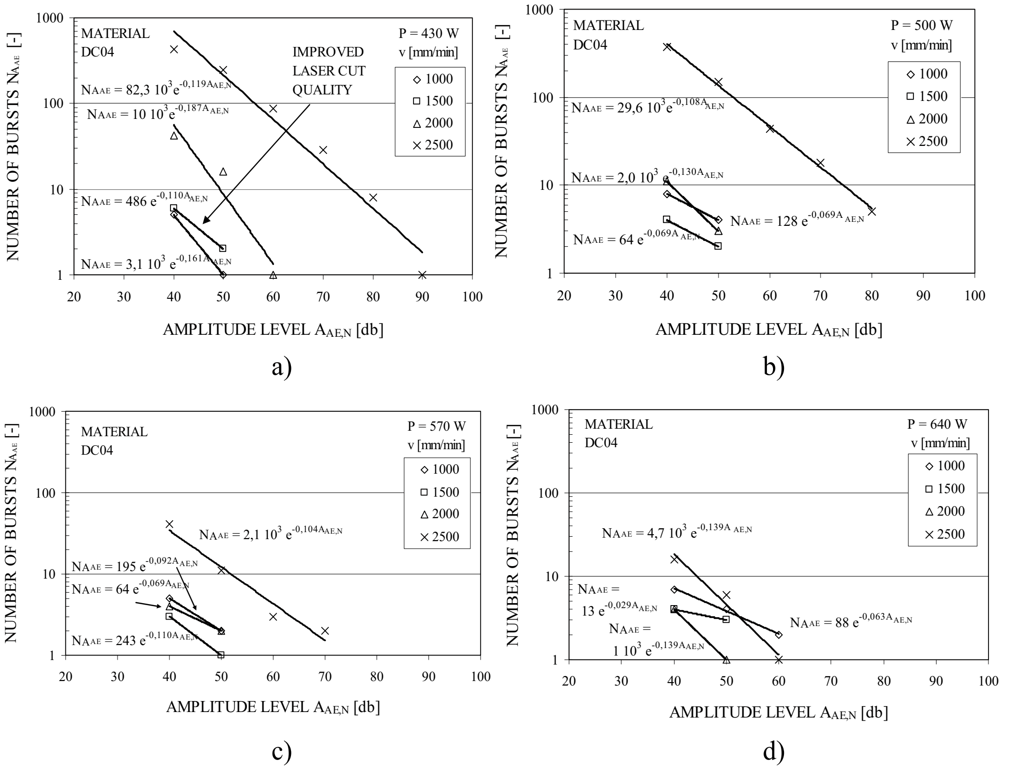
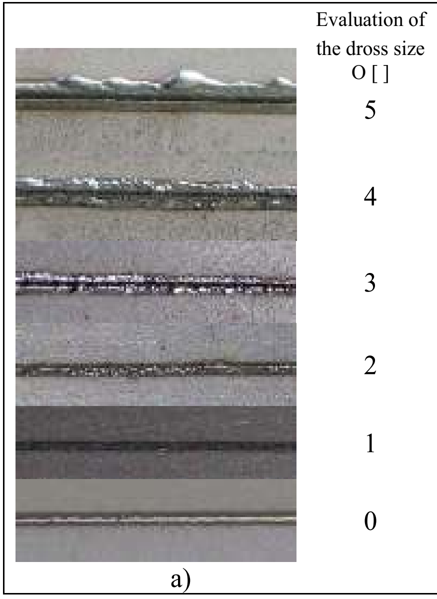
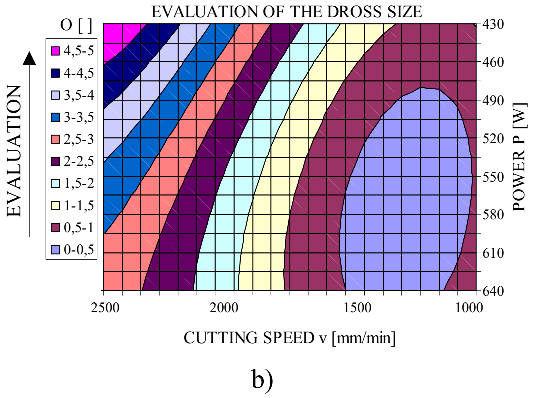


Fig. 3. Number of AE bursts N_{AAE} above various AE signal amplitude levels $A_{AE,N}$ after laser cutting with different powers: a) P = 430 W, b) P = 500 W, c) P = 570 W, d) P = 640 W.





Slika 4: a) Reference image of the lower laser-cut and accompanying evaluation of the dross size and b) influence of the laser cutting conditions on evaluation of the dross size.

reference images of the lower laser-cut edge and the manner of evaluating the cut quality with reference to the dross size. A distinctive dross enlargement can be detected with smaller energy inputs of a laser-beam to the cutting front.

Figure 5 shows a mutual dependence of a cumulative number of the bursts in a time period of 30 s after termination of laser cutting $N_{AE,30s}$ and the evaluation of dross size O in cutting of the flat sheet DC04. The enlarged dross will show in a higher cumulative number of bursts $N_{AE,30s}$. A poorer mutual dependence can be noticed only with lower values $N_{AE,30s} < 10$, i.e. in the range of acceptable dross size at the lower laser-cut edge. A circle in Fig. 5 marks number $N_{AE,30s}$ after the 1st and 3rd laser cut, and with a square number $N_{AE,30s}$ after the 2nd laser cut in cutting of a mud-guard from a deep-drawn part. A good agreement with the results of laser cutting of the flat sheet can be stated.

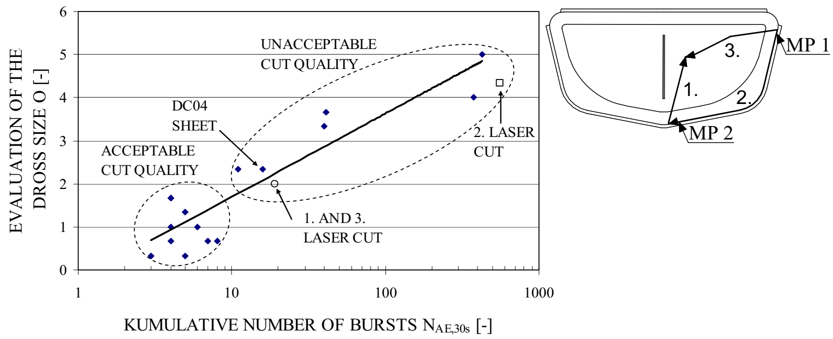


Fig. 5. Dependence between number of AE bursts $N_{AE,30s}$ and evaluation of dross size O.

3.2. LASER CUTTING OF AUSTENITIC STAINLESS STEEL X5CrNi18-10

The laser cuts obtained at austenitic stainless steel differ from those obtained at unalloyed steels. With stainless steels a laser-cut surface doesn`t show pronounced striations [5]. Surface roughness of a laser cut at stainless steels results primarily from rapid solidification of a thin film of the melt flowing out during cutting. The laser-cut surface is covered by the oxide layer consisting of a mixture of iron (Fe_2O_3) and chromium oxides (Cr_2O_3). The portions of the iron and chromium oxides in the oxide layer are approximately equal, which indicates higher affinity of chromium to oxygen atoms in comparison to iron atoms [1]. The ratio of iron to chromium in the substrate is namely ~ 3,8:1. The chromium content in the substrate is ~ 18 % and that of iron ~ 69 %. During laser cutting the hot melt in the cutting front is exposed to the oxygen jet. The iron and chromium atoms enter an oxidation reaction. Greater affinity of chromium results in a higher chromium content at the outer layer of the melt flowing out and lower chromium content below the oxide layer. Below the oxide layer there is a quickly solidified layer of the unoxidised substrate. This results in a re-solidified melt holding to the substrate and the presence of dross at the lower cut edge. Larger amounts of the solidified oxides and of the substrate at the cut surface and in the form of dross at the lower cut edge in comparison with unalloyed steel were confirmed also by the results of the analysis of the AE bursts after the termination of cutting. Figure 6 shows the amplitude distributions of AE burst signals in a period of 30 s after the termination of laser cutting of the flat sheet of steel X5CrNi18-10. The results shown refer to cutting with a power P = 430 W and with various cutting speeds. Similarly as with DC04 steel, an exponential trend line can be attributed to the amplitude distributions. In cutting with different cutting speeds but with the same power, i.e. 430 W, different qualities of the cut will be obtained. The latter are indicated also by the appertaining reference images of dross at the lower cut edge. Similarly as with unalloyed steel, poorer cut quality will show in a larger number of bursts after the termination of cutting. A reduced cutting speed with the power chosen permits a higher energy input into the cutting front. This results in scarcer occurrence of dross and a cut of higher quality, which is confirmed by a displacement of the exponential trend line towards the origin of the coordinate system in the diagram of the amplitude distribution of AE signals.

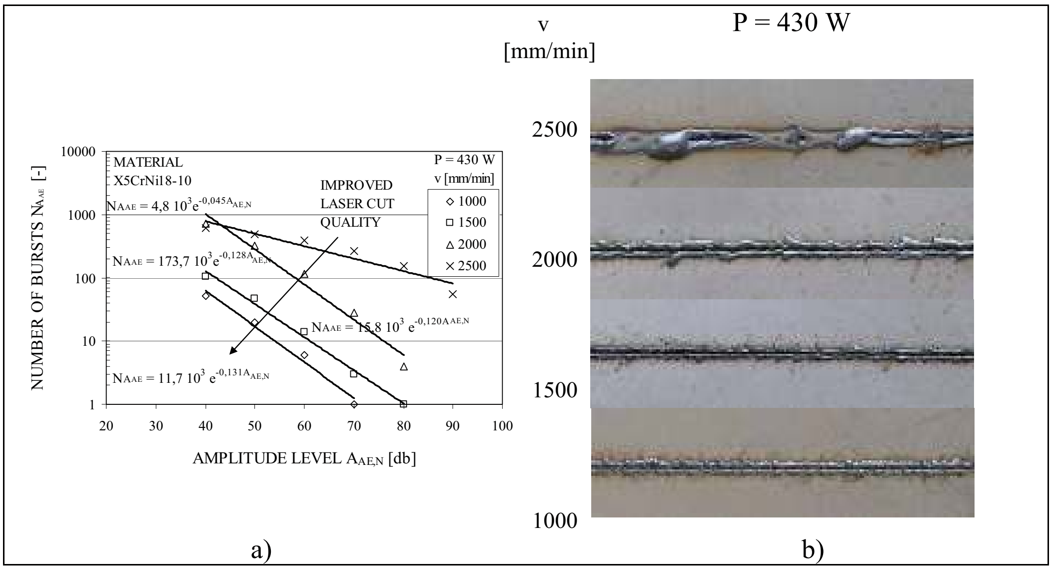


Fig. 6. a) Number of AE bursts NAAE above selected amplitude levels of AE signals $A_{AE,N}$ immediately after termination of laser cutting of sheet X5CrNi18-10 with power P = 430 W and b) images of dross at lower cut edge.

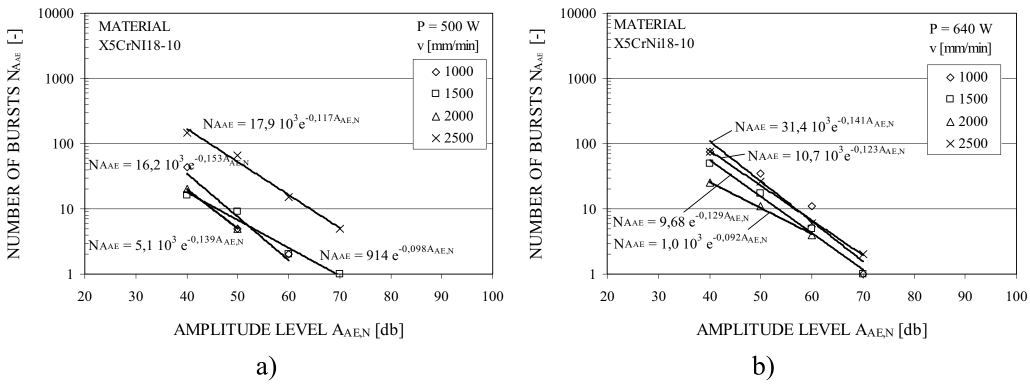


Fig. 7. Amplitude distribution of AE burst signals after laser cutting of austenitic stainless steel under different conditions: a) P = 500 W, b) P = 640 W.

Figure 7 shows the amplitude distributions of AE burst signals in a period of 30 s after the termination of laser cutting taking into account the other laser-beam powers. In laser cutting of the sheet X5CrNi18-10 under the cutting conditions chosen within a wide range of energy inputs, the occurrence of dross at the lower edge could not be avoided. Also, smaller differences in the dross size will occur, which is confirmed by the proximity of the exponential trend lines. The difference in the dross size with the chosen conditions of laser cutting of stainless steel X5CrNi18-10 is less distinctive than in cutting of sheet DC04, which was confirmed also in the analysis of AE bursts.

3.3. LASER CUTTING OF A DEEP-DRAWN PART

With unalloyed steels, the acoustic emission after the termination of laser cutting of a sheet makes it possible to very successfully predict the quality of a laser cut under different cutting conditions. Poorer quality is noticed with an increased number of AE bursts after the termination of cutting, which is shown in an increased activity n_{AE}. The increased activity n_{AE} is a result of the way the AE signals are treated. In the analysis the continuous signals were divided into defined time intervals of 0,1 s each. This means that the AE activity with the continuous signals does not exceed a value of 10/s. In case the AE bursts occur after the termination of cutting, the signal duration is less than 0,1 s because of which the AE activity can be essentially higher. Figure 8 shows an AE activity during cutting mud-guard out from a larger deep-drawn part made of DC04 sheet of 1,5 mm in thickness. During and after cutting at selected measuring points, i.e. MP1 and MP2, acoustic emission was monitored with the PZT contact sensor. The signals captured showed that the activity mightily increase after the 2nd cut. This indicates a poorer quality of the 2nd cut in comparison to the 1st and 3rd cuts.

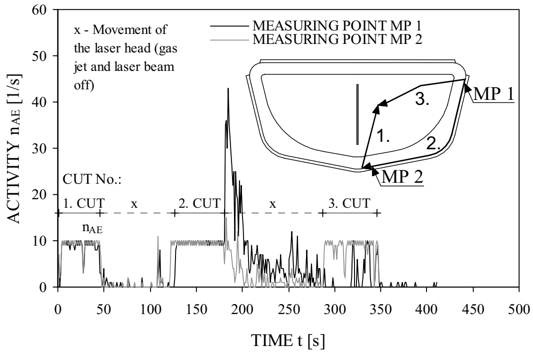


Fig. 8. Activity n_{AE} of AE signals during and after cutting operations in laser cutting of deep-drawn part.

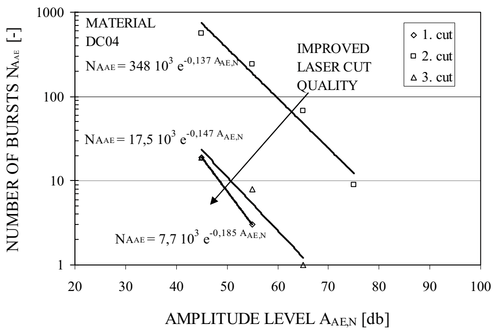


Fig. 9. Amplitude distribution of AE burst signals in laser cutting of mud-guard.

Figure 9 shows the amplitude distribution of the AE burst signals immediately after individual laser cuts in a period of 30 s. The highest number of bursts N_{AAE} was obtained after the 2nd cut. A higher number of AE bursts after the 2nd cut indicates the occurrence of larger dross at the lower cut edge. This is a result of cutting at an acute angle to the surface of the sheet due to the specific shape of the deep-drawn part.

4. CONCLUSIONS

AE monitoring in laser cutting with the PZT contact sensors makes it possible to efficiently control the quality of laser cutting. A good agreement between the quality of a laser cut and the number of bursts after the termination of laser cutting of the sheet made of unalloyed steel DC04 was found. The results of AE measurements confirm that more intense acoustic emission after the termination of laser cutting indicate the presence of larger dross at the lower cut edge. Intense acoustic emission in the form of bursts is mainly attributed to cracking and peeling-off of the oxide layer formed at the surface of the laser cut and dross. The presence of dross increases the amount of the oxide layer.

With a quantitative way of treating AE signals, the determination of quality of the laser cut is more demanding in cutting of the sheet made of austenitic stainless steel X5CrNi18-10 under different conditions than in cutting of unalloyed steel. This is a result of the presence of distinctive dross under different laser-cutting conditions used, which is a result of an increased Cr concentration in the substrate.

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