AE SIGNALS DURING LASER CUTTING OF DIFFERENT STEEL SHEET THICKNESSES

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Abstract

Laser cutting is an established industrial method for cutting of various steels in the production process. However, each laser cut poses a question of quality estimation during and immediately after the laser cutting process. The capturing and evaluating of acoustic emission (AE) signals reveals a great potential for the laser cut quality estimation. This paper presents the results of the AE bursts measurement after the laser cutting of steel sheets of various thicknesses using oxygen or nitrogen as cutting gas. The method of the laser cut quality estimation described here was applied to the austenitic stainless steel, mild steel, and structural steel. The laser cut quality, which is related to the size of the dross and the waviness of the cut surface can be successfully forecast based on the captured AE signals.

Keywords: Burst acoustic emission, laser cutting, PZT sensor, dross, unalloyed steel, austenitic stainless steel

Introduction

The price of the equipment and operation costs are considerable when it comes to laser systems, but the higher cost is well justified by exceedingly faster treatment processes as well as good dimensional accuracy and repeatability. Laser cutting quality depends mainly on the selection of the process parameters that were established with trial and error method. Changes in the beam quality, gas flow and surface of materials can lead to reduced laser cut quality. In order to eliminate these weaknesses, the monitoring and adequate adjustments of the treatment need to be ensured.

Laser cut quality is defined primarily by the condition of the laser cut surface and the presence of the re-solidified material occurring as dross at the lower cut edge. The condition of the laser cut surface is defined to a great extent by the occurrence of striations. There are a number of interpretations of mechanisms of striation formation. The three more important models are presented below.

1) Schuöcker attributed the periodic striation formation to a pulsation of the melt layer on cutting front. The fluctuations in the laser beam energy absorption and reactive gas flow causes thickness and temperature oscillations of the melt layer (Schuöcker 1987). The fluctuations in the laser beam energy absorption can be influenced by the periodic nature of the laser beam or the changes in the material’s absorptivity. The changes in the heat generated by the oxidation reaction can be the result of an oscillation in the cutting gas flow due to the turbulences in the laser cut.

2) The second model describing striation formations on the laser cut surfaces was introduced by Arata, Miyamoto and Maruo and is generally more established. They defined the laser cutting mechanism as ignition and extinction of oxidation reaction (Arata et al. 1979). The model is convincing in explaining the formation of striations on the laser cut surface. However, certain researchers consider it as a quality model with lacking mathematical definition (Di Pietro and
Yao 1995). Despite this incomplete definition of the cutting process, it nevertheless offers the most widely adopted definition of striation formation occurring on the laser cut surfaces during the cutting processes performed on structural steels.

(3) Arata’s model was upgraded by Iverson and Powell by describing more accurately the cyclic laser cutting oxidation processes (Iverson et al. 1994). The speed of the oxidation reaction depends on oxygen diffusion in the cutting front, which changes with time. At the beginning the oxidation velocity is high, but it rapidly reduces as the thickness of the oxide layer increases. This means that the oxide layer thickens intensely in the initial phase and then gradually slower. If the oxide layer is sufficiently thick, the oxygen flow can blow it off the cutting front surface and a new oxidation cycle will begin. The most important contribution by Iverson and Powell is an explanation of the termination of the oxidation process during laser cutting.

The waviness of the laser cut surface depends on the laser cutting parameters. Striving for a more cost-efficient laser cutting by accelerating the cutting speed increases the waviness of the laser cut surface and even causes deterioration in striation pattern, mainly at the lower cut edge. This in turn reduces laser cut quality. Accelerating the cutting speed also leads to an accumulation of the re-solidified material at the lower cut edge. A lower energy input at the interaction zone caused by increased cutting speed results in lower temperature and increased viscosity of the melt. The portion of the oxidized melt also decreases. When the melt flows out from the cutting front, droplets 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’s leftover solidifies 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 edge and the cracking of the oxide layer produce AE bursts in the continuous signal.

With the AE signals captured during and immediately after the termination of laser cutting process, the deterioration of the laser cut surface and occurrence of dross formation at the lower cut edge can be detected. It has been determined that captured AE signals offers good information for controlling the laser cutting process in order to ensure high laser cut quality.

**Experimental Procedure**

The laser cutting of steel sheets was performed using a CO₂ laser system with a TEMₐ₀ laser beam power distribution. The steels used in the process were unalloyed deep-drawing steel DC04 of 1.5-mm thickness and austenitic stainless deep-drawing steel X5CrNi18-10 of 1.5-mm thickness. Both types are commonly used in the production of automotive body parts. Oxygen was used as cutting gas. In addition to the thinner steel sheets, structural steel St37 of 8-mm thickness and austenitic stainless steel X5CrNi18-10 of 6-mm thickness were laser cut, using oxygen and nitrogen, respectively.

During the laser cutting process, the steel sheets were positioned on a soft rubber support to eliminate noise. For the detection of AE, a contact resonant PZT sensor was used. The sensor measures ultrasonic waves in a frequency range between 100 and 450 kHz. The sensor was connected to an AE measuring device, via a pre-amplifier.

**Laser Cutting of Unalloyed Steel with Different Thicknesses**

During the laser cutting process, a turbulent flow of the cutting gas produces continuous AE signals, in which changes of the signal amplitude and frequency can be detected (Kek et al.
Laser cut quality depending on the laser cutting parameters can be determined from both the continuous signals and AE bursts after the termination of laser cutting. Figure 1 shows the influence of the position of the laser-beam focal point regarding the sheet’s surface on the AE signals captured during laser cutting. Due to the bent steel sheet and the straight movement of the laser head the laser-beam focal point moves away from its ideal position, which reduces the energy density in the cutting front leads to poorer cut quality and dross formation. The solidification of the molten material persisting at the lower cut edge and the cracking of the oxide layer produce AE bursts in the continuous signal and an increase of the amplitude value in the continuous signal.

![Diagram showing the influence of the position of laser-beam focal point during laser cutting on the AE signals. DC04, \( \delta = 1.5 \text{ mm} \), P = 430 W, O\(_2\), v = 1500 mm/min.](image)

Figure 2 shows the changes in laser cut quality that occur with the changing of the cutting speed with constant power. A pronounced dross growth can be detected at the lower cut edge with deviation from ideal parameters of the laser cutting. There is no formation of secondary striations on the laser cut surface in the cutting of the unalloyed steel sheet DC04 (\( \delta = 1.5 \text{ mm} \)). Only a change in striation form at the lower cut edge can be seen with greater cutting speeds. The reduced laser cut quality in the cutting of thinner steel sheets is attributed mainly to dross formation at the lower edge.

Striations can be divided to primary and secondary. Primary striations are generally detected in the laser cutting of thin low-carbon steel sheets using oxygen. In the cutting of steel sheets thicker than 2 mm, primary striations occur only in the upper part of the cut, while in the lower part usually more random pattern of secondary striations is formed. As a rule, it can be said that the lower cut edge is more closely linked to the forces causing the ejection of the melt due to shear and the pressure gradient, which are connected to the gas flow (Iverson et al. 1994, Shariff et al. 1999). Therefore, the highest quality of the lower surface can be obtained when the local maximum of the gas mass flow rate has been reached, which is connected with a turbulence of gas stream flowing to the cutting front.
Fig. 2. a) Images of dross at lower cut edge at cutting of DC04 with different cutting speeds ($\delta = 1.5 \, \text{mm, O}_2$).
b) laser cut surface at $v = 1000 \, \text{mm/min}$ and
c) laser cut surface at $v = 2500 \, \text{mm/min}$.

Fig. 3. Laser cut surfaces of the structural steel St37 for different laser cutting parameters.
Figure 3 shows the influence of different cutting speeds on the quality of the laser cut surface in the structural steel sheets St37. This figure also shows characteristic pattern of primary and secondary striations. Degradation of the secondary striation pattern at the lower part of laser cut, and a greater surface waviness, are important indicators of laser cut quality. In this case, reduced laser cut quality is not to be attributed to greater dross formation.

On the basis of the captured AE signals, laser cut quality level can successfully be determined in instances of dross formations at the lower cut edge and changes (degradation) of striation patterns.

When cutting is stopped, AE in the form of bursts with appertaining signal duration can 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). Figure 4 shows the relation between AE bursts and laser cut quality after termination of laser cutting of the DC04 steel sheet (δ = 1.5 mm). The distance of the exponential trend line from the origin of the coordinate system indicates laser cut quality. In comparison, Figure 5 shows AE bursts obtained in the considerably thicker structural steel St37 (δ = 8 mm). A distinct Fe₂O₃ oxide layer can be noticed on the mild steel and structural steel laser cut surfaces. Different coefficient of thermal expansion and the resultant shear stresses between the base material and the oxide layer cause the oxide layer to crack and peel during cooling, which provokes intensive burst AE. The formation of dross or intensive striation pattern on the surface of the laser cut results in an increased area of the oxide layer, which is reflected in the measured AE. Thicker steel sheets therefore reveal a greater number of AE bursts. Although no significant dross formation occurs at the lower cut edge during the cutting of the thicker structural steel sheet, its quality can nevertheless be evaluated.

![Amplitude distribution after termination of laser cutting of DC04 steel sheet, using oxygen.](image)

**Laser Cutting of Austenitic Stainless Steel Sheet with Different Thicknesses and Different Cutting Gas Jets**

The laser cuts obtained with austenitic stainless steel differ from those with unalloyed steels. With stainless steels a laser-cut surface does not show pronounced striations. Surface roughness
Fig. 5. Amplitude distribution after termination of laser cutting of St37 steel sheet, using oxygen.

of a laser cut on 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 (Fe₂O₃) and chromium oxides (Cr₂O₃). 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 (Powell 1993). 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 unoxidized substrate. This results in a re-solidified melt holding to the substrate and the presence of dross at the lower cut edge (Fig. 6). 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.

High-quality cuts can be produced by using pressure inert-gas jet rather than the more usual oxygen jet. The quality is superior to laser-oxygen cutting, but production costs are up to three times higher. Cutting mechanism is melt shearing. The resulting cut surface on austenitic stainless steel is unoxidized. The absence of oxidation means that the cut edge will have the same corrosion resistance as the bulk material. Also the cut edges may be welded without any post-cutting preparation. Greater thicknesses of stainless steel can be cut by high-pressure inert-gas cutting than are possible by oxygen cutting, but speeds are very low. Figure 7 shows the laser-cut surfaces obtained in the cutting of the austenitic stainless steel X5CrNi18-10 of 6-mm thickness, using nitrogen. Although the nitrogen is not completely inert gas, this is also used in place of inert gas. The reason nitrogen was chosen over the completely inert argon is the cost.
Fig. 6. a) Images of dross at lower cut edge by cutting with different cutting speeds. b) Laser-cut surface at $v = 2000$ mm/min. (X5CrNi18-10, $\delta = 1.5$ mm, $P = 430$ W, $O_2$).

Fig. 7. Austenitic stainless steel laser surfaces for different process parameters. (X5CrNi18-10, $\delta = 6$ mm, $P = 2.4$ kW, $N_2$).

Figure 8 shows the amplitude distributions of AE burst signals in a period of 30 s after the termination of laser cutting of the flat X5CrNi18-10 steel sheet. The results shown refer to cutting with a power $P = 430$ W and with various cutting speeds. Similarly as with DC04 steel, an
A fitted exponential trend line can be used to analyze amplitude distributions. Cutting with different speeds but at the same power, i.e., 430 W, results in varying cut qualities. Lower quality is indicated by a higher number of acoustic emissions (bursts) post-cutting. A reduced cutting speed with a chosen power allows for more energy input at the cutting front, leading to less dross and higher quality cuts, confirmed by a trend line shift towards the origin in the amplitude distribution graph.

**Fig. 8.** Amplitude distribution after laser cutting of austenitic stainless steel sheet X5CrNi18-10, \( \delta = 1.5 \) mm, using oxygen.

**Fig. 9.** Amplitude distribution after laser cutting of austenitic stainless steel sheet X5CrNi18-10, \( \delta = 6 \) mm, using nitrogen.
Greater differences in the captured AE signals are found when laser cutting of austenitic stainless steels is performed with nitrogen (Fig. 9). Using nitrogen as cutting gas significantly reduces the oxidation of the laser cut surface. The whirling of the gas at the lower part of the cutting edge induces the oxidation of a smaller section of the heated material, which results in AE bursts even in excellent cuts. In case of dross formation, the surface of the oxide layer increases and causes the exponential trend line to move away from the origin of the coordinate system. Comparing Figs. 8 and 9, a marked difference can be noted in the measured AE bursts between the cutting processes using oxygen and nitrogen, even with four times greater thicknesses.

Conclusions

The following conclusions can be drawn from the analysis of the AE signals captured during laser cutting process:
- The AE signals captured during the laser cutting process and immediately after its termination allow the estimation of laser cut quality defined by the state of the laser cut surface and the occurrence of dross at the lower cut edge.
- The measurements confirm that this method of laser cut quality determination is applicable to unalloyed and alloy steels with different thicknesses.
- The method of the laser cut quality estimation was performed for laser cutting using oxygen and nitrogen as cutting gases.
- The laser cut quality estimation requires a prior system calibration for various types of materials and cutting gases.

The new AE monitoring technique described in this paper was developed at the Faculty of Mechanical Engineering, University of Ljubljana, and proves to be a promising method of the laser cutting production monitoring system.

References

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