Analysis of Heat Effects in Laser Cutting of Steels

J. Grum and D. Zuljan

Efficient control of laser cutting processes is closely related to knowledge of heat effects in the cutting front and its surroundings. Similar to other machining processes using high power densities, in laser cutting processes it is very important to monitor the heating phenomena in the workpiece material due to heat input. In laser cutting processes with oxygen as an auxiliary gas, cutting energy is a combination of laser beam energy and the energy of the exothermic reactions occurring in the cutting front. The presence of oxygen in the process increases cutting efficiency, but also causes additional physical processes in the cutting front that render a more detailed analysis of the cutting phenomena difficult. The aim of this article is to analyze the emission of infrared rays from the cutting front with a photodiode, statistically analyze the temperature signals, and optimize the laser cutting process based on a critical cutting speed. The measured infrared radiation temperature signal was, on the basis of calibration, converted into a temperature that was related to the formation of macro- and microstructures and to the change in microhardness in the surface layer of the cut. On the basis of experimental results, it was proved that heat effects in the cutting front decisively influenced the quality of cut. Finally, factor analysis was used to establish statistical relations among variables of the laser system, variables of the cutting process, and geometrical characteristics of the cut.

Keywords

austenitic stainless steel, factor analysis, geometrical characteristic of cut, laser cutting, laser cutting parameters, temperature, temperature signals

1. Introduction

THEORETICAL investigations of temperature in the vicinity of the cutting front were carried out for gas welding by Rosenthal (Ref 1) and for laser cutting by Rykalin et al. (Ref 2), Schuöcker (Ref 3), and Arata et al. (Ref 4). The Rykalin analysis was limited to a circular laser source, such as Gaussian source, and to the determination of the temperature on the surface of the cutting front. Olsen (Ref 5) very carefully analyzed the cutting front, plotting isothermal lines and then determining the thickness of the molten and recrystallized layers of the workpiece material. One of his important findings is that in the case of a high temperature gradient, a thin layer of the molten and recrystallized material and a small thickness of the heat-affected zone (HAZ) are obtained, which ensures a good, uniform quality of cut.

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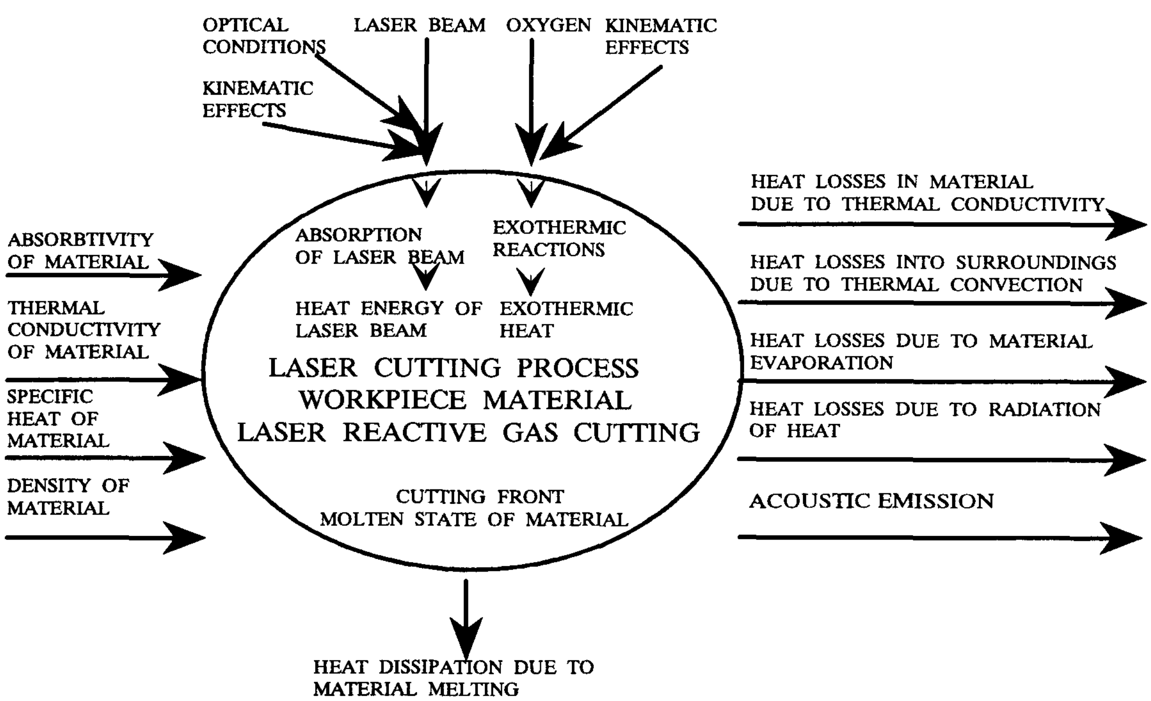


Fig. 1 Inventory of heat effects in the cutting front in laser cutting with coaxial supply of oxygen as an auxiliary gas

Rajendran (Ref 6) used thermoelements for temperature measurement in the vicinity of the cutting front and then analyzed the so-called temperature cycles. He found that the cut quality is strongly related to the temperature gradient in heating and cooling.

Chryssolouris (Ref 7) surveyed the various ways of sensing individual physical phenomena in the workpiece material during laser cutting processes. He studied various possibilities of temperature measurement and acoustic emission perception and presented several methods of on-line monitoring of the temperature in the cutting front and of acoustic emission in the workpiece material.

2. Experimental Procedure and Results

Experimental testing was carried out on a laser machining system (ISKRA-LMP 600; Fotona, Ljubljana, Slovenia) with a laser power of up to 600 W and with a positioning table speed from 2 to 50 mm/s. In laser cutting, oxygen was supplied as auxiliary gas, contributing additional exothermal heat to the process and blowing the molten metal and oxides away from the cutting front.

Figure 1 presents a schematic description of various physical processes occurring in the workpiece material during laser cutting using the selected laser source power and optical and kinematic conditions of the system. When describing a laser cutting process, account should be taken of energy input into the workpiece material, which varies due to a partially pulse-type operation of the laser generator and different laser beam absorption in the workpiece. The most important influence on the temperature in the cutting front is exerted by various exothermal chemical processes. During laser cutting, thermal losses occur due to material evaporation that is too strong, heat transfer into the surroundings of the workpiece material, heat radiation into the surroundings, and energy loss due to acoustic emission.

Table 1 Constant machining conditions of the laser machining system

Parameter,	
Laser power (*PL*), W	450
Focal distance of the lens (*zf*), mm	63.5
Focal point/workpiece distance (*g*), mm	0.0
Nozzle/workpiece surface distance (*s*), mm	2.0
Nozzle diameter (*d*), mm	1.0
Oxygen pressure (P_{O_2}), bar	4.5
Gas flow, L/min	80
Test pieces (plates), mm	100 × 100

Table 2 Laser cutting process variables

Material designation (ASTM)	Material thickness, mm	Cutting speed, mm/s
Austenitic stainless steel (A276-82A)	0.6	35, 40, 45, 50
	0.8	30, 35, 40, 45
	1.0	25, 30, 35, 40
	1.5	20, 25, 30, 35
Low-carbon steel (A620)	2.0	30, 35, 40, 45

Investigations were carried out applying a commonly used austenitic stainless steel alloyed with chromium and nickel 18/10 (ASTM A276-82A). The other steel grade studied was a low-carbon structural steel (ASTM A620).

In order to study the processes in the cutting front and investigate the quality of cut, certain parameters were selected as process constants and other parameters as process variables. Table 1 lists constant process parameters, such as laser power, characteristics of the optical system, and characteristics of the shape and arrangement of the nozzle designed for coaxial supply of oxygen as auxiliary gas, oxygen pressure, and workpiece size. Table 2 presents the laser cutting process variables.

This article presents a part of the results obtained in the investigation on indirect temperature measurement by means of infrared radiation intensity emitted from the cutting front. The aim of the temperature measurement was to monitor thermal phenomena in the cutting front in the laser cutting process with coaxial supply of oxygen as the auxiliary gas, which causes not only laser beam power but also additional exothermal heat that affects the temperature changes in the cutting front.

For this purpose, the following activities were carried out:

- Assembly of a sensor for measurement of infrared radiation from the cutting front
- Elaboration of a system of analysis and assessment of temperature signal measurements
- Macro- and microanalyses of the cutting edge based on measurement of geometrical characteristics of the cut

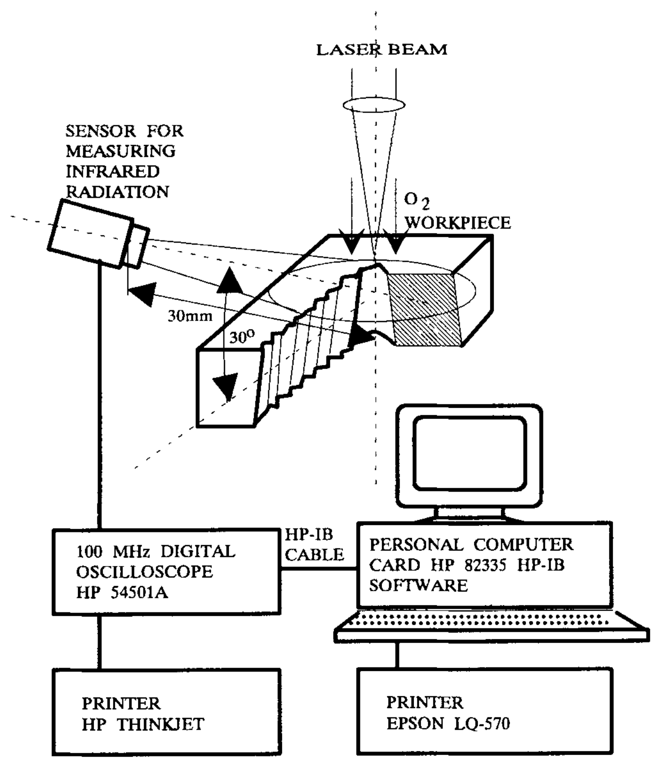


Fig. 2 Setup for temperature signal measurement by means of IR radiation

- Statistical analysis, known as factor analysis, of variables of the laser machining system and of geometrical characteristics of the cut
- Optimization of the laser cutting process on the basis of mean values of temperature signals at various cutting speeds

Figure 2 shows the measuring setup for measurement of infrared (IR) radiation from the cutting front, including components for capture, storage, analysis, and assessment of the temperature signals. A temperature signal is proportional to intensity of IR radiation, spreading from the cutting front, which is detected by a sensor. The sensor consists of a photodiode (CENTRONIC-BPX 65; Centronic, Mountainside, NJ) with an electromagnetic radiation sensibility range of from 0.4 to 1.0 μm, an amplifier, and a transformer. During the laser cutting process, such a sensor is directed toward the cutting front so that it intercepts the radiation from the cutting front and its surroundings, transforming it into a temperature signal (TS) expressed in millivolts. The value of the temperature signal in cutting a given kind of material and a given thickness depends on:

- Intensity of IR radiation of the overheated material, of the molten pool, and the plasma in the cutting front due to energy input by the laser beam
- Additional intensity of IR radiation from the cutting front due to exothermal reactions

The measuring assembly, particularly the sensor for intensity measurement of IR radiation, shows a satisfactory response function in the frequency range of up to 200 kHz, which corresponds to our measuring requirements regarding the output temperature signal from the photodiode. The measuring range for the temperature signal is limited by sampling duration, $T = 0.2$ s, which gives us 2000 data on the temperature signal, considering that the interval duration selected for signal digitization is $t = 0.1$ ms. With regard to the temperature signal value, the maximum horizontal value of the voltage measured on the oscilloscope, $U = 390$ mV, is selected, which is then sorted out into 250 classes in increments of temperature signal sensing $\Delta U = 1.5626$ mV.

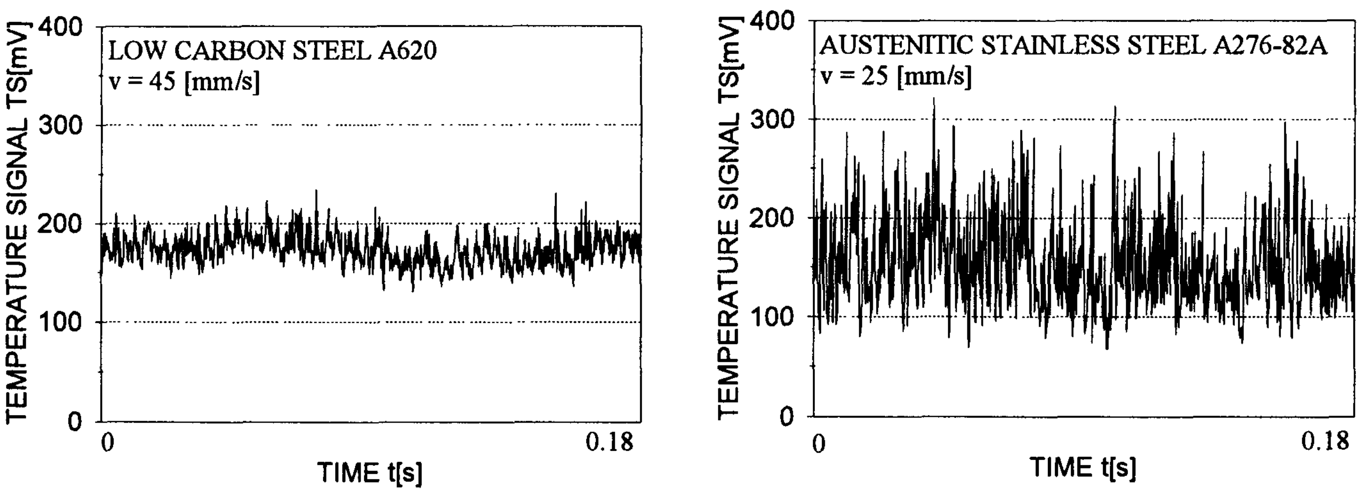
The frequency measuring range of the temperature signal was selected with reference to our previous studies and the study carried out by Schuöcker (Ref 3), who analyzed the variation of thickness of the molten layer. The thickness variation of the molten layer along the cutting front depends on the temperature signal variation (i.e., its temperature). The expected frequencies of variation in the molten layer thickness depend on the cutting speed and vary between 100 and 800 Hz (Ref 3). The temperature signal from the photodiode is finally led into a 100 MHz digital oscilloscope, where it is digitized and stored on a floppy disk for subsequent statistical processing.

Figure 3 shows portions of the recordings of the temperature signal as a function of time that were preliminarily digitized and simulated on the computer monitor. On the basis of the digitized and simulated temperature signal, important differences in the signal amplitude can be established, which will be confirmed by coefficient of variability and by an analysis of frequency distribution.

At the photodiode outlet, the temperature signal (TS) is expressed by voltage measured in millivolts and is suitable only for a relative assessment of the thermal phenomena in the cutting front. For photodiode calibration, a heated tungsten filament fed with various voltages was applied. This served to change the IR radiation intensity (i.e., the heated filament temperature). The photodiode calibration was carried out with an infrared pyrometer; thus, a relationship between the temperature signal and the temperature was determined. In order to simplify the determination of temperature from the temperature signal, the following equation of conversion was used:

$$T(°C) = \frac{\log TS(mV) - \log A}{B} \quad \text{(Eq 1)}$$

where A and B are constants (A = 0.000270179, B = 0.006218263) determined by means of a regression curve with



(a) (b)

Fig. 3 Temperature signals registered in laser cutting. (a) 2.0 mm thick low-carbon steel A620. (b) 1.0 mm thick austenitic stainless steel A276-82A correlation coefficient $r_{TS\text{-}T} = 0.9975$. In the photodiode calibration, account was taken of the temperature expected in the cutting front, which ranged from the melting point temperature of ferrous oxide (1380 °C) to that of chromium oxide (2200 °C) (Ref 4).

Figure 4 shows the coefficient of variation (CV) of the temperature signal from the cutting front in cutting low-carbon steel with a thickness of 2 mm and austenitic stainless steel having various thicknesses (i.e., 0.6, 0.8, 1.0, and 1.5 mm). The coefficient of variation of the temperature signal provides more information than standard deviation (STD) of the temperature signal; therefore, it is recommended for the description of signal variation by numerous authors. Coefficient of variation is a quotient obtained by dividing the standard deviation of sample by the mean value (MV) of the sample temperature signal:

$$CV = \frac{STD}{MV} \cdot 100(\%) \qquad \text{(Eq 2)}$$

Based on the calculated coefficients of variation of temperature signals, the following observations about the laser cutting process can be made:

- In laser cutting a 2 mm thick low-carbon steel at the selected cutting speeds, the calculated coefficients of variation of the temperature signal range from 8 to 9%.
- In laser cutting austenitic stainless steel of various thicknesses at different cutting speeds, the calculated coefficients of variation are much higher, ranging from 23 to 32%.
- The coefficient of variation of the temperature signal is relatively high in both steel grades analyzed; therefore, it can be stated that in both cases there is a very important variation of the temperature signal in the vicinity of the mean value.

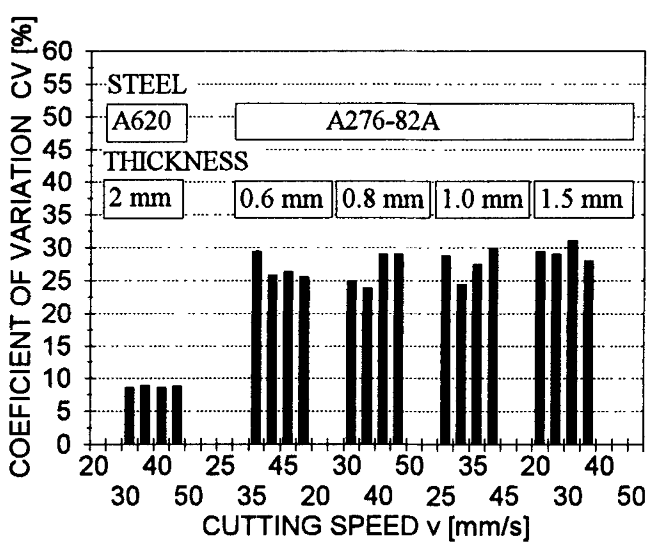


Fig. 4 Coefficient of variation of temperature signals for low-carbon steel and austenitic stainless steel at various cutting speeds

- Exceptionally high values of variation of temperature signals are a result of a number of exothermal reactions occurring in the cutting front, which are more important and stronger in austenitic stainless steel. The balanced chemical equations for exothermal reactions at austenitic stainless steel are:

$Fe + O \rightarrow FeO$ + heat (267 kJ)
$3Fe + 2O_2 \rightarrow Fe_3O_4$ + heat (1120 kJ)
$2Fe + 1.5O_2 \rightarrow Fe_2O_3$ + heat (825 kJ)
$Cr + 3O_2 \rightarrow 2Cr_2O3$ + heat (1163.67 kJ)
$Ni + 1.5O_2 \rightarrow NiO$ + heat (248.23 kJ)

Figure 5 shows the frequency distribution of temperature signals for laser cutting austenitic stainless steel of various thicknesses at a cutting speed of 35 mm/s. In general, the frequency distribution of the temperature signal enables us to determine the expected mean value and its lowest and highest expected values. By comparing individual frequency distributions of temperature signals, a good insight into the laser cutting process can be obtained, assuming that machining

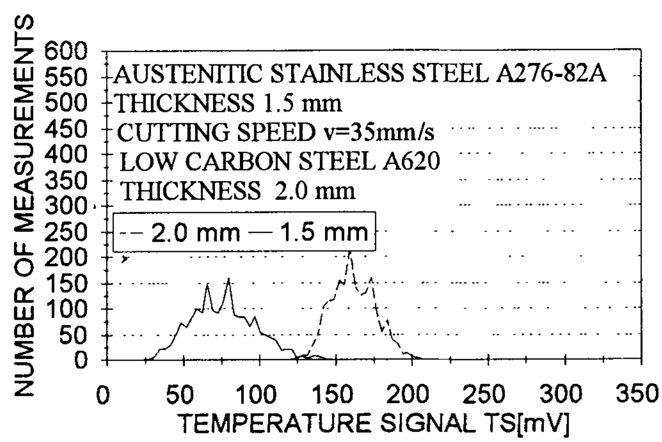


Fig. 5 Frequency distribution of temperature signal for low-carbon steel and austenitic stainless steel at cutting speed of 35 mm/s

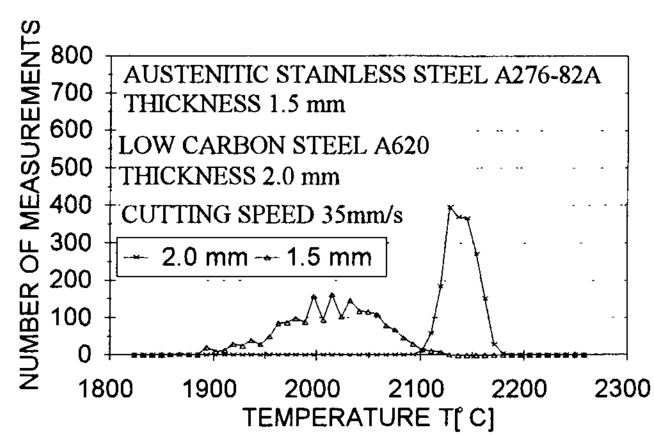


Fig. 6 Frequency distribution of temperature (Eq 1) for low-carbon steel and austenitic stainless steel at cutting speed of 35 mm/s

conditions are being changed carefully. In our case, cutting speeds (i.e., energy input into the cutting front) were changed with regard to various thicknesses of the workpiece material. Based on the frequency distribution of temperature signals, the following characteristics of the laser cutting process can be stated:

- The mean value of the temperature signal from the cutting front is higher in cutting thick workpieces of low-carbon steel than in cutting austenitic stainless steel.
- Frequency distributions of temperature signals in cutting austenitic stainless steel of various thicknesses have an asymmetrical form with several distinctive temperature signal peaks. The frequency distribution of the temperature signals confirms the presence of exothermal reactions occurring in the vicinity of the melting temperature of chromium oxide. The temperature signal variation in time is also affected by power variation of the laser source, by variation in the amount of laser light absorbed into the workpiece material, and by randomness of exothermal reactions in the cutting front. The frequency distribution of the temperature signal in cutting low-carbon steel shows that exothermal reactions occur in the melting front and that they primarily affect the mean value of the temperature signal
- The frequency distribution of various temperature signals shows that individual values of temperature signals in cutting low-carbon steel range from 120 to 150 mV, while for austenitic stainless steel they range from 50 to 300 mV.
- The mean values as well as the frequency distribution of temperature signals in laser cutting of austenitic stainless steel are very much alike for cutting materials having thicknesses of 0.6, 0.8 and 1.0 mm. More important deviations can be observed only in cutting austenitic stainless steel with thickness of 1.5 mm.

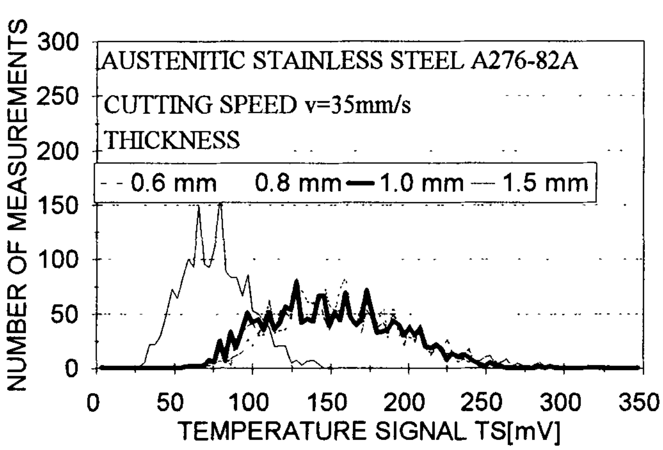


Fig. 7 Frequency distribution of temperature signal in the cutting front for austenitic stainless steel

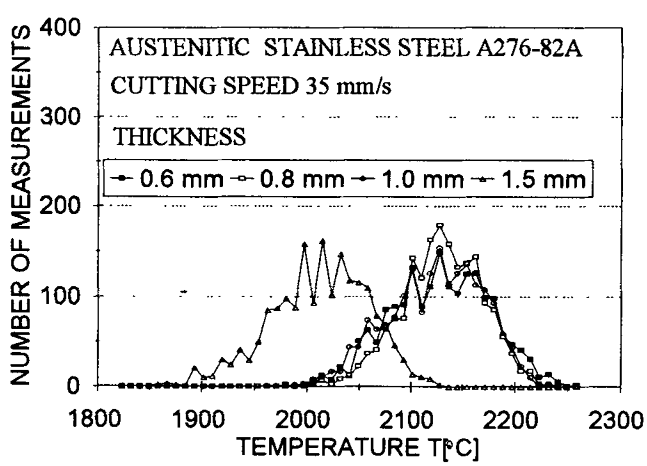


Fig. 8 Frequency distribution of temperature (Eq 1) in the cutting front for austenitic stainless steel

Figure 6 shows the frequency distribution of temperature in the cutting front for cutting austenitic stainless steel of various thicknesses. The temperature signal was transformed into a temperature in accordance with Eq 1, and then the frequency distribution of the temperature was determined. The temperature in the cutting front ranged from 1950 to 2250 °C (Eq 1), which for the chromium-nickel steel is estimated as too low for the narrowest cut ensuring high surface quality. Considering the melting temperatures of iron and chromium oxides, the lowest temperature achieved in the cutting front, according to our prediction, should be around 2200 °C (Eq 1).

Figure 7 compares the frequency distribution of the temperature signal and Fig. 8 the frequency distribution of temperature in the cutting front for laser cutting low-carbon steel and austenitic stainless steel with a cutting speed of 35 mm/s. The graphs show that the processes occurring in the cutting front differ greatly. Various influences are exerted on the frequency distribution of the temperature signal or temperature in the cutting front:

- In laser cutting with oxygen, exothermal reactions are induced in the austenitic stainless steel, and a greater quantity of energy is released than in low-carbon steel.
- The thermal conductivity of low-carbon steel is much higher than that of high-alloy austenitic stainless steel. A result of the lower thermal conductivity and the greater heat released in the cutting front of austenitic stainless steel is that a wider cut is made than in low-carbon steel. This results in a lower mean value of the temperature signal (i.e., temperature in the cutting front).
- The oxygen used in thermal cutting processes as auxiliary gas fulfills a double function: It oxidizes iron in low-carbon steel and iron and chromium in austenitic stainless steel, and it blows away the molten metal (i.e., oxides) from the cutting front. The temperature signal measured in the cutting front shows that the processes of oxidation and blowing succeed one another. The two processes occur intermittently within some microseconds, affecting the amplitude and frequency of the temperature signals intercepted in laser cutting with various cutting speeds.
- When comparing the frequency distribution of temperature signals or temperature, additional consideration should be given to thickness variations of the steels. This means that at the same material thickness, a somewhat higher mean value of the temperature signal from the cutting front may be expected in cutting low-carbon steel than in cutting

austenitic stainless steel. This is conditioned by a greater width of cut obtained. A lower amplitude of the temperature signal in cutting low-carbon steel proves that the share of the heat released due to the exothermal relationship between iron and oxygen is smaller. This means that the frequency of oxidation and of blowing the molten metal is limited to shorter time intervals than in austenitic stainless steel.

Figure 9 shows a bar chart of the mean values of temperature signals (TS) (black) and magnitude of standard deviations of temperature signals (STD-TS) (white) after cutting austenitic stainless steel with various thicknesses. Figure 10 shows a bar chart of the mean values of the temperature that was determined from the temperature signal by means of the conversion equation (Eq 1). It is interesting that, according to different studies (Ref 3, 4), the temperatures in the cutting front differ considerably from one another; therefore, there is every reason to believe that either mathematical modeling of thermal phenomena in the workpiece material is a very difficult task or difficulties occur in temperature signal measurement based on IR radiation intensity.

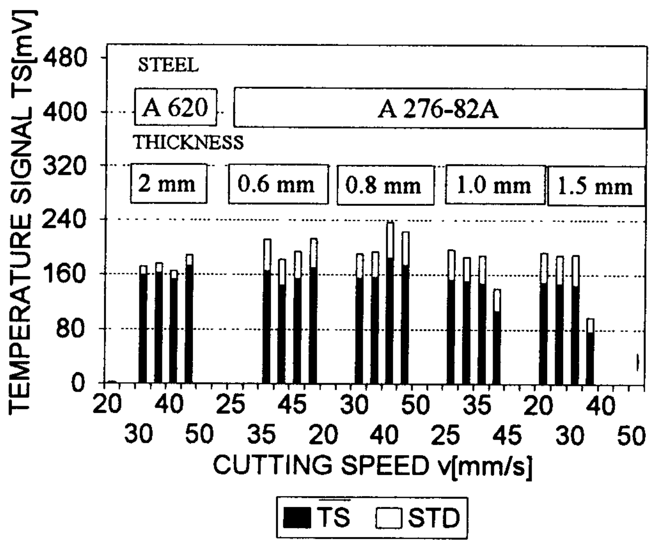


Fig. 9 Bar chart of the temperature signal measured for various steels, material thicknesses, and cutting speeds

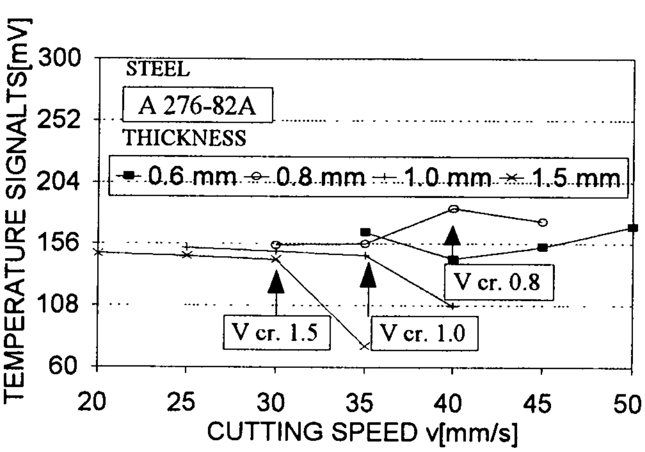


Fig. 11 Determination of critical cutting speed for various thicknesses of austenitic stainless steel

A comparison of the data provided by the temperature signal or temperature in the cutting front in cutting the investigated materials with various cutting speeds shows that:

- The mean values of temperature signals in cutting low-carbon structural steel range from 155 to 175 mV, with a standard deviation of about 14 mV.

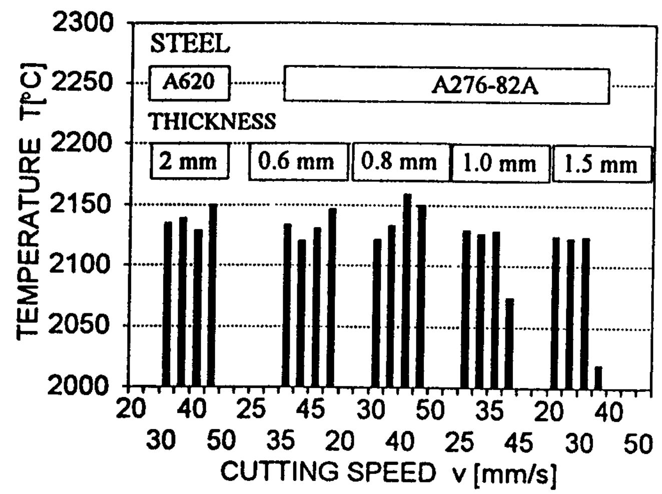


Fig. 10 Bar chart of the temperature calculated (Eq 1) for various steels, material thicknesses, and cutting speeds

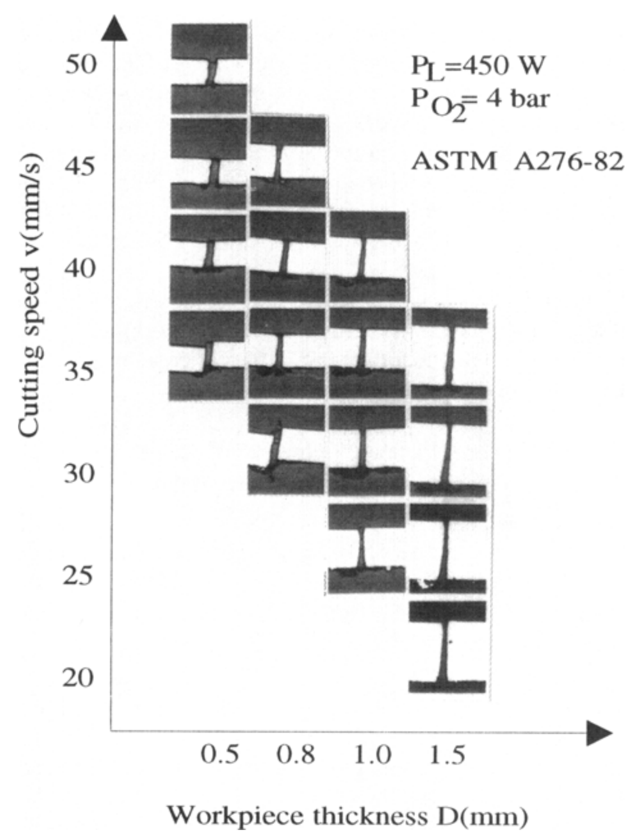


Fig. 12 Macrographs of the laser cut on austenitic stainless steel of a specified thickness

- The mean values of temperature signals in cutting austenitic stainless steel of various thicknesses range from 145 to 185 mV, with a standard deviation of about 40 to 45 mV. The sole exception is the temperature signal in cutting thicknesses of 1.0 and 1.5 mm with the highest speeds, where the mean value of the temperature signal decreases even to 110 and 75 mV, respectively.
- The low mean values of temperature signals measured in cutting 1.0 or 1.5 mm thick austenitic stainless steel with the highest cutting speed can be considered as a warning of the troubles in cutting caused by an energy input that is too low.

A consequence of the low energy input is a low-quality cut. At a specific laser source power, critical cutting speeds for individual kinds of materials and different thicknesses can be defined. The critical cutting speed is the highest cutting speed that, with regard to the value of the temperature signal, still ensures a good quality of cut. Cutting speeds lower than the critical speed produce an excessively high energy input in the cutting front, which results in an increased cut width and formation of a deeper HAZ.

Figure 11 shows the magnitude of the mean values of temperature signals as a function of cutting speed for various thicknesses of austenitic stainless steel. Quick variations of temperature signals with material thicknesses of 1.5 and 1.0 mm can easily be observed, and thus critical cutting speeds can be determined for both cases uniformly. If a material thickness is 1.5 mm, the critical cutting speed is 30 mm/s, and if the material thickness is 1.0 mm, the speed is 35 mm/s. It is more difficult, however, to determine critical cutting speeds for smaller material thicknesses, because the mean values of the temperature signal at higher cutting speeds are even higher than those at lower cutting speeds, which is the result of reduction in cut width. Thus, a critical cutting speed of 45 mm/s could be chosen for a material thickness of 0.8 mm; for the smallest material thickness; however, additional tests should be carried out at higher cutting speeds in order to determine its critical value.

Figure 12 shows macrographs of a cut on austenitic stainless steel with regard to various cutting speeds and workpiece thicknesses. To assess the quality of cut, different geometrical characteristics were selected:

- Parallelism of the left and right sides of the cut
- Uniform cut width throughout the material thickness
- Burr appearance and size
- Uniform and fine striations in the upper as well as in the lower parts of the cut
- No craters or grooves on either the upper surface and/or the lower surface of the cut

The macrographs show that the majority of the cuts shown can be classified in the highest quality class considering the machining conditions specified. This proves that in the case of austenitic stainless steel, the cutting speeds were suitably chosen for the particular material thicknesses. An analysis of the cut quality confirms that the laser cutting process can be successfully optimized by determining critical cutting speeds on the basis of individual temperature signals. From the viewpoint of optimization of the laser cutting process based on the critical cutting speed, even a cutting speed that is higher than 50 mm/s may be chosen for a material thickness of 0.6 mm.

Figure 13 shows the microstructure of the edge of the laser cut on 1.5 mm thick austenitic stainless steel. From a microstructural point of view, we can assess that the cut is very smooth and slightly enlarged on the upper side. The thickness of the HAZ is very uniform in the upper part of the cut, ranging around 12 μm, and gradually increases in the bottom third of the cut until reaching a value of around 50 μm. The HAZ represents a smaller part of the melted and resolidified material because of a very rapid removal of heat from the boundary surface between the melt and solid state.

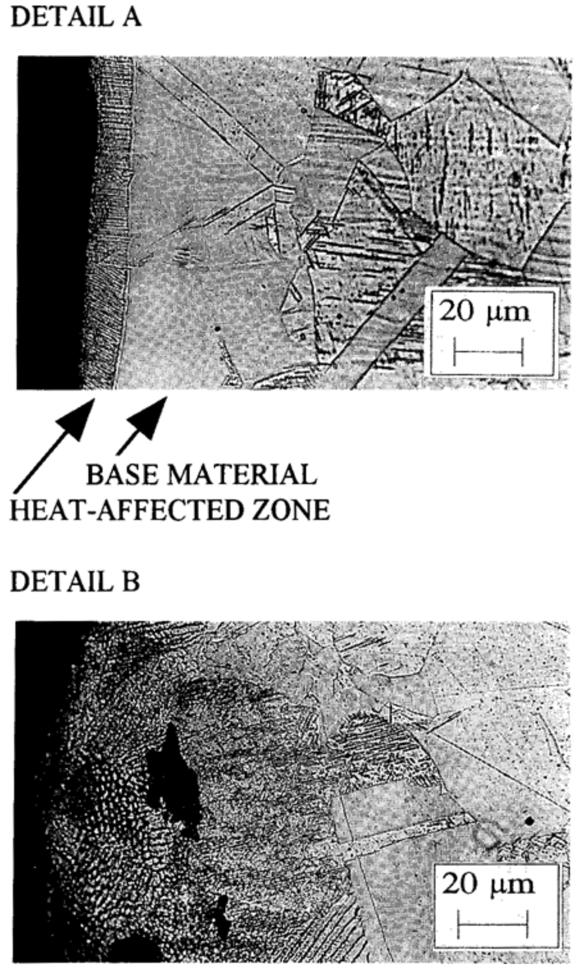
The extreme conditions in heating and cooling the material in the cutting front give rise to the following processes:

- Melting of the material occurs in the cutting front, and solidification of a smaller part of the melted material occurs on the edge of cut. The created structure of the melted or heat-affected zone is austenitic, with fine globoidal crystals and scarce column-shaped crystals directed similarly.
- The surface of the cut is due to intensive flow of the oxygen gas oxidized. The thin oxide layer has failed off the surface of the cut because of the metallographic sample preparation technique. At several places on the bottom edge of the cut, draws can be observed that are filled with oxides of iron and alloying elements.
- Because of fusion of the melt and oxides on the bottom part of the cut, burr with a more or less expressed height is visible, its height depending on the thickness of the material.
- In the bottom part of the cut where HAZ thickness increases, microlunkers are present. These indicate where the speed of solidification of the melted material was lowest.

The variation of the HAZ thickness indicate that in the bottom part of the cut more intensive chemical processes are occurring between the melted material and the oxygen gas; hence, heat is released. In the bottom inclined part of the cut, due to flow of the melt, heat from the melt is additionally transferred into the cool surroundings of the cut.

3. Factor Analysis of Variables in Laser Cutting

In the literature, experimental results of laser cutting are usually represented in graphs showing cut quality as a function of machining conditions. By means of statistical factor analysis, we can examine the relationships among variables of the machining system, variables of the cutting process, and geometrical characteristics of the cut. Our objective was to establish, by factor analysis, whether IR radiation intensity in the cutting front in various machining conditions can be used to predict laser cutting characteristics and their effects on cut quality. A basic issue in factor analysis is how to determine, on the basis of the correlation existing among individual variables, the factors that load the variables specified (Ref 8, 9). The analysis as such is a three-step process in which we:



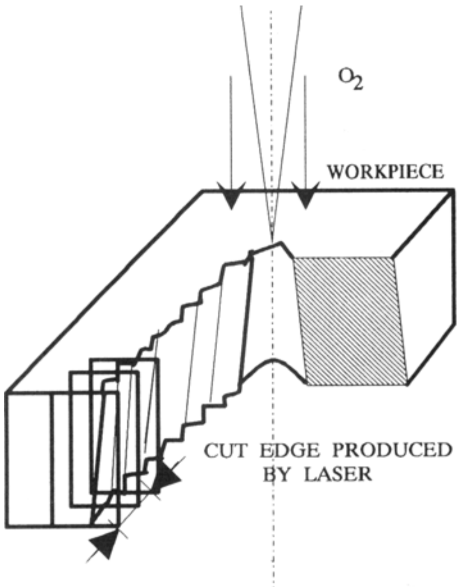
Material thickness	D=1.5 mm
Cutting speed	v=30 mm/s
Laser power	PL=450 W
Oxygen pressure	PO_2=4.5 bar

Fig. 13 Micrograph of edge of laser cut on 1.5 mm thick austenitic stainless steel workpiece

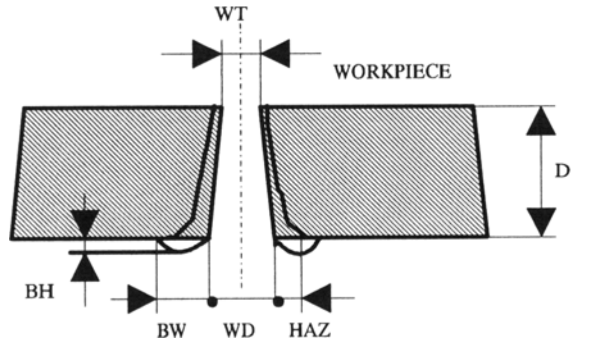
- Decide on the variables we want to analyze.
- Decide on a factor extraction technique. In our case, we decided on the method of unweighted least squares (ULS) (Ref 9, 10).
- Decide on a factor rotation technique as an aid in interpretation. In our case, we decided on the Varimax method of factor rotation (Ref 9, 10), which permits the most synoptic interpretation of results.

With reference to the statistical method, the laser cutting variables were classified into three groups:

- Variables of machining system control that manifest themselves as changes in cutting speed, *v*, and as various workpiece material thicknesses, *D*. In our case, the cutting speeds and the workpiece material thicknesses were selected from a limited range guaranteeing the required cut quality. All the machining conditions are specified in section 2 and had been determined on the basis of previous tests.
- A laser cutting process variable is the temperature signal measured by sensing IR radiation intensity with a photodiode. For each laser cutting condition, the temperature signal was expressed in millivolts so that the mean value of the temperature signal and its standard deviation as well as the presence of noise in the temperature signal (SU) could be calculated. The presence of noise is described by a noise coefficient in laser cutting, which is determined on the basis of the correlation function of the temperature signal intercepted at a particular cutting speed. The coefficient of noise present in the temperature signal can be read from the standardized correlation function. Its value is related to the nature of the laser cutting process. It was established that



(a)



(b)

Fig. 14 (a) Selection of measuring points at the laser cut. (b) Description of cut quality by geometrical characteristics

the laser process noise was stronger in cutting austenitic stainless steel than in cutting low-carbon steel. The appearance of noise can be attributed mainly to various oxidation processes occurring in the cutting front and to blowing-off of the molten pool from the cutting front by oxygen.

- Variables of the laser cut, which include the geometrical characteristics of the cut, permit assessment of the quality of cut and the cutting process. Laser-cut workpieces were inserted into Resin-5 (Struers, Copenhagen, Denmark) and then cut in the transverse direction into ten testpieces for measurement of geometrical characteristics of the cut. The characteristics selected were measured on laser cuts performed under various machining conditions. Measurements of individual characteristics were performed on an optical measuring microscope, with ten measurements for each cut; then the relevant mean values and standard deviations were calculated. Figure 14(a) shows the formation of a laser cut and a sampling technique for measuring the geometrical characteristics. Figure 14(b) shows the individual geometrical characteristics as measured by the optical measuring microscope. The characteristics relevant to the description of the cut quality and that were taken into account in factor analysis include: mean value of the upper width of cut (WT), mean value of the bottom width of cut (WD), mean value of the depth of the HAZ, mean value of the burr width (BW), mean value of the burr height (BH), and mean arithmetic value of cut roughness (Ra).

Figures 15 to 17 show bar charts of the mean values (black) and standard deviations (white) for WD, BH, and the depth of the HAZ, respectively, for austenitic stainless steel. The diagrams show these geometrical characteristics for laser cutting of various workpiece thicknesses with various cutting speeds.

Figure 18 shows a bar chart of Ra for laser cutting of austenitic stainless steel with various workpiece thicknesses at various cutting speeds. The mean arithmetic roughness was measured with a roughness gage (TALYSURF; Rank Taylor Hobson Ltd., Leichester, England) on the cut surface with a measuring length of 2.0 mm. Since surface roughness varied with the height of cut and workpiece thickness was relatively small, measurements were carried out in the middle of the left side of the cut.

Figures 19 and 20 show bar charts of mean values (black) and standard deviations (white) for WT and BW, respectively, for laser cutting of austenitic stainless steel with various material thicknesses at various cutting speeds.

Factor analysis results are given in Table 3. By factor analysis, we wanted to establish those groups of variables that best explain variability in the whole intercorrelation matrix of all variables. A factor itself represents a new mathematical variable that correlates best with the variables showing the highest degree of mutual correlations. In general, there can be as many factors as variables; then the whole range of variations can be included in the description. By reducing the number of factors involved, we combine the effects of individual variables, which means that a reduced variability range of the variables is gathered. In our case, the three factors describing 69.5% of the whole range of variations of the variables were selected from a matrix of 11 factors. The factor analysis performed permitted us to select individual variables having higher correlation with regard to individual factors. The results given in Table 3 can be interpreted as follows.

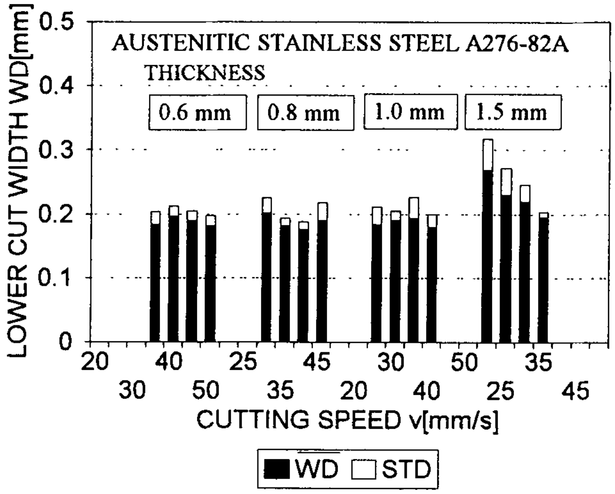


Fig. 15 Bar chart of mean values (black) and standard deviations (white) for lower cut width (WD)

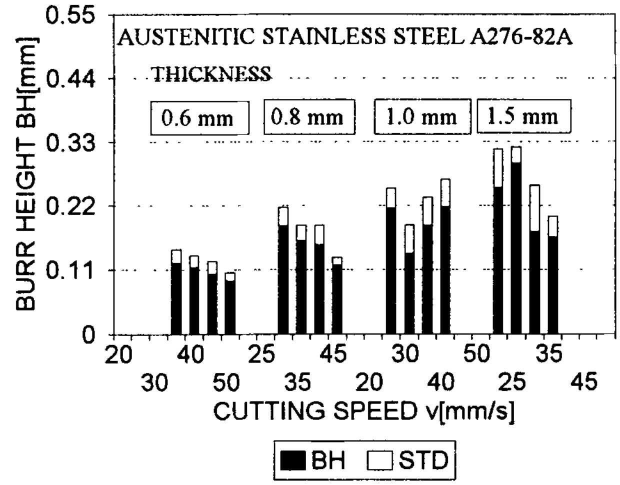


Fig. 16 Bar chart of mean values (black) and standard deviations (white) for burr height (BH)

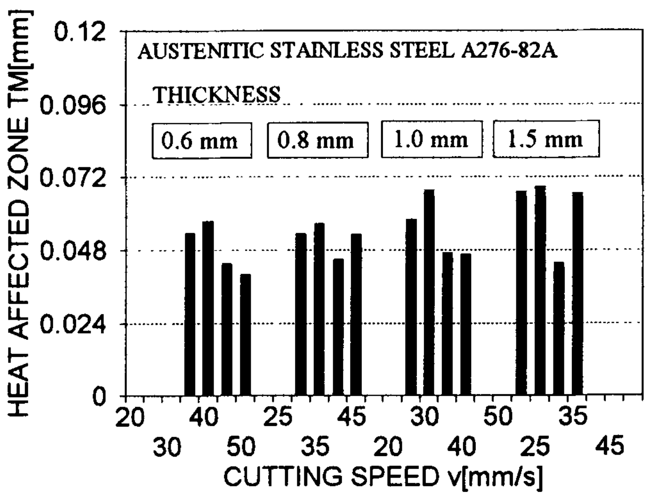


Fig. 17 Bar chart of mean values for depth of HAZ

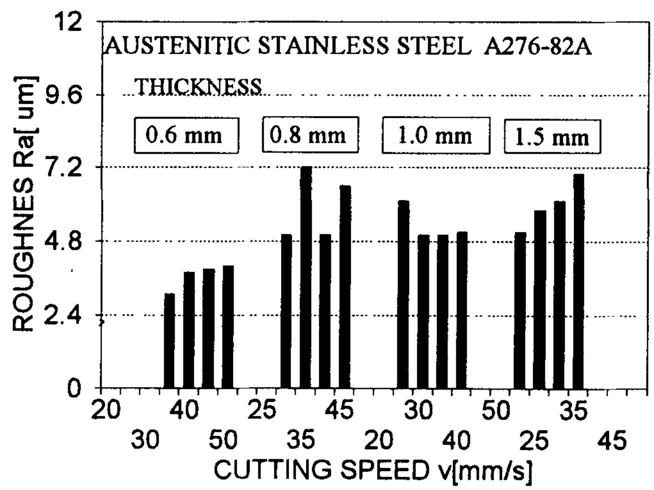


Fig. 18 Bar chart of mean arithmetic roughness (Ra) for austenitic stainless steel workpieces of various thicknesses at various cutting speeds

The first factor is loaded by the variables of the machining process, *v* and *D*, and the variables of the laser-cut WD, BH, and HAZ. From the positive or negative correlation coefficient between the factor and the variable we can state the correlation between them. It can be said that the first factor is loaded positively by the variables of the geometrical characteristics of the cut (WD, BH, HAZ) and plate thickness, *D*, whereas it is loaded negatively by the variable of the cutting speed (*v*). From these data, it can be generally concluded that with increasing workpiece material thickness and decreasing cutting speed, the geometrical characteristics of the cut increase. Cut quality can be described, using the data of the first factor, by the cut width and burr height on the bottom side of the workpiece. It is statistically confirmed that by an equal energy input and by increasing the workpiece material thickness we achieve greater bottom width of cut and wider burr, as well as a wider HAZ. The confidence interval for the correct value of the correlation coefficient between the material thickness (*D*) and the burr height (BH) in the basic population ranges from 0.363 and 0.905, including a 5% risk. Considering the correlation coefficient between the plate thickness and the burr height ($r_{D-BH} = 0.7481$), a good and quite reliable correlation between the two can be confirmed.

The second factor is loaded positively by the mean value of the temperature signal (TS) and the standard deviation of the temperature signal (STD-TS), and negatively by the mean arithmetic cut roughness (Ra). With regard to extremely high correlation coefficients of both variables mentioned with the second factor (i.e., $r_{TS\text{-}STD} = 0.8988$ and $r_{TS\text{-}Ra} = 0.58$), it can be concluded that the strongest influence on Ra and the cut formation is exerted by the temperature in the cutting front. Another observation is that, with the temperature signal increasing in the cutting front, temperature dissipation also increases, which points out that more intensive and irregular exothermal processes are going on at higher temperatures. The confidence interval for the correct value of the correlation coefficient between the variables TS and STD-TS in the basic population

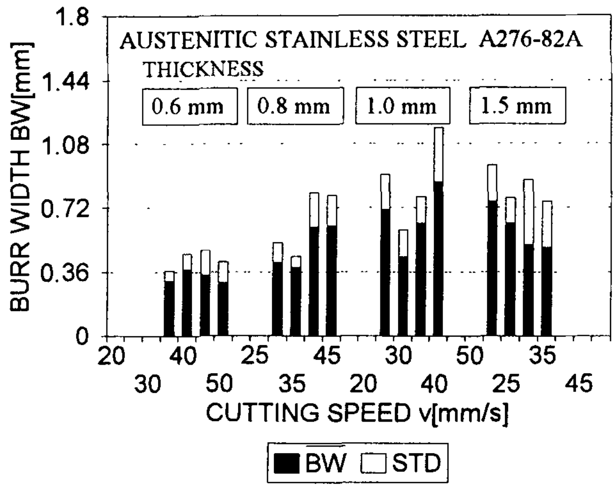


Fig. 19 Bar chart of mean values (black) and standard deviations (white) for burr width (BW) for austenitic stainless steel workpieces of various thicknesses at various cutting speeds

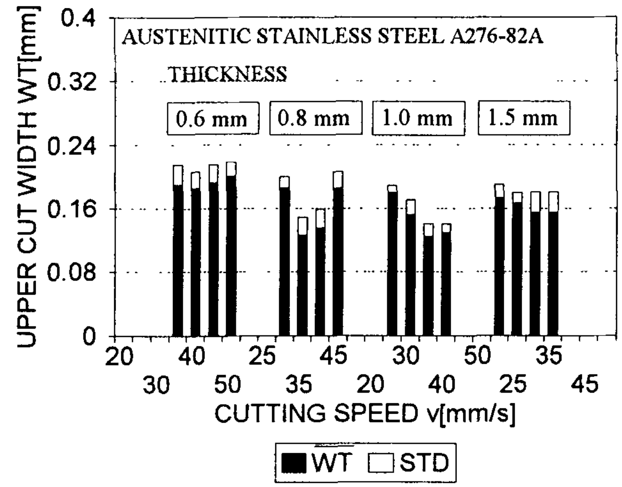


Fig. 20 Bar chart of mean values (black) and standard deviations (white) for upper cut width (WT) for austenitic stainless steel workpieces of various thicknesses at various cutting speeds

Table 3 Factor classification of variables and coefficients of correlations among factors and variables in the laser cutting process

Variable	Factor 1	Factor 2	Factor 3
WD	**0.82968**	0.01745	–0.02880
V	**–0.82424**	–0.02166	–0.29505
D	**0.75623**	–0.25663	0.41122
BH	**0.74467**	0.02813	0.55905
HAZ	**0.65477**	–0.29892	–0.00150
STD-TS	–0.02902	**0.93527**	–0.14281
TS	–0.18408	**0.916653**	–0.30149
Ra	0.02732	**–0.62508**	–0.10835
WT	0.01274	0.06233	**–0.78999**
SU	0.22787	–0.33404	**0.67297**
BW		0.10851	0.57943

ranges between 0.696 and 0.963, including a 5% risk. With regard to the fact that the temperature signal and roughness are included in the second factor, we can expect a successful optimization of the cut roughness and a good quality of cut by monitoring and controlling the temperature signal in the cutting front during the cutting process.

The third factor negatively loads WT and positively loads BW on the bottom side of the cut and the noise coefficient of the laser process (SU). The correlation coefficient of a sample between WT and SU is –0.584. This statistically confirms that the increase in WT results in a decrease of noise in the laser cutting process. On the basis of a statistical test, it was established that the confidence interval for the correct value of the correlation coefficient between WT and SU in the basic population ranges from –0.09 to –0.84, including a 5% risk.

4. Conclusions

The analysis of heat effects in laser cutting of the studied steels is extremely important. It explains very complex physical phenomena in the cutting front and provides a way for determining optimum cutting conditions. In laser cutting, the amount of energy input into the cutting front varies due to oscillations in laser source power, changes in the heat released in exothermal reactions, and heat losses. The results of the present study show that thermal changes in the cutting front can be successfully monitored by the temperature signal measurement via IR radiation intensity.

Based on analysis of temperature signals from the cutting front and measurement of the geometrical characteristics of the cut, the following can be stated:

- The temperature signals measured, or temperatures in the cutting front, range from 1950 to 2250 °C (Eq 1), which are the expected limits considering the experimental results of Arata et al. (Ref 4).
- A criterion was developed for determination of the optimum laser cutting speed, representing the critical cutting speed at which the temperature in the cutting front starts decreasing distinctively. The results concerning the optimum laser cutting conditions were confirmed by microstructure analysis, visual assessment of cut quality, and statistical description of the geometrical characteristics of the cut by factor analysis.
- By statistical processing of laser cutting variables (i.e., variables of the machining system, variables of the cutting process, and geometrical characteristics of the cut), it was established that cut quality may be affected by changes in cutting speed or in laser beam power.
- The procedure for determining the critical cutting speed is:

a. A specified cutting speed is selected, the temperature is measured by means of IR radiation intensity in the cutting front, and its mean value is determined.

b. The procedure is repeated by continuous or stepwise changing of cutting speed.

c. Upon a rapid decrease of the mean value of the temperature signal, the critical cutting speed is achieved, which, in accordance with our criteria, represents the optimum cutting speed.

The proposed procedure allows determination of the critical cutting speed during the cutting process itself, which can be utilized for process control. The procedure is both practical and simple. By changing laser source power and/or optical and kinematics conditions, it is possible to determine the optimum laser cutting conditions. The same optimization procedure of the laser cutting process can also be used for other related materials.

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