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An experimental analysis and optimization of CO_2 laser cutting process for metallic coated sheet steels

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Abstract

An experimental investigation is presented which analyses the CO_2 laser cutting process for difficult-to-cut metallic coated sheet steels, GALVABOND. It shows that by proper control of the cutting parameters, good quality cuts are possible at high cutting rate. Plausible trends of the energy efficiency (percentage of energy used in cutting) with respect to the various process parameters are analysed. Visual examination indicates that when increasing the cutting rate to as high as 5000 mm/min, kerfs of better quality than those produced using the parameters suggested in an early study can be achieved. Some kerf characteristics such as the width, heat affected zone and dross in terms of the process parameters are also discussed. A statistical analysis has arrived at the relationships between the cutting speed, laser power and workpiece thickness, from which a recommendation is made on the selection of optimum cutting parameters for processing GALVABOND.

Keywords: Laser cutting; Sheet metal processing; Metallic coated sheet steels; Process parameter selection.

1. Introduction

Sheet metals with a thin layer of zinc and/or aluminium coatings, such as GALVABOND, have found extensive industrial applications due to their various merits, such as corrosion resistance. Traditionally, the processing of sheet metals relies on processes such as punching, blanking and guillotining. However, manufacturing is getting more time conscious and the requirement for prototyping and small production batch is increasing. This has placed a need for the use of some non-traditional machining technologies, such as laser beam cutting. It is important to note that the coatings on metallic coated sheet steels have high light reflectivity and thermal conductivity, and lower melting point than the substrate materials. This together with the sandwiching influence imposes some difficulties and limitations on processing this kind of materials using lasers and there is little knowledge of the control and optimization of the cutting processes, although a considerable amount of work has been reported on laser processing of sheet metals [1-3].

In a recent study [4], the potential and feasibility to apply CO_2 lasers to the processing of metallic coated sheet steels have been explored. This study focuses on three types of materials, i.e. GALVABOND, ZINCALUME and ZINCANNEAL of 1.0 mm thick, and shows that these materials can be cut at commercially acceptable rates with high laser powers. It also shows that the cuts on GALVABOND are associated with pronounced surface disintegration by distinct oxide formation along the cuts and slightly high (20%) cutting speed should be used, as compared with the other two materials. According to this study, fine and good cuts can be obtained on GALVABOND with cutting speed between 40 and 60 mm/min at the laser power from 400 to 550 W, while cutting speeds between 15 and 40 mm/min are recommended for the other two materials. However, this work has been based on the experimental findings with the cutting speed varying from 10 mm/min to 60 mm/min. Whether or not the cutting speed can be increased for improved productivity while achieving good quality cuts remains to be further investigated. The claim of the cutting speeds used being commercially acceptable is also in question. Furthermore, severe thermal damage on the workpiece has been noticed at these cutting speeds and further study is required to examine the machinability of the materials at high cutting speeds and to suggest appropriate cutting parameters for good quality cuts and high cutting rates.

Based on an experimental investigation, this paper analyses the CO_2 laser cutting process for GALVABOND, a material appearing to be most difficult to cut with lasers. Three different material thicknesses are considered to examine the cutting rate and cut quality. A laser-material interaction is carried out to study the energy efficiency involved and to understand the cutting process. Kerf characteristics such as the width, heat affected zone (HAZ) and dross in terms of process parameters are then discussed. Finally, the relationships between the cutting speed and laser power for good quality cuts are established for each workpiece thickness and optimum process parameter combinations recommended for practical applications.

2. Experimental work

The experiments were conducted on a Cincinnati CL-5 Laser Centre. This machine used 10.6 μm wavelength CO_2 laser with a guaranteed energy output of 750 W for continuous laser generation. The laser beam was focused using a 127 mm focal length lens with a focused spot size of 0.025mm. The other optical elements included two beam bender mirrors and a circular polarizing mirror. A conical nozzle with an exit diameter of 1.7 mm was employed. The nozzle-workpiece standoff distance was controlled at 1 mm by the material follower available on the machine. For all the experiments, no coolant was used.

The specimens used were GALVABOND of 0.55, 0.8 and 1.0 mm thick. These materials are hot-dipped zinc-coated commercial forming steel with a spangled surface. The coating thickness is about 0.02 mm on each side and the chemical composition as well as mechanical and physical properties of the substrate are given in Table 1. The reason for choosing this kind of materials is that difficulty has been reported in the cutting process [4] and that it was hoped to improve the cut quality and cutting rate through this study.

<Take in Table 1>

The selection of the cutting conditions was based on experience for similar workpiece and some trial runs. When using oxygen as an assist gas at pressures varying from 200 to 800 KPa (or 2 to 8 bars), it was found that cutting speeds as high as 3,500 mm/min and 5,000 mm/min for laser power of 400 W and 700 W, respectively, could produce through cuts on the specimens. It was also noticed that at low cutting speeds, severe burn and thermal damage to the workpiece occurred. Thus, cutting speeds between these values were considered with a view to locating the appropriate cutting conditions to increase the economic and technological performances. In this experimental design, four levels of laser power (continuous wave) and cutting speed were considered at three levels of assist gas pressures for the three thicknesses of specimens. Details of the cutting parameters are given in Table 2. Thus, the first set of tests involved 144 cuts of 100 mm long straight slits.

<Take in Table 2>

In addition, more than 50 cuts using the recommended parameters [4, 5] were undertaken in order to further examine the machinability at low cutting speeds and for comparison purpose. For this set of tests, three levels of laser power (400, 500 and 600 W) were considered at three levels of cutting speed. These cutting speeds were: 45, 55 and 65 mm/min for 1.0 mm specimens, 50, 60 and 70 mm/min for 0.8 mm specimens, and 55, 65 and 75 mm/min for 0.55 mm specimens. Oxygen and compressed air at various pressures were used as assist gases. It should be noted that at low cutting speeds, compressed air did not result in noticeable improvement in kerf quality as compared to oxygen, while oxygen showed great advantage in increasing the cutting speed for acceptable through cuts. Therefore, oxygen was the only assist gas used for high speed cutting in this study. Consequently, in total about 200 tests were conducted.

3. Laser - material interaction and energy efficiency

Laser cutting process is to increase the temperature of a localised area, hence melting and/or evaporating the workpiece material. The melt is then removed by a jet of gas. The gas jet may also react chemically with the melt, which generates a secondary heat input to the cutting zone to aid the cutting process. Laser cutting process is highly dependent on the heat or energy that is absorbed by the work material, which in turn dependent on the laser energy input and the material's physical properties. It has been reported [4] that metallic coated sheet steels have very high reflectivity to the CO_2 laser radiation. This property makes it difficult to establish a localised molten zone on metallic coated sheet steels. Fortunately, It has been reported [4] that the reflectivity reduces as the temperature of the work material increases so that the energy absorbent rate increases. The small percentage of energy absorbed by the material is converted into heat which is then quickly dissipated into the material and across the material surface by virtue of the high thermal conductivity of the substrate and coating materials. This in turn results in damages to the workpiece such as heat affected zone. Consequently, a localised hot spot is not readily established and, as such, the cutting of metallic coated sheet metals is considered as a less energy efficient and difficult process. It is thus necessary to study the energy efficiency in the cutting process and their relationship to the cutting variables with a view to optimizing the cutting process.

Apart from the reflected energy which cannot be considered as energy input into the cutting process, the energy losses by conduction, convection and radiation are a function of the temperature of the cutting front and the surrounding area. This has made the modelling of energy used for cutting difficult. In the present study, a simplified energy balance equation [6] was used to calculate energy efficiency in laser cutting process. In this model, the energy supplied to the cutting zone is taken as the sum of the energy used in cutting and the thermal losses by conduction, convection and radiation. If assuming that the energy to the surrounding (other than the processing) area by conduction, convention and radiation does not contribute to the cutting process and that the specific cutting energy for the work material remains constant, the energy efficiency may be determined by:

$$\text{Efficiency} = \frac{\text{Enegy used for cutting}}{\text{Total laser energy input}} 100\% = \frac{\rho V e\, k\left[c_p (T_m - T_r) + L\right]}{P} 100\% \qquad (1)$$

where the symbols are as defined in the nomenclature and the relevant values are given in Table 1. In this study, the 0.02 mm zinc coating has been ignored in the energy evaluation and it is anticipated that this will result in less than 4% errors [7].

The results show that the energy efficiency for all the tests ranges from as low as about 5% to about 24%. In general, the cutting conditions (assist gas pressure, cutting speed and laser power) and the material thickness affect the percentage of energy used for cutting. It has been found that high energy efficiency can be achieved at high cutting speed and assist gas pressure, low laser power and thicker materials

<Take in Fig. 1>

Fig. 1 shows the general trends of the energy efficiency with respect to the process parameters. As the cutting speed increases, the percentage of energy used for cutting increases constantly at any input of laser power, as shown in Fig. 1(a). This is because at higher cutting speeds more of the beams strikes the workpiece instead of passing straight through. In addition, the energy used for cutting a unit volume of material is constant and is independent of the cutting time, while the energy losses may be considered as proportional to the surface area of the cut front and the cutting time. It thus follows that increasing the cutting speed (or reducing the cutting time) increases the energy efficiency.

As the assist gas pressure increases, the energy efficiency shows a rapid increase initially but the increase rate is reduced as the pressure is further increased (Fig. 1(b)). The experimental results show that about 7% increase in the energy used in cutting can be attained in most cases when the gas pressure is increased from 200 KPa to 800 KPa while this increase occurs primarily as the pressure varies from 200 to 500 KPa. This phenomenon is a result of the increased drag removing the melt and the oxidation rate of the work material with the assist gas (oxygen). At the gas pressure of 800 KPa, cooling action become effective which offsets the action of oxidation. It has also been noticed that laser power affects the kerf width in a similar fashion to the energy efficiency [7]. As the power increases from 500 to 800W, the kerf width increasing rate is reduced and, in some cases, vanished possibly due to the same reasons as for the energy efficiency. However, it is noted that at the gas pressures of 500 and 800 KPa, oxidation resulted in low quality cuts in most cases with excessive dross on the workpiece surface.

Examining the effect of input laser power reveals that less percentage of energy will be used for cutting at higher laser power, as shown in Fig. 1(c). An increase in the laser power increases the laser beam intensity at the focal point, which in turn increases the local temperature and temperature gradient. As a result, more heat losses occur and the excessive heat at the focal area causes thermal damage to the workpiece. The figure also shows that the increased laser power allows a higher cutting speed to be used which is associated with an increased energy efficiency as discussed earlier.

It is noted from Fig. 1(d) that the material thickness also affects the process efficiency. An increase in material thickness requires more heat to melt or evaporate the extra material and makes more energy to expose to the cut zone (less energy passing through the kerf without touching the material) so that lesser thermal loss occurs. This indicates that lower energy efficiency and cut quality due to thermal damage for thin materials may be anticipated, as compared to thick materials, and the selection of optimum process parameters is more important in controlling the cut quality. In addition, the reduced kerf width at the bottom of the cut also contributes to the increase of the energy efficiency calculated based on top kerf width.

The foregoing analysis has shown that from the energy efficiency and economical point of view, high cutting speed coupled with high assist gas pressure and low laser power should be used. However, an increase in the cutting speed requires high laser power to be used, implying a need to determine the optimum combination of laser power and cutting speed. Fortunately, the effect of laser power on the energy efficiency is to a lesser extend when compared to cutting speed, particularly in the high power range. Thus, in practice high laser power may be used (as high as 700 W in the present study) together with highest possible cutting speed that gives acceptable cut quality. While the gas pressures at above 500 KPa show some advantage in terms of energy efficiency but they result in low cut quality. Late analysis will show that 200 KPa in fact gives the best cut quality and, if cut quality is a major concern, a gas pressure of 200 KPa may be selected. It should be noted that kerf width, which is proportional to the volume of material removed and energy used, increases with increases in the laser power and gas pressure, and a decrease in the cutting speed, as will be discussed later. This will further complicate the analysis and kerf quality and cutting rate will need to be considered in recommending the cutting parameters.

4. Kerf characteristics and quality

Kerf quality is assessed based on the three classes of cuts or shapes (for through cuts only) shown in Fig. 2. In addition, kerf characteristics such as kerf width, HAZ, dross deposition on the bottom edges (or burrs) and thermal damage to the coatings are also considered as technological performance measures to assess the kerf quality. In this study, the size of HAZ was determined from the top kerf edge to where clear colour change on the material (coating) could be identified under an optical microscope. From the 144 tests, it is found that when 400 W laser power and 200 KPa assist gas (oxygen) pressure were used for cutting 1.0 mm specimens, non-through cuts occurred. For the remaining 140 tests, class III or II through cuts were achieved, which will be further analyzed later in this section. However, it is noticed that for over 50 cuts using the low cutting speeds and other parameters recommended in Refs. [4, 5], only class II cuts were obtained with massive dross attached at the bottom edges and the surrounding area. Visual examination under an optical microscope revealed that the kerfs produced by high cutting speeds are slightly rougher than those from using the low speeds, as indicated in Fig. 3. This may be attributed to any incomplete cutting action and melt resolidification on the side walls (rather than at the lower edges as for low speed cutting). Nevertheless, the cuts are still considered to have good quality, given the nature of laser metal processing.

<Take in Figs. 2 & 3>

It appears that the assist gas pressure played an important role in the formation of kerf shape. At the pressure of 200 KPa, most cuts on 0.55 and 0.8 mm specimens are class III cuts with minimum dross at the exit. It is also found that at the laser power of 700 W, the control of cutting in achieving class III cuts for 0.55 mm material was not possible for all the cutting speeds and gas pressures used in the study. In such cases, dross was found at the lower edges and larger HAZ was noticed. The cutting speed did not show any significant effect on the kerf shape (or class of cut) for the range considered.

The kerf width generally increases with increases in assist gas pressure and laser power and a decrease in cutting speed. For all the cuts carried out on the three different specimens, the top kerf width varied from 110 to 270 μm, which in most cases are about 50% of those produced by using the low cutting speeds. As such, kerf width is not only dependent on the combination of laser-lens-metal, as claimed in earlier studies [4, 5], but also to a considerable extent on the cutting speed.

When examining the HAZ and dross deposition, it is found that for all the cuts using low cutting speeds (45 to 75 mm/min), there were severe thermal damage to the workpiece. A moderate case is shown in Figs. 3(a) and (b). Up to 1.5 mm of the coatings from the upper edges were molten down from the substrate (coating in almost all area covered by Fig. 3(a) has been molten down). The molten material draws towards the sides of the cuts (the cooler zone) and is propelled downwards along the kerf walls by the gas jet together with the molten substrate. The melt eventually deposits at the exit to form excessive burrs, as shown in Fig. 3(b). Slag can also be noticed to deposit in the surrounding area of the exit kerf. There was no marked difference in quality between the kerfs from different cutting speeds in this range, possibly due to the small spacing between the speeds.

<Take in Fig. 4>

By contrast, the cutting with high speeds has resulted in high quality cuts with minimum HAZ, as evidenced by Fig. 3(c). By properly selecting the process parameters, the oxides presented on the outlet face can also be minimized to form class III cuts. From the study with high cutting speeds, it is found that the size of HAZ generally increases with an increase in laser power, but reduces with an increase in cutting speed, as shown in Fig. 4. In many cases, varying cutting speed in the lower region did not result in significant change in the size of HAZ and in some cases lower cutting speeds even caused a reduced HAZ size. This can be explained as a result of longer cooling time by the assist gas as well as the increase in kerf width at lower cutting speeds. The effect of assist gas pressure on the size of HAZ is interesting. While an increasing trend of HAZ size has been noticed when the gas pressure varies from 200KPa to 500KPa due to the oxidation related exothermic reaction, the effect of gas pressure appears to vanish and it even results in a decrease in the HAZ size, as the pressure is changed from 500 KPa to 800 KPa. This is because the cooling effect of the assist gas has become dominant at the pressure of 800 KPa. Quantitatively, the ranges of HAZ for the 0.55, 0.8 and 1.0 mm specimens are respectively about 200 to 315 μm, 210 to 290 μm and 194 to 270 μm. These figures also reveal the effect of material thickness on HAZ, although this is expected. It appears that assist gas pressure has pronounced burring effect and most class III cuts formed at the pressure of 200 KPa.

5. Selection of process parameters

The overall cut quality as assessed by kerf shape (class III cuts), kerf width, HAZ and the deposition of dross on the lower edges has been analyzed and the graphs indicating the combination of parameters for class III cuts with minimum HAZ and dross are given in Fig. 5. It should be noted that the maximum variation of kerf width for the tests is about 160 μm, and the variation for each material under the cutting conditions recommended in Fig. 5 is much smaller. Thus, kerf width is not used as a criterion in recommending the process parameters. Based on the ranges of parameters considered in this study and the experimental findings, an assist gas pressure of 200 KPa is generally favoured and is recommended for cutting the materials under consideration. When cutting 0.55 mm specimens, laser power at 700 W could not produce class III cuts at the cutting speeds and assist gas pressures considered and oxides or burrs were found along the lower edges. The results also show that although the cutting speed may be increased for good quality cuts as the laser power increases, this does not apply when the laser power is above 500 W. A similar trend was also found when cutting 0.8 mm specimens, where the threshold value for laser power was found to be 600 W. Analysing the results for cutting 1.0 mm specimens has found that at laser power of 400 W and assist gas pressure of 200 KPa, the laser beam could not penetrate the workpiece at any cutting speeds considered, while 500 and 800 KPa at this laser power could produce good quality cuts at cutting speed up to 3000 mm/min. Fig. 5(c) also shows the potential to increase cutting speed by increasing laser power for class III cuts, but the capacity of the laser cutting centre has limited this attempt.

<Take in Fig. 5>

From this analysis, if cutting speed and energy consumption (laser energy input) are considered as economic measures while cut quality is the technological performance measure, the combinations of process parameters which may be used for good quality cuts are given Table 3. This recommendation is also consistent with that derived from the energy efficiency analysis presented above. The calculated cutting speeds for a given laser power and assist gas pressure from the two empirical models (curve fitted from experimental data) in the literature [8] for sheet metals are also obtained for comparison. It is apparent that Querry’s model does not give cutting speeds to obtain class III cuts for the materials. By contrast, Miyazaki’s model may be applicable although the cutting speed for 1.0 mm specimens is below the test range in the present study. Nevertheless, higher productivity can be achieved by using the recommendation from this study.

<Take in Table 3>

6. Conclusions

An experimental analysis of the CO_2 laser cutting process for metallic coated sheet steels, i.e. 0.55, 0.8 and 1.0 mm GALVABOND, has been presented. It has been shown that these materials can be cut at high cutting rate of up to 5,000 mm/min while the cut quality is superior to that with low cutting speed recommended in an early study. The difficult nature in processing this kind of materials is attributed to their anomalous behaviour when subjected to laser light by virtue of the high light reflectivity and thermal conductivity of the coatings as well as the difference in the physical properties between the coating and the substrate. Plausible trends of the percentage of energy used in cutting with respect to the process parameters have been analysed. It has shown that the energy efficiency ranges from as low as 5% to about 24% under the test conditions. High cutting speed and low laser power are favoured from the energy efficiency point of view and this condition also gives small size of HAZ. Some kerf characteristics such as kerf width, dross and HAZ in terms of the process parameters have been discussed. It has revealed that although high laser power permits high cutting speed to be used for good quality cuts, this trend does not apply when the laser power is above a threshold value in which case no class III cuts can be produced. The combinations of process parameters for class III cuts with minimum HAZ and dross have been graphically presented together with the recommended optimum process parameters for practical applications.

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Nomenclature

c_p	spcicific heat (J/g.°K)
e	material thickness
k	kerf width
L	latent heat for melting (J/g)
P	laser power supply
P_r	assist gas pressure
T_m	melting temperature (°K)

T_r	room temperature (°K)
V	cutting speed
ρ	material specific mass (mess density) (kg/m^3)

Table 1. Properties of the substrate of the specimens.

Chemical Composition		Mechanical Properties		Physical Properties	
Carbon (C%)	0.100	Yield strength (MPa)	280-330	Specific heat (J/g.°K)	0.465
Phosphorus (P%)	0.025	Tensile strength (MPa)	330-380	Melting temperature (°K)	1793
Manganese (Mn%)	0.450	Hardness (HR30T)	50-60	Latent heat (J/g)	331
Slphur (S%)	0.030			Specific mass (kg/m^3)	7833

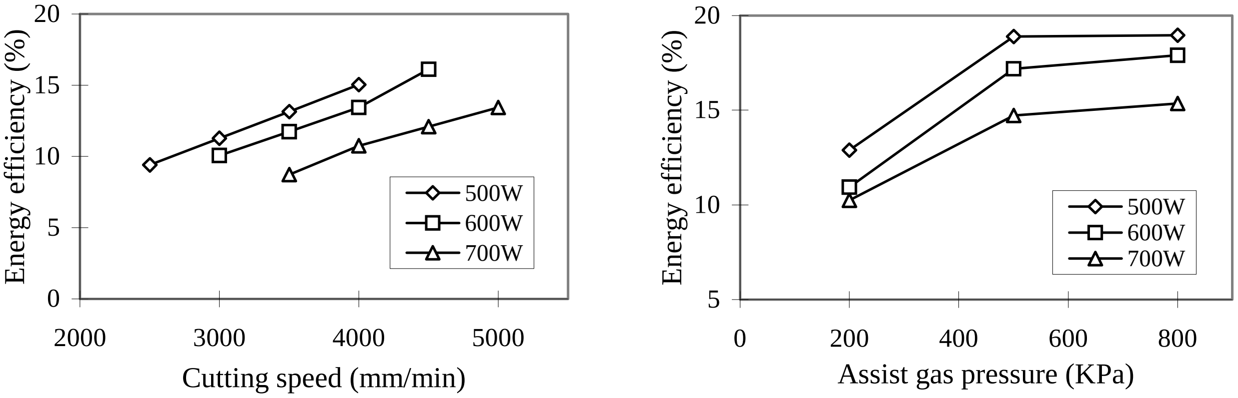
Table 2. Process parameters used in the experiments.

Material thickness (mm)			0.55	0.8	1.0			
Assist gas (oxygen) pressure (KPa)			200	500	800			
Laser power (W)	400		500		600		700	
Cutting speed (mm/min)	2,000	2,500	2,500	3,000	3,000	3,500	3,500	4,000
	3,000	3,500	3,500	4,000	4,000	4,500	4,500	5,000

Table 3. Recommended combinations of parameters for cutting GALVABOND and model predicted cutting speeds.

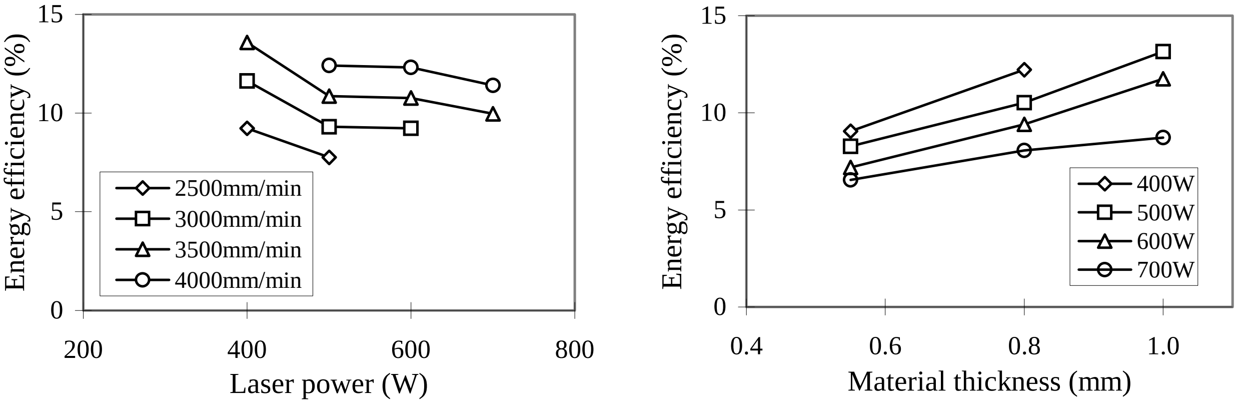
Thickness (mm)	Assist oxygen pressure (KPa)	Laser power (W)	Cutting speed (mm/min)	Querry's model: $V = 7430e^{-1.06}P^{0.63}$	Miyazaki's model: $V = 3500e^{-0.56}P^{0.5}$
0.55	200	500	4000	9048	3459
0.80	200	600	4500	6823	3072
1.00	200	700	5000	5935	2928

where e is in mm and P is in KW.



(a) e=1 mm and P_r=200 KPa.

(b) e=0.8 mm and V=4000 mm/min.



(c) e=0.55 mm and P_r=500 KPa.

(d) V=3500mm/min and P_r=200 KPa.

Fig. 1. Effect of process parameters on energy efficiency.

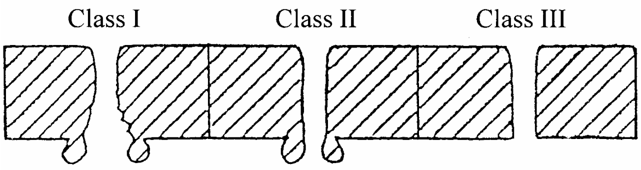
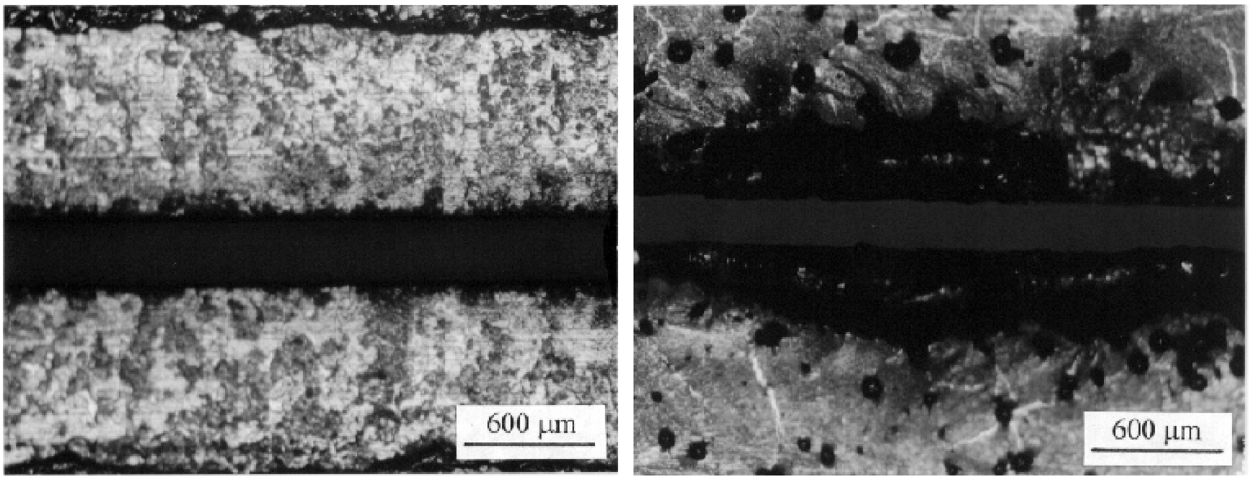
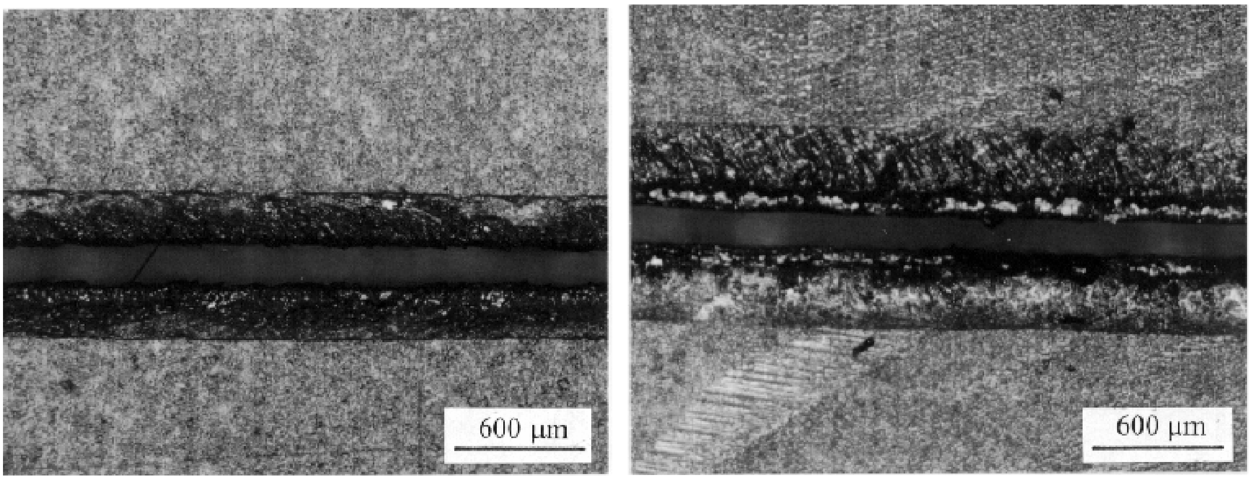


Fig. 2.Three classes of through cuts.

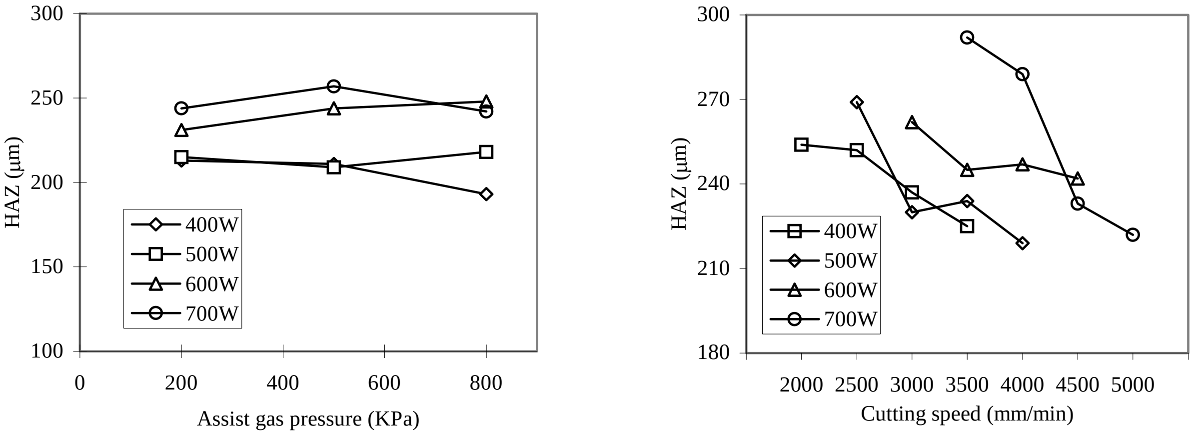


(a) Top view. (b) Bottom view.



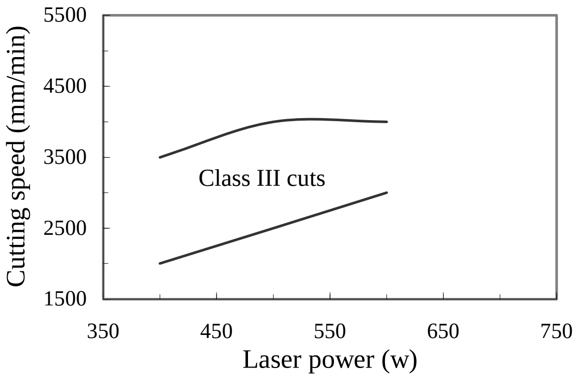
(c) Top view. (d) Bottom view.

Fig. 3. Kerfs produced by CO_2 laser on 1.0 mm specimens.
Views (a) and (b): P = 500 W, V = 45 mm/min, P_r = 500 KPa;
Views (c) and (d): P = 500 W, V = 4000 mm/min, P_r = 200 KPa.

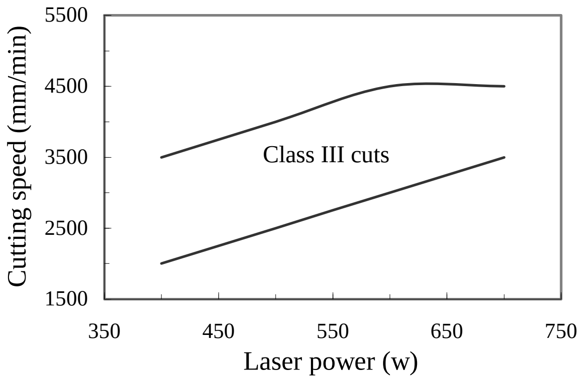


(a) V=3500mm/min and e=0.8 mm. (b) P_r=200 KPa and e=0.55 mm.

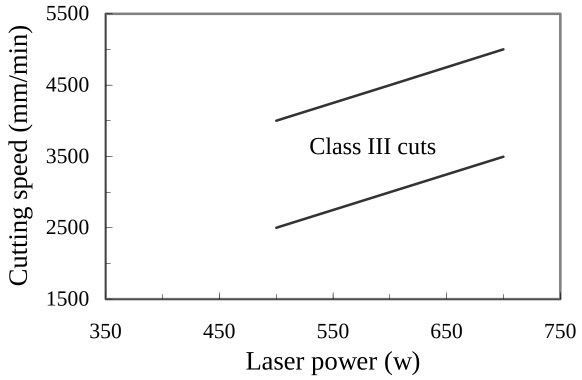
Fig. 4. Effect of process parameters on HAZ.



(a) 0.55 mm thick GALVABOND.



(b) 0.8 mm thick GALVABOND.



(c) 1.0 mm thick GALVABOND.

Fig. 5. Combination of process parameters for good quality (class III) cuts with minimum HAZ and dross (assist gas pressure: 200 KPa or 2 bar).