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The Role of the Assist Gas Nature in Laser Cutting of Aluminum Alloys

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Abstract

Laser cutting is a standard industrial process for cutting sheet metals. The process relies on the removal of the melted material with the aid of a pressurized assist gas. Among the main variables controlling the process, the assist gas type is an essential factor. This gas is normally chosen taking into account the material to be processed and the required cut quality. While the effect of the utilization of different assist gas is perfectly studied in cutting steels, the influence of the assist gas type during laser cutting of aluminum alloys is not well studied. This work presents a study on the influence of different assist gases (argon, nitrogen, oxygen and air) on the edge quality and its surface chemistry during laser cutting of a typical Al-Cu alloy.

Keywords: laser cutting; assist gas; oxidation; aluminium alloys

1. Introduction

Sheet-metal cutting is the single largest, in terms of sales, global industrial laser application. In this process, the material melted by the laser beam is removed from the kerf with the aid of a pressurized assist gas. The assist gas plays a crucial role in laser fusion cutting mainly due to the aerodynamic interactions between the molten material and the assist gas, interaction that has an enormous effect on the final cut quality [1-2]. On the other hand, this gas can chemically react with the molten material. Assist gases used in laser cutting can be classified, in general, as inert or reactive gases from this point of view [3]. When a reactive gas is used, it delivers additional exothermic energy through the chemical reaction between the gas and the molten material. This reaction supplies additional energy that enhances the cutting process. In this sense, the utilization of oxygen during the laser cutting of mild steel supplies up to the 60% of the energy required to cut this material. Thus cutting speeds are usually, at least, doubled using oxygen as assist gas [4]. However, since there is a chemical reaction, some chemical change of the material in the cut edge may be expected. In this sense, a very thin resolidified layer of metal oxide is formed on the cut edges. In order to avoid this reaction, inert gases, such as argon or helium, are normally used [3]. These gases only provide the

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mechanical force necessary to eject the melt from the cut zone and avoid undesirable chemical reactions.

Due to the fact that steels are the main material cut by laser, the influence of the assist gas type on the cutting of these materials has been widely studied [3]. Precedent research work pointed out the great sensitivity of the process to the type of assist gas used for cutting steels. On one hand, oxygen is most commonly used for cutting carbon steels. However, this produces oxidized edges. On the other hand, nitrogen is used for cutting carbon and stainless steels when high quality edges are required. Furthermore, several works have reported a great influence of the gas purity on the laser-cutting efficiency and edge quality [5-8]. It has been demonstrated that cutting speeds are reduced by 50% or even more if the oxygen purity is reduced by even 3% [9]. However, despite aluminum and alloys are important industrial metals and have vast applications, for example in the aerospace or automotive industry, the influence of the assist gas type on the laser-cutting efficiency and edge quality, during their processing is not well-studied. In this sense, some authors consider that nitrogen is the best alternative when cutting aluminum alloys, whereas oxygen is better for pure aluminum [10]. Nevertheless, a comprehensive study on the selection of the best assist gas for cutting aluminum alloys is not found in the literature.

In this work we have examined the effect of the utilization of four common assist gases (argon, nitrogen, oxygen and air) on the cutting speed, edge quality and surface chemistry during laser cutting of Al-Cu alloy sheets. To perform this task, we have used a supersonic cutting head based on its demonstrated advantages to obtain high performance and cut quality [11-12].

2. Experimental

Flat plates of a 2024-T3 commercial aluminum-cooper alloy, with a thickness of 3 mm, were used as processing workpiece. The experiments were carried out using a 3.5 kW CO_2 slab laser, the laser mode being a TEM_{00}. The laser beam was focused onto the surface of the workpiece using a 127 mm focal length lens and tests were only conducted in CW mode. In this work, all tests were performed using a computer numerical controlled (CNC) X-Y-Z table. In order to compare the results, the experiments were performed only on unidirectional straight line.

Cutting tests were performed with the aid of a cutting head incorporating an off-axis De Laval nozzle to inject the assist gas at a pressure of 8 bar. The nozzle was designed in order to operate at a Mach number M=2. The off-axis De Laval nozzle was set forming an angle of 35° with the laser beam axis and at a distance of 4 mm to the workpiece. Details concerning with this assist gas injection system can be consulted in Ref [11]. Four kind of assist gases were used in this study (argon, nitrogen, oxygen and air). The commercial designation, quality and main impurities for the four considered assist gases are summarized in Table 1.

Table 1. Quality and main impurities (in ppmv) in the four assist gases used during the whole experimentation.

Gas designation	Quality	Impurities (ppmv)
Air S1	77-80% N_2 20-23 % O_2	< 10 H_20
Oxygen 5.0	99.999%	$H_20 \leq 2$; $C_nH_m \leq 0.1$; $CO_2 \leq 0.2$; $CO \leq 0.2$; Inerts ≤ 10
Nitrogen S1	$\geq$ 99.99%	$H_20 \leq 10$; $O_2 \leq 10$
Argon 4.8	99.998%	$H_20 \leq 4$; $O_2 \leq 3$; $N_2 \leq 15$; $C_nH_m \leq 1$

The inspection of the specimens, in frontal and cross-sectional view of the edges of the kerf, was accomplished by means of an optical stereoscopic microscope (Nikon Optiphot) equipped with an XY stage positioner. A photographic system was coupled to the microscope in order to record and store the images.

Evaluated parameters during the processing were maximum cutting speed, average roughness of the cut edge, dross height (measured from the lower face of the workpiece), and extension of the heat affected zone (HAZ).

Roughness was evaluated by means of a roughness meter Taylor-Hobson Form Talysurf Plus with a gaussian filter corrected in phase. Roughness was measured in different locations of the cut edge and an average value was extracted for every experimental condition. On the other hand, the area of the HAZ was measured in the cross section of the polished samples. Selected samples were sectioned perpendicularly to the cut edge with a precision cut-off machine (Struers Minitom) and subsequently embedded in epoxy resin. Subsequently they were polished with a series of abrasive SiC papers up to grade 1200, followed by diamond paste finish up to 0.1 μm. Next, samples were carbon coated and examined by scanning electron microscopy (SEM). In order to reveal the grain structure, the samples were chemically etched previously to be carbon coated. The chosen etchant was Keller's Reagent with immersion times of 10 s.

Finally, the chemical composition of the surface of the cutting edges of samples was determined by means of XPS surface measurements. The XPS measurements were performed using monochoromatic Al-Kα radiation by means of a Thermo Scientific K-Alpha ESCA instrument. Neutralization of the surface charge was performed by using both a low energy flood gun (electrons in the range 0 to 14 eV) and a low energy Argon ions gun. The XPS measurements were carried out using monochromatic Al-Kα radiation (hν=1486.6 eV). Photoelectrons were collected from a take off angle of 90º relative to the sample surface. The measurement was done in a Constant Analyser Energy mode (CAE) with a 100 eV pass energy for survey spectra and 20eV pass energy for high resolution spectra. Charge referencing was done by setting the lower binding energy C1s photopeak at 285.0 eV C1s hydrocarbon peak. The atomic concentrations were determined from the XPS peak areas using the Shirley background subtraction technique and the Scofield sensitivity factors.

3. Results and Discussion

Experimental tests conducted in order to evaluate the influence of the assist gas nature on the cutting performance (here quantified in terms of cutting speed) revealed argon as the most effective gas, then oxygen, compressed air and finally nitrogen (see Figure1a). The consequence of using an assist gas different from argon is a reduction of the cutting speed as shown in Figure 1b.

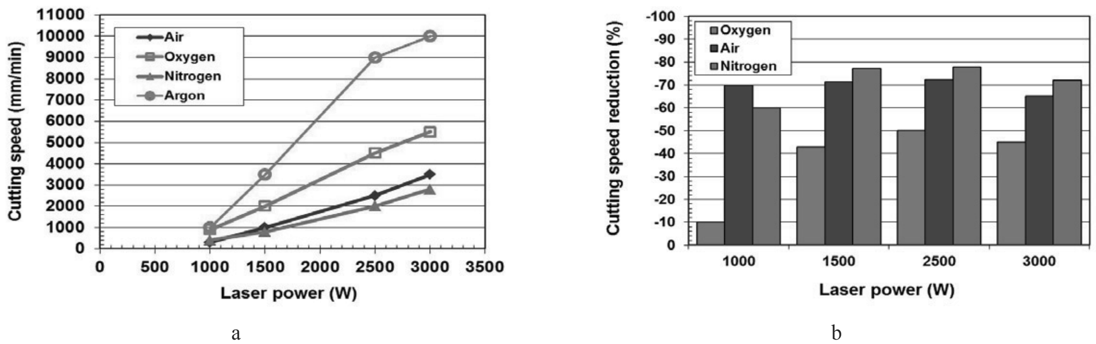


Figure 1. (a) Maximum cutting speed as a function of the laser power for considered assist gases; (b) Reduction in cutting speed as a consequence of the utilization of an assist gas different from argon.

Furthermore, the chemical reaction of pure oxygen with aluminum delivers more energy than the chemical reaction of oxidation of iron:

$$4Al + 3O_2 \rightarrow 2Al_2O_3 \qquad \Delta H_c = -1675\ kJ/mol \qquad (1)$$

$$2Fe + O_2 \rightarrow 2FeO \qquad \Delta H_c = -538.8\ kJ/mol \qquad (2)$$

This fact means that the cutting speed is substantially reduced in the case of steels compared to aluminum alloys [13-14]. On the other hand, nitrogen also can exothermically react with molten aluminum at temperatures higher than 830ºC, in the same order of magnitude to the cutting front as in the oxidation of the material [15-16]:

$$Al + N \rightarrow AlN \qquad \Delta H_c = -1050.4\ kJ/mol \qquad (3)$$

However, the reduction is even more pronounced that in the case of using oxygen as assist gas [17].

The average reduction, as compared to those values obtained when argon is used as assist gas is: 37 % for oxygen, 70 % for compressed air and 72 % for nitrogen. Therefore, nitrogen is the assist gas which more affects the cutting speed; however, this reduction is similar to that produced when using compressed air. Finally, it can be observed that, the reduction in cutting speed does not depend on the laser power in the case of using nitrogen or compressed air; however, this reduction is a function of the laser power when oxygen is used.

Regarding the kerf width, the utilization of compressed air tends to produce larger kerfs, whereas argon is the gas which produces the smallest kerfs for the range of considered laser powers. Oxygen and nitrogen also produce kerfs larger than in the case of using argon.

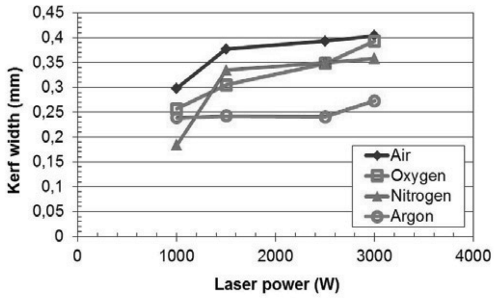


Figure 2. Influence of the laser power on the kerf width for the considered assist gases: compressed air, oxygen, nitrogen, and argon.

Regarding the cut edge quality, a clear influence of the assist gas type can be observed as shown clearly in Figure 3. Inspection of cut edges reveals the outstandingly smoother topography obtained when argon is used as assist gas and high laser power is applied.

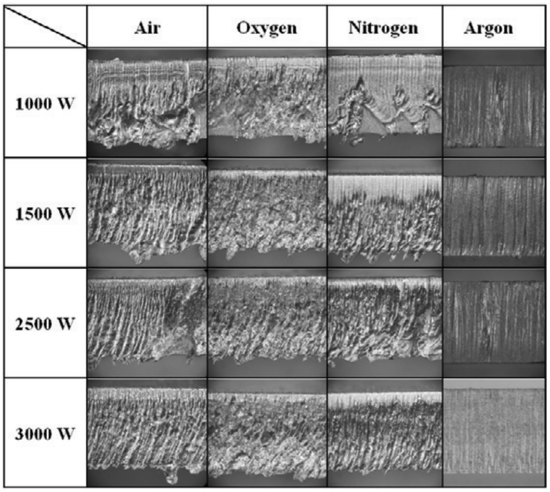


Figure 3. Optical micrographs of the surface morphology of cut edge of samples processed by means of selected assist gases as a function of the laser power.

As noted in Table 2, the maximum average roughness is obtained when oxygen or nitrogen are used, whereas the utilization of compressed air slightly decrease this parameter. The minimum average roughness, reaching a mean value of 3.7 µm for the tested conditions, was obtained by means of the utilization of argon as assist gas.

The inspection of the lower part of the cut edge in samples processed by means of oxygen (see Figure 4) reveals the presence of large amount of voids which are responsible for the great non-uniformity of the edge. In this case, micro cracks can be observed along the edge.

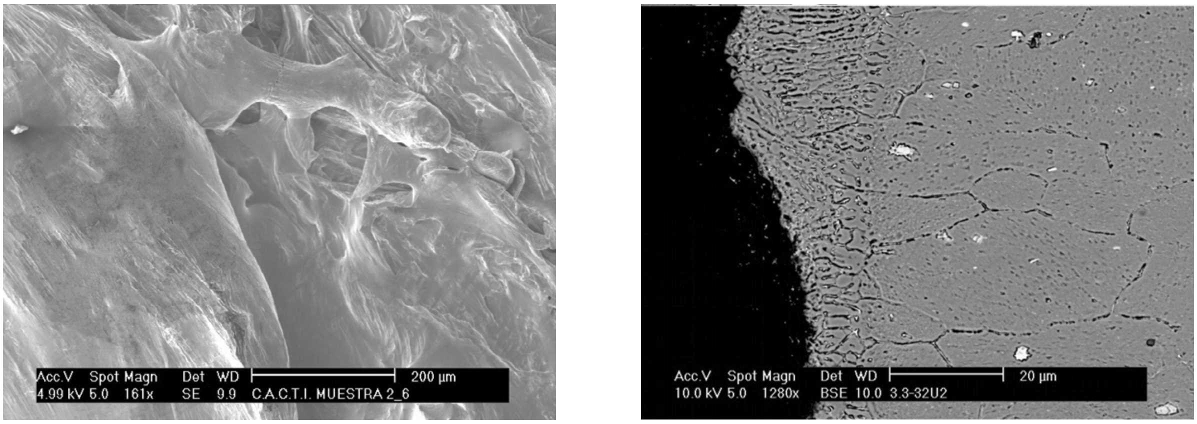


Figure 4. Micrographs of the lower part of the cut edge and b) cross sectional view obtained by SEM microscopy of a sample processed using oxygen as assist gas.

Table 2. Average roughness (evaluated for maximum cutting speed conditions obtained during processing at 1000, 1500, 2500 and 3000 W) and HAZ extension as a function of the tested assist gases.

Assist gas	Average roughness (µm)	HAZ extension (µm^2)
Compressed air	8,2	131147
Oxygen	14,2	182242
Nitrogen	13,1	94591
Argon	3,7	15469

The characterization of the cross section of the samples indicates that a large HAZ can be formed depending on the processing conditions. As noted in Figure 4b, a fine dendritic microstructure is formed in the cut edge. In this region, a strong precipitation of second-phase particles is produced (dark areas). Furthermore, a clear influence of the nature of the assist gas is observed, as summarized in Table 2. Oxygen and compressed air are the gases that produce cuts with larger HAZ. This is a consequence of the heat delivered by the oxidation of the molten material. However, argon tends to produce cuts with a HAZ extension one order of magnitude lower than in the rest of considered assist gases. Finally, despite the chemical reaction of nitrogen with the molten material is approximately as exothermic as in the oxidation, the HAZ is not so pronounced that in the case of using compressed air or oxygen.

Utilization of oxygen and compressed air, the most reactive gases with the molten aluminum, induces the highest dross height. On the other hand, the utilization of nitrogen decreases the level of dross; however, argon is the only gas which is able to produce dross-free cuts as depicted in Figure 5. It must be point out that these results were obtained with a supersonic cutting head. Nevertheless argon allows reasonable good cuts of aluminum alloys also when using a conventional cutting head [18].

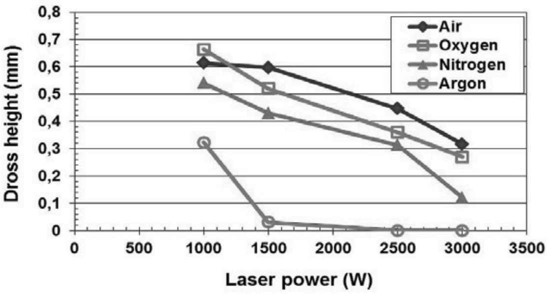
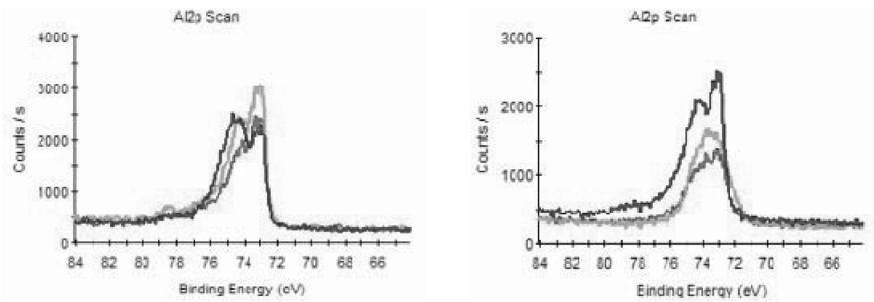


Figure 5. Evolution of the dross height (measured from the lower part of the workpiece) as a function of the laser power for the considered assist gases.

In order to determine the possible influence of the kind of assist gas on the chemistry of the cut edge and to explain the previous results, XRD and XPS analyses were performed in selected samples. XRD analyses were performed on the cut edge of samples processed under a laser power of 1000 and 2500 W. Despite the XRD characterization was performed at grazing incidence the results did not completely reveal the surface chemistry. Therefore, XPS analyses were performed on the cutting edge due to the better resolution in depth (approximately 1-10 nm). After performing a survey scan, detailed scans of photoelectron peaks in Al2p, C1s, O1s and N1s regions were performed in the upper, middle and bottom part of cutting edge of samples processed by the four assist gases and under a laser power of 3000 W. In samples processed by means of compressed air, nitrogen and argon oxide/hydroxides and aluminum nitrides were detected, while in those samples processed by means of oxygen only aluminum oxide is present. The level of oxide/hydroxides and nitrides is substantially higher in the samples processed by means of compressed air, nitrogen and oxygen than in the case of using oxygen, as collected in Table 3.

The observed finishing can be related to the chemistry on the surface of the cutting edge. The formation of oxides and/or nitrides tends to increase the viscosity and surface tension of the melt and drastically reduce the removal of molten material by the gas jet producing cuts with dross and a large HAZ. Argon was arisen as the more efficient assist gas to obtain best quality results because it produces a less amount of oxides and/or nitrides (as seen in the XPS spectra of Figure 6a). Oxygen, nitrogen and compressed air react to a greater or lesser extent with the molten material (see Figure 6b) and this largely influences the extraction of molten material generating cuts with an uneven profile, large amount of clinging dross and thermal affectation of cuts.



a b

Figure 6. High resolution XPS spectra of the sample processed with nitrogen in the Al2p window for (a) argon, (b) nitrogen (red, green and blue lines are respectively the spectra for the three analysed locations in the cutting edge: the upper, middle and lower part).

Table 3. Chemical composition (in at. %) of the cut edge of samples processed by means of compressed air, oxygen, nitrogen and argon

	AlN (at.%)	Al metal (at. %)	Oxide / Hydroxide (at. %)
Air	4.6	95.4	
Oxygen	-	17.8	82.2
Nitrogen	23.8	76.2	
Argon	17.0	83.0	-

4. Conclusions

A detailed investigation on the influence of different assist gases on the laser cutting efficiency and cut quality of an Al–Cu alloy was carried out. Results indicate a clear influence of the assist gas nature on the finishing characteristics. This result can be related to the chemistry into the surface of the cut edge. Formation of oxides and nitrides were observed to modify the cut quality and cutting speed. Oxygen, nitrogen and compressed air react to a greater or lesser extent with the molten material generating a large amount of oxides and/or nitrides. This largely affects the cutting speed and cut quality of the obtained cuts. On the other hand, argon was arisen as the more efficient assist gas to obtain best quality results and with the higher eficiency. Then, from the point of view of quality and efficiency argon is the best choice for processing Al-Cu alloys.

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