Lasers in Manufacturing Conference 2017

Pulsed laser cutting of granite

A. Riveiro[a,*], A. Mejias[b], R. Soto[a], F. Quintero [a], J. del Val[a], M. Boutinguiza[a], F. Lusquiños[a], J. Pardo[b], J. Pou[a]

[a] *Applied Physics Department, University of Vigo, EEI, Lagoas-Marcosende, Vigo, E-36310, Spain*
[b] *Business Organization Department, University of Vigo, EEI, Lagoas-Marcosende, Vigo, E-36310, Spain*

Abstract

Natural stones, in particular granites, are excellent materials for construction, engineering or monumental applications. These materials are able to withstand adverse weather conditions, which ensures a long and durable usage; but also, their aesthetic appeal is greatly appreciated. Despite, they are widely used, these materials are difficult to machine by conventional methods. High level of noise and large amount of powder are produced during their cutting. In this work, CO_2 laser cutting of 10 mm thick granite slabs is presented. Influence of the processing parameters on quality characteristics, during pulsed laser cutting, is studied. Costs associated to the process were calculated, and the main factors affecting on them identified. Results from the cutting experiments show that it is possible to obtain sound cuts, free of fractures in this kind of materials at an affordable cost.

Keywords: laser cutting; granite; pulsed mode; quality

1. Introduction

Granites are commonly used for construction, engineering or monumental applications due to their aesthetic appeal and high resistance to withstand adverse weather conditions. The large application in construction is highlighted by the fact that 1.265 billion m² natural stone (value based on stone slabs 2 cm in thickness) were used in construction or similar in 2011 according to Montani (Montani, 2012).

Cutting of granites is commonly performed by means of diamond coated tools, e.g. diamond wire saws or circular diamond saw blades. As stated by Howarth et al., Eyuboglu et al., and Sánchez Delgado et al., the sawability of a stone is correlated with its hardness (Howarth et al., 1986; Eyuboglu et al., 2003; Sánchez

* Corresponding author. Tel.: +34-986-812-216; fax: +34-986-812-210.
E-mail address: ariveiro@uvigo.es.

Delgado et al., 2005). Eyuboglu et al. (Eyuboglu et al., 2003) showed that the wear rate is related to the hardness of the stone. Sánchez Delgado et al. (Sánchez Delgado et al., 2005) also corroborated that a 10% increase in rock hardness results in a 54% decrease in sawing rate for Pink Porriño granites. On the other hand, tons of powder, and high levels of noise are generated during cutting stones. Some of the dust produced during the sawing process may be fine enough to breathe deeply into the lungs and cause harm to health of employees. These facts, among others, make the processing of stones an arduous task, and certainly unsafe for the worker. Therefore, alternative cutting methods have been explored. In this sense, abrasive waterjet cutting can be effectively applied to cut stones; however, several drawbacks appear (low cutting speeds, waste management required, high noise level, or high maintenance cost).

As an alternative process, laser cutting can overcome these drawbacks. This is a well-established cutting process in the industry. It is characterized by high cutting speeds, high precision, high quality, low level of noise, flexibility, ease of automation, or very low waste production (Steen, 2010). Despite its high entry cost, even higher than in the case of the waterjet cutting, the higher cutting speeds can overcome this initial investment in this technology. Some approaches to apply laser cutting to cut natural stones are found in the literature. Gurvich et al. (Gurvich et al., 1993) explored the CO_2 laser cutting of different granite stones and concrete. They found that cracks induced by thermal stresses in the cutting region are frequently observed. Miranda et al. (Miranda, 2004; Miranda and Quintino, 2004) demonstrated the capabilities of the CO_2 laser to cut calcareous stones. The assist gas pressure was determined as the most relevant parameter to obtain high quality cuts. Kumar et al. (Kumar et al., 1995) and also Pires et al. (Pires et al., 1998) studied the laser cutting of marble and its thermal effects on the material. Boutinguiza et al. demonstrated the capabilities of lasers in cutting slate (Boutinguiza et al., 2002). A review of these results demonstrate that these works only concentrates in the demonstration of the viability of the technique; nevertheless, the optimization of the cut quality, and their possible utilization in the industry was not discussed.

On the other hand, these works involve the utilization of a conventional cutting head, in which converging coaxial nozzles injecting the assist gas are used to remove the molten material. However, this processing system prevents the utilization of this technique to cut natural stones for aesthetical applications due to the poor cut quality. The inefficient removal of molten material, very rough cuts, large amount of dross, and a large heat affected zone (HAZ). An alternative to increase the assist gas performance is the utilization of off-axial supersonic nozzles.

The main aim of this work is to study CO_2 laser cutting of granite plates using a cutting head assisted by an off-axis supersonic nozzle in order to improve the cut quality results. This approach has been successfully used in the past for cutting metals (Ivarson et al., 1991; Riveiro et al., 2010) , ceramics (Black et al., 1998; Quintero et al., 2004), polymers (Caiazzo et al., 2005; Choudhury and Shirley, 2010), or wood (Mukherjee et al., 1990); however, it has not been widely explored for cutting granite stones. Influence of processing parameters was evaluated by means of statistically planned experiments. Quality characteristics (kerf width and average roughness) in continuous wave (CW) and pulsed mode processing, and chemical modifications of the laser treated region were determined. Finally, costs associated to the process were estimated.

2. Experimental procedure

2.1. Base Materials

The base material for all the experiments was “Zimbabwe black” gabbro plates (10 mm in thickness). This stone has a medium-coarse grain and a high specific gravity, and is commonly used in construction and in the funeral art. This is a stone with a so called “granitic texture”, and it is chemically equivalent to basalt. It is mostly composed of calcium-rich plagioclase feldspar, pyroxene and olivine; however, unlike common granites, is low in silica content, and has no quartz (Fenton and Fenton, 2003).

2.2. Experimental methods

Cutting experiments were performed using a 3,5 kW CO_2 slab laser (Rofin-Sinar), the laser mode being a TEM_{00}. Tests were conducted in continuous wave (CW) and in pulsed mode using ZnSe lenses with 127 mm in focal length to focus the raw laser beam. The laser focal spot was placed 2 mm underneath the surface of the workpiece in all the experiments taking into account previous cutting experiments.

Cutting trials were performed using a cutting head with an off-axis supersonic nozzle to inject the assist gas (compressed air) at a maximum pressure of P=8 bar. The nozzle exit diameter was 1,7 mm, and it was designed to operate at a Mach number M=2. Details regarding the cutting head geometry and applications can be consulted in Refs. (Quintero et al., 2006; Riveiro et al., 2008).

Laser cutting process was studied in CW and pulsed mode. In CW mode, a response surface methodology (RSM) was applied to determine a mathematical model which relates the main factors (laser power and cutting speed) with the selected quality responses (kerf width and average roughness). Table 1 summarizes the experimental conditions used during CW mode processing and the associated responses. In pulsed mode, only the influence of the pulse frequency was investigated.

Table 1. Values of the factors and results of the experiments during CW mode processing.

Exp. No.	Power (W)	Speed (mm/min)
1	2500	7,0
2	2000	5,0
3	2000	5,0
4	1500	3,0
5	2000	5,0
6	1293	5,0
7	2000	5,0
8	2707	5,0
9	2000	7,8
10	2000	2,2
11	2000	5,0
12	2500	3,0
13	1500	7,0

Based on these experiments, response surface models for the kerf width and average roughness during CW mode processing were developed. In pulsed mode, only the influence of the pulse frequency on the process was assessed. Pulse frequencies of 100, 500, 1000, 2000, 3000, and 4000 Hz were evaluated. The average power used during these experiments was 2000 W, a cutting speed of 3 mm/s was selected, and a duty cycle of 50% was maintained fixed along the whole cutting experiments. The remaining processing parameters were the same used during CW processing mode.

2.3. Characterization techniques

After cutting experiments, some selected samples were sectioned perpendicularly to the cut edge with a precision cut-off machine (Struers Minitom), and subsequently embedded in epoxy resin, and finally grinded with SiC paper and polished by diamond paste up to 1 µm finishing. These specimens were inspected in frontal and cross-sectional direction to the cut edge using an optical stereoscopic microscope (Nikon SMZ-10A) with a photographic system in order to record and store the images. Furthermore, both the cut edge, and its cross-section were studied after the laser cutting process through scanning electron microscopy (SEM). Samples obtained from each specimen were covered with a thin gold layer and examined in a Philips XL-30 SEM.

Roughness was measured using a stylus profiler (Taylor-Hobson Form Talysurf Plus) with a Gaussian filter corrected in phase in three locations of cut edges: upper, middle and lower part of them. Then, an average value was extracted to characterize the finishing of cut edges. Measurements were performed in accordance with the recommendations specified in the International Standard ISO 4288:1996.

Determination of crystalline phases, and chemical composition of the base and resolidified material after the laser cutting was determined using X-Ray diffraction (XRD) and X-Ray Fluorescence (XRF) analyses.

XRD analyses were performed with a Siemens D-5000 diffractometer operating in Θ–2 Θ geometry, using Cu Kα radiation. The X-ray generator operated at 45 kV and 40 mA. To determine the phase composition, the diffractometer was operated in grazing incidence geometry. Data were collected over the 2 Θ range 5°–90° with a step size of 0.02° and a count time of 5 s.

X-ray fluorescence composition analysis was obtained from powdered samples by a Siemens SRS 3000 spectrometer, equipped with an Rh anode and a 60 kV X-ray generator.

3. Results and Discussion

3.1. Cut quality (CW mode)

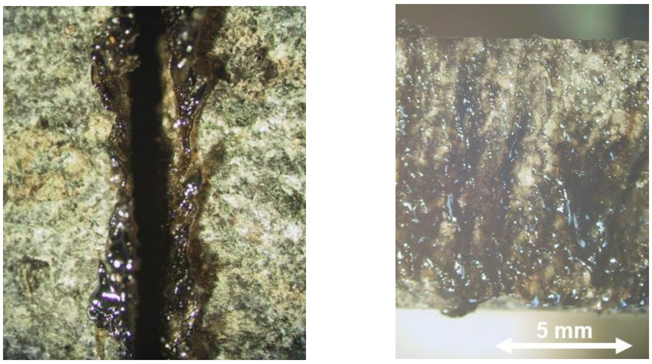
A typical entry side of the cut kerf, and the cut edge during processing in CW mode is depicted in Fig. 1. Cuts along the whole depth of the 10 mm thick plates were obtained. In the entry and exit sides of the cut, some dross is formed due to the inclination of the assist gas jet. On the other hand, the cut wall exhibits the characteristic ripple pattern produced during laser cutting. Some amount of resolidified material is also found on the cut walls because the assist gas (despite its high velocity) is not able to completely remove all the molten material due to its high viscosity. This resolidified layer has an average thickness about 150 µm.

Thermal induced cracks were not observed after processing, despite the high tendency of this material to thermal cracking due to the polycrystalline nature of the studied material. Then, the utilization of supersonic jets to inject the assist gas reduces the cracking susceptibility, typically found during the laser processing of these materials.

The variation of the average kerf regarding the laser power and cutting speed is depicted in Figure 2a. Typical values of this parameter are found in a range from 0,5 mm to 0,7 mm. Experimental results indicate a well-known increment of the kerf width with the laser power due the higher amount of energy available in the process for melting. However, the increment of the cutting speed produces a decrease of the average kerf width; however, close to the maximum cutting speed, and for a fixed laser power, the kerf width increases with a further increase in speed. Therefore, the minimum cutting speed is obtained, for each laser power, at values slightly lower than the maximum cutting speed. This minimum is located at cutting speeds around 5-6 mm/s, for the tested laser powers.

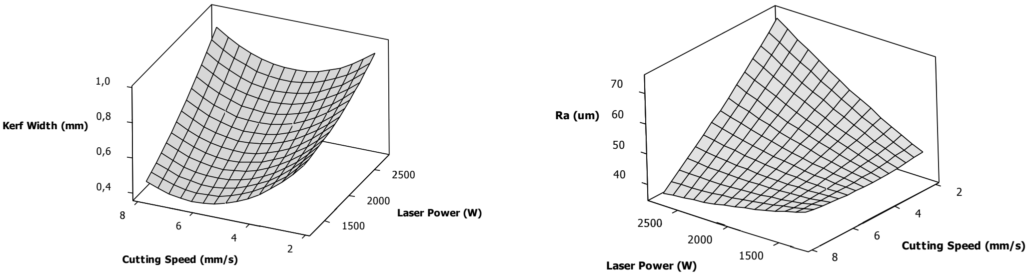
The average roughness was measured in different locations of the cut walls and a mean value was extracted. Typical values for this parameter are in a range around R_a=30 µm to 50 µm. Figure 2b depicts the influence of the laser power and cutting speed on this parameter. As observed, both parameters have a simultaneous influence on the roughness. For low laser power levels, the average roughness remains almost unchanged when the cutting speed is varied; but, at high laser power levels, the average roughness is strongly reduced with the cutting speed. On the contrary, the increment of the laser power for low cutting speeds tends to increase the average roughness, while at high cutting speeds this parameter is slightly decreased. The increment of the roughness at high laser power levels and low cutting speed is due to the inefficient removal of molten material by the assist gas when a large amount is produced.

Smooth cuts were found at high laser powers and high processing speeds (i.e. for a laser power and cutting speed higher than 2000 W and 8,0 mm/s respectively).



a b

Fig. 1. Optical images of a typical (a) entry side, and (b) cut edge during the processing under CW mode conditions (Processing conditions: Laser Power: 2000 W, Cutting Speed: 8 mm/s).



a b

Fig. 2. Variation of the a) kerf width, and b) average roughness (Ra) with the laser power and the cutting speed during the processing in CW mode.

3.2. Cut quality (pulsed mode)

Cut edge of a typical sample processed in pulsed mode is depicted in Fig. 3. Cut striations are more marked in this case as compared to the processing in CW conditions. Dross and resolidified material were not avoided during laser cutting in pulsed mode.

The variation of the kerf width with the pulse frequency is depicted in Fig. 4a. Kerf widths are larger than in CW mode. An increment in the kerf width with the pulse frequency is observed, reaching the kerf width a maximum value for pulse frequencies around 3000-4000 Hz. On the contrary, the average roughness is reduced with the pulse frequency (see Fig. 4b). The average roughness reaches a stable value around R_a=70 µm for pulse frequencies larger than 500 Hz. As observed, the average roughness is also higher in pulsed mode than in CW mode, especially for low repetition rates.

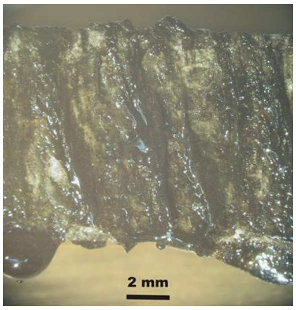


Fig. 3. Optical image of a typical cut edge for a sample processed in pulsed mode (Processing conditions: Laser Power: 2000 W, Cutting Speed: 3 mm/s, Frequency: 3000 Hz, Duty cycle: 50%).

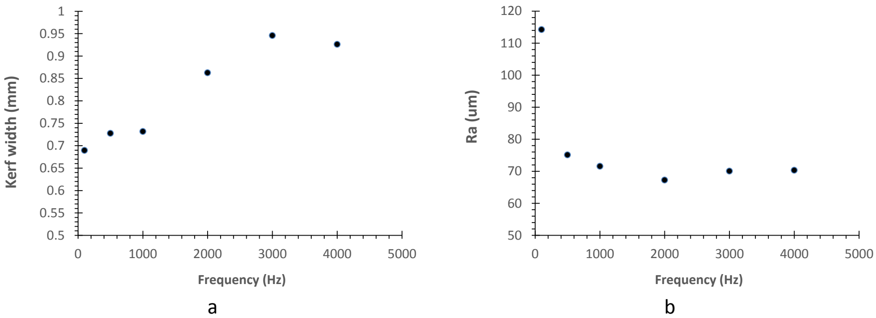


Fig. 4. Variation of the a) kerf width, and b) average roughness (Ra) with the laser power and the cutting speed during the processing in pulsed mode.

3.3. X-Ray characterization

The chemical compositions of the base material and in the cut edge after laser cutting were found very similar (see Table 2) are very similar, as determined by means of XRF analyses. This suggest that no significant chemical changes were induced during the process. The only detected modification was the amorphization of the laser treated material along the cut edge, as corroborated by XRD analyses.

3.4. Economic analysis of the process

In order to estimate the economic viability of the laser cutting of natural stones, costs of the process were estimated using a similar model to that developed by Riveiro et al. (Riveiro et al., 2014). The laser sources used in the present estimation include CO_2, fibre, and Nd:YAG lasers, sources commonly used in the industry for laser cutting.

Compressed air was considered to be the assist gas with a typical volumetric flow rate of $\dot{V}$=400 l/min commonly used in high-pressure cutting (see for example, Ref. (Caristan, 2004)). An XY table with a power consumption of 8 kW was selected.

The calculated costs also take into account the maintenance (time required for performing the maintenance tasks was assumed to be 24 h). Two work shifts (WS) per day were considered. The temporal interval of a work shift (WD) was assumed to be 8 hours. The work week (WW) was considered to consist of 5 days per week, and the effective weeks (W) along the year available for machining to be 52 weeks. Typical maintenance intervals (M) have been considered for each laser source.

Table 2. Chemical composition of the base material, and the resolidified material formed on the cut walls after laser cutting determined by means of XRF analyses.

Base material										
Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	Fe_2O_3
1,86	7,21	15,72	45,4	0,047	0,19	0,11	15,1	1,08	0,2	13,08
Laser affected material										
Na_2O	MgO	Al_2O_3	SiO_2	P_2O_5	SO_3	K_2O	CaO	TiO_2	MnO	Fe_2O_3
2,605	6,7	15,33	47,52	0,06	0,13	0,15	13,72	0,91	0,19	12,68

In order to compare costs, these are evaluated under the same base; therefore, all the evaluated costs are calculated as the ratio of costs per unitary length of cut (€/cm) to perform this task.

Costs associated to the laser cutting of granite are summarized in Table 3. Costs associated to the utilization of the CO_2 laser (0,03 €/cm), are smaller to those associated to the fiber laser (0,04 €/cm), while the utilization of a Nd:YAG laser (0,07 €/cm) costs almost twice. Higher costs associated to this laser source can be explained due to its lower efficiency (we have assumed an efficiency of 2% for the Nd:YAG laser, and 25% and 10% for the fiber and CO_2 lasers, respectively). In summary, these results suggest that the CO_2 laser is the most suitable laser source from an economic point of view to cut natural stones.

Table 3. Costs per unitary length of cut (€/cm) for three different laser sources: CO_2, Nd:YAG and Fiber lasers

CO_2 laser	*Nd:YAG laser*	*Fiber laser*
0.03 €/cm	0.07 €/cm	0.04 €/cm

Although the presented quality results indicate that these are not superior to those obtained by means of mechanical methods, the economic viability of the process and the advantages of the laser processing (flexibility, automation, no dust, less consumables, etc.) can still make this process attractive for the industry. As depicted in Fig. 5, complex shapes can be produced in granite, avoiding fractures or cracks in the edges.

4. Conclusions

In this work the capabilities of lasers to cut natural stones were demonstrated. Using an experimental approach based on statistically planned experimentation, main cut quality characteristics during CO_2 laser cutting of Zimbabwe black granite were determined. Moreover, the economic viability of the process was assessed by estimating the costs associated to the process. The following main conclusions can be highlighted from this study:

- In CW mode processing, the kerf width exhibits a minimum value close to the maximum cutting speed, in a range of 5-6 mm/s. Average roughness exhibits typical values from Ra=30 µm up to 50 µm.
- In pulsed mode, the pulse frequency influences the kerf width and the roughness of the cut wall. Kerf width is increased with the pulse frequency, but the roughness is decreased with this parameter.
- No cracks are formed in the cut edge. A minimum layer of resolidified material, typically 150 µm in width, is produced and the dross, mainly adhered to the bottom part of the cut can be easily removed by secondary operations. The material in the cut edge is mainly amorphized.
- CO_2 and fiber lasers seem to be the most affordable options to process natural stones.
- Laser cutting is able to produce complex shapes.

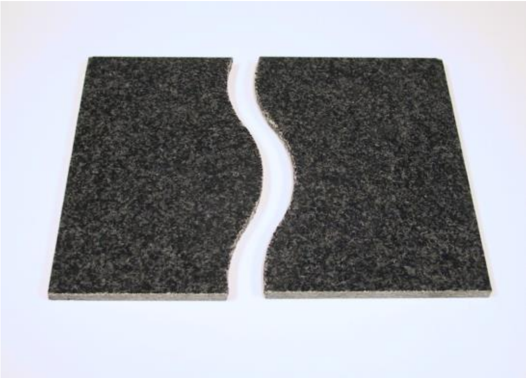


Fig. 5. Viability of laser cutting to produce complex shapes in Zimbabwe black granite.

Acknowledgements

The authors wish to thank the technical staff from CACTI (University of Vigo) for their help with sample characterization. This work was partially supported by the Spanish Government, (MAT2015-71459-C2-P), and by Xunta de Galicia (ED431B 2016/042, and Plan I2C Grant Program POS-A/2013/161 and ED481B 2016/047-0).

References

Black, I., Livingstone, S.A.J., Chua, K.L., 1998. A laser beam machining (LBM) database for the cutting of ceramic tile. Journal of Materials Processing Technology 84, 47-55.

Boutinguiza, M., Pou, J., Lusquiños, F., Quintero, F., Soto, R., Pérez-Amor, M., Watkins, K., Steen, W.M., 2002. CO2 laser cutting of slate. Optics and Lasers in Engineering 37, 15-25.

Caiazzo, F., Curcio, F., Daurelio, G., Minutolo, F.M.C., 2005. Laser cutting of different polymeric plastics (PE, PP and PC) by a CO2 laser beam. Journal of Materials Processing Technology 159, 279-285.

Caristan, C.L., 2004. Laser Cutting Guide for Manufacturing. Society of Manufacturing Engineers (SME), Dearborn, Michigan.

Choudhury, I.A., Shirley, S., 2010. Laser cutting of polymeric materials: An experimental investigation. Optics and Laser Technology 42, 503-508.

Eyuboglu, A.S., Ozcelik, Y., Kulaksiz, S., Engin, I.C., 2003. Statistical and microscopic investigation of disc segment wear related to sawing Ankara andesites. International Journal of Rock Mechanics and Mining Sciences 40, 405-414.

Fenton, C.L., Fenton, M.A., 2003. The Rock Book. Dover Publications, Mineola, N.Y.

Gurvich, L., Yatsiv, S., Shachrai, A., 1993. Rock processing with CO2 laser radiation, Proceedings of SPIE: 8th Meeting on Optical Engineering in Israel: Optoelectronics and Applications in Industry and Medicine, Tel Aviv, Israel, pp. 297-305.

Howarth, D.F., Adamson, W.R., Berndt, J.R., 1986. Correlation of model tunnel boring and drilling machine performances with rock properties. International Journal of Rock Mechanics and Mining Sciences and 23, 171-175.

Ivarson, A., Powell, J., Magnusson, C., 1991. The role of oxidation in laser cutting stainless and mild steel. Journal of Laser Applications 3, 41-45.

Kumar, M., Biawas, A.K., Sriniwas, K., Nath, A.K., 1995. Marble cutting with CW CO2 laser, Proceedings of SPIE, Novel Applications of Lasers and Pulsed Power, San Jose, CA, United States, pp. 34-39.

Miranda, R.M., 2004. Structural analysis of the heat affected zone of marble and limestone tiles cut by CO2 laser. Materials Characterization 53, 411-417.

Miranda, R.M., Quintino, L., 2004. CO2 laser cutting of calcareous stones. Materials and Manufacturing Processes 19, 1133-1142.

Montani, C., 2012. XXIII Report Marble and Stones in the World 2012. Aldus Casa di Edizioni, Carrara, Italy.

Mukherjee, K., Grendzwell, T., Khan, P.A.A., McMillin, C.W., 1990. Gas flow parameters in laser cutting of wood - nozzle design. Forest Products Journal 40, 39-42.

Pires, M., Ferreira, A., Ribeiro, M., Teixeira, R., Rodrigues, C., 1998. Laser technologies in industries Proceedings of SPIE, pp. 622-625.

Quintero, F., Pou, J., Lusquiños, F., Boutinguiza, M., Soto, R., Pérez-Amor, M., 2004. Quantitative evaluation of the quality of the cuts performed on mullite-alumina by Nd:YAG laser. Optics and Lasers in Engineering 42, 327-340.

Quintero, F., Pou, J., Fernández, J.L., Doval, A.F., Lusquiños, F., Boutinguiza, M., Soto, R., Pérez-Amor, M., 2006. Optimization of an off-axis nozzle for assist gas injection in laser fusion cutting. Optics and Lasers in Engineering 44, 1158-1171.

Riveiro, A., Quintero, F., Lusquiños, F., Pou, J., Pérez-Amor, M., 2008. Laser cutting of 2024-T3 aeronautic aluminum alloy. Journal of Laser Applications 20, 230-235.

Riveiro, A., Quintero, F., Lusquiños, F., Comesaña, R., Pou, J., 2010. Parametric investigation of CO2 laser cutting of 2024-T3 alloy. Journal of Materials Processing Technology 210, 1138-1152.

Riveiro, A., Mejías, A., Lusquiños, F., del Val, J., Comesaña, R., Pardo, J., Pou, J., 2014. Laser cladding of aluminium on AISI 304 stainless steel with high-power diode lasers. Surface and Coatings Technology 253, 214-220.

Sánchez Delgado, N., Rodríguez-Rey, A., Suárez del Río, L.M., Díez Sarriá, I., Calleja, L., Ruiz de Argandoña, V.G., 2005. The influence of rock microhardness on the sawability of Pink Porriño granite (Spain). International Journal of Rock Mechanics and Mining Sciences 42, 161-166.

Steen, W.M., 2010. Laser material processing, 4th ed. Springer, New York.

Turchetta, S., Carrino, L., 2005. An energy based model for laser cutting natural stone. International Journal of Machine Tools and Manufacture 45, 761-767.