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Performance and efficiency of an industrial direct diode source with an extremely low BPP in laser cutting of Fe-based and reflective alloys

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Abstract

The performance and efficiency of a 2kW industrial direct diode laser source with an extremely low BPP are investigated when carbon and stainless steels as well as aluminium and brass sheets are laser cut. The results confirm the industrial feasibility and robustness of the direct diode laser source as tool for laser processes. In particular in the oxidation laser cutting of iron-based alloys the low BPP together with relative larger transport fiber diameter allows quality and cutting speed equivalent to the active fiber and disk laser sources in a very large range of thickness (up to 15 mm). When higher power densities are required, because inert laser fusion cutting of structural steel is carried out or because high reflective alloys need to be cut, the low BPP and the shorter wavelength are favorable figures and produce comparable performances with the mentioned laser sources.

Keywords: Direct diode; Laser cutting; Fe-based alloys; Reflective alloys, Performance; Efficiency;

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1. Introduction

In recent years new laser sources operating directly with a diode light launched into fiber are emerging on the market as the next generation of industrial lasers. Several confirmations are reported in literature (see Table 1) showing a preliminary feasibility of the diode laser source as cutting tool. Industrial interests come out from the possibility to implement the new source into a well-established process like laser cutting of metals. In this paper our aim is to confirm the diode laser source as valid tool and compare the performance with active fiber and disk laser sources in cutting tool in terms of economical and technical feasibility. At the actual state of art of the industrial practice, the strengths of high power diode laser source are: high efficiency, simple architecture and low cost of maintenance. Nevertheless, future perspective regards tunable wavelengths suitable for different materials and eye safety as well as ability to shape the power density distribution of the laser beam at the spot according to the thickness and material to be cut.

A few groups and companies have already experimented high brightness diode laser source for cutting metals. Lentijes et al. [1] used a 2kW diode laser system to cut medium thickness of mild and stainless steel with a comparable cutting edge quality of the consolidated laser technologies. Costa Rodriguez et al. [2] tested a prototype of direct diode laser capable to cut materials at industrially relevant cutting speeds and quality. For oxidation cutting process the performances were similar to fiber and CO_2, but for the fusion cutting process at the same output power the cutting speed was higher than CO_2 and lower than the reference fiber laser, while the surface quality was good only for thin sheets. Furthermore they presented theoretical considerations regarding the absorption in metals considering different laser sources [3, 4]. Wahab et al. [5] presented a deep analysis to optimise process parameters of direct diode cutting of 5 mm mild steel and 6 mm stainless steel. Recently groups from DirectPhotonics [6] and Amada [7,8] presented their solutions for applying the direct diode laser as a cutting tool for metals.

However in all the published references in Table 1 the BPP of the diode sources is very high and consequently the resulting spot diameter is large in comparison with the ones generally available with fiber and disk laser sources. Therefore productivity, quality and costs are difficult to be compared.

Table 1: Figures of merit of the commercial or prototypal diode laser sources recently used for laser cutting

DIREC DIODE LASER	Ref	Power [W]	λ [nm]	Delivery fiber [μm]	BPP [mm*mrad]	Spot diameter [mm]
LIMO DIOCUT 2000	[1]	2000	808 - 980	200 – 400	22	Na
Prototype DDL	[2,3,4]	2000	926	400	27-23	0.280 -0.406
LIMO DIOCUT 2500	[5]	2500	950	400	24	0.400 – 0.333
DIRECTPROCESS 900	[6]	2000	950	105	7.5	Na
AMADA ExC	[7,8]	2000	930	200	9	0.208

The paper shows an experimental investigation of a new industrial direct diode laser source whose figures of merit are significantly superior (at 2kW BPP is measured 3.90 mm*mrad) to prervious direct diode technologies. The study is aimed at investigating the feasibility area of the TeraDiode Inc. TeraBlade^{TM} diode laser source [9,10,12] in the laser cutting process of carbon and stainless steels as well as aluminum and brass sheet. The results are very encouraging since they confirm the equivalence of the performances of the new type of laser source in an industrial context and open the door to further exploration and investigation of this new source capability.

2. Experimentation design

2.1. Laser source

Laser cutting experiments were performed with a direct diode laser (DDL) TeraDiode Inc. TeraBlade, with a maximum output power of 2000 W based on the wavelength beam combining (WBC) technology. WBC is an incoherent, multi-wavelength process in which a dispersive optical element, such as a diffraction grating, is used to spatially overlap beams at different wavelengths and to provide feedback to each emitter in an array via a series of lenses. The laser resonator is formed between the high-reflective coated back facet of the emitter and the output coupler.

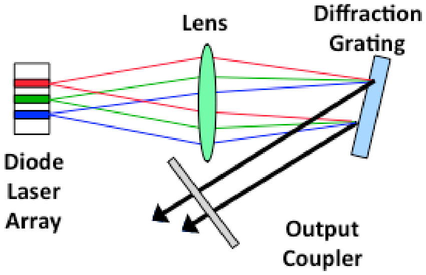


Fig. 1.Wavelength beam combining architecture.

This technology allows for brightness scaling of an emitter array because all of the laser elements are spatially overlapped at the output coupler, maintaining the output beam quality of a single element while scaling the output power by the number of elements in the array. Moreover WBC preserves the advantages of direct-diode lasers, including high efficiency, high reliability, low cost and long lifetime. [9, 10 ,11, 12]
The main characteristics of the TeraBlade source used in this paper are summarized in Table 2.

Table 2. Main characteristics of the DDL TeraDiode Inc. TeraBlade used in the experimentation.

Characteristics	DDL TeraDiode TeraBlade 2kW
Maximum output power [W]	2000
Fiber Diameter [μm]	100
BPP at the fiber exit [mm*mrad]	4.0
Wavelength [nm]	970 ± 20

The cutting experimentation was carried out on the BLMGroup LT Combo machine, a fully automatic laser cutting system that is able to process both tubular profiles (maximum tube length 6500 mm and maximum diameter 250 mm) and flat sheet metals (maximum working area 3000 x 1500 mm^2). The BLMGroup LT Combo machine was operating with a Precitec HP-SSL head equipped by standard collimation and focusing optics with a coating designed for laser sources operating at 1030 ÷ 1090 nm. All the experimentation was executed on sheets using the flatbed configuration of the machine.

The BLMGroup LT Combo machine is used to working with an active fiber laser (AFL) source (see its main characteristics in Table 3). Therefore in the paper the comparison between the standard configuration with the fiber source is presented. The purpose of the comparison is not to compare the pure performances (in terms of cutting speed) between the two laser sources, since the knowledge shown in the case of the fiber laser source is the result of a best practice and long experience, often commanded not by performance needs but by different requirements.

Table 3. Main characteristics of the AFL IPG YLS used as comparison in thee experimentation.

Characteristics	AFL IPG YLS 2000W
Maximum output power [W]	2000
Fiber Diameter [µm]	50 - 100
BPP at the fiber exit [mm*mrad]	1,7 - 3,2
Wavelength [nm]	1070 ± 3

2.2. Materials

Structural steel sheets S235 JR (ISO EN 10027), in the thickness range between 1 to 15 mm, were used as work pieces for investigating the laser oxidation cutting process. Instead, the laser fusion cutting process was investigated on AISI 304 (ASTM A 240) stainless steel and on Al 5754 aluminum alloy sheets in the thickness range between 1 to 6 mm. Moreover cutting tests were performed on high reflective C464 (ASTM B21) brass and 110 (ASTM B152) copper alloy sheets using high pressure flow of nitrogen and high pressure flow of oxygen respectively.

2.3. Process feasibility range and optical setups

The aim of the cutting experimentation was to determine the cutting speed limit that ensures a quality of the cut edge comparable with the industrial state of the art of the laser cutting with an AFL source. Main criteria for the qualitative analysis were the smooth homogeneous appearance of the surface and the absence of burr and dross. Oxidation and fusion laser cutting were tested in accordance with the material and gas used. Different optical setups and consequently different process parameters ranges were chosen according to the material and cutting strategy (oxidation or fusion cutting) used.

2.3.1. Laser oxidation cutting

Thanks to the well know reaction of the iron with oxygen the S235 JR structural steel was selected to be laser cut in oxidation modality. The laser power and assist gas pressure were varied to obtain the best cutting condition according to the range listed in Table 4. On the other hand the focal position and the stand-off distance between the workpiece surface and the nozzle were kept constant. In particular the focal position was kept above the surface.

Table 4. Feasibility range of the process parameters in the case of the laser oxidation cutting with the DDL source.

Oxidation Cutting	DDL TeraBlade
Material	S235 JR
Thickness Range [mm]	1÷15
Cutting Speed [m/min]	0÷12
Power [W]	1000÷2000
Assist gas pressure [bar] and type	0,5÷7 O_2

An optical setup able to ensure a magnification factor M equal to 2 suitable for all the S235 JR thicknesses was used. The comparison with the AFL was based on a fiber laser with a 100 µm feeding fiber diameter and the same optical setup of the DDL (see Table 5), to the point that the power densities are equal.

Table 5. Optical setup used for the oxidation cutting experiments in the case of DDL and AFL sources.

Oxidation Cutting	DDL TeraBlade	AFL IPG YLS
Fiber Diameter [µm]	100	100
BPP [mm*mrad]	3.9	3.2
Collimation length f_{col}[mm]	75	75
Focus length f_{col}[mm]	150	150
Magnification factor	2	2
Spot Diameter [µm]	200	200
Power Density at maximum power [MW/cm^2]	6.4	6.4

Thanks to the contribution of the oxidation indeed the magnification M=2 allowed to test different thickness with enough power density for both sources, diode and fiber.

2.3.2. Laser fusion cutting

With the exception of the S235 JR structural steel, the fusion cutting process was investigated for all the other alloys experimented. The process feasibility was investigated at the maximum power available keeping the focal position on the surface or below (but within the thickness of the sheet) and varying the assist gas pressure (see Table 6). The stand-off distance was kept constant. Although the copper 110 sheets were cut in an oxygen atmosphere, the cut belongs to fusion cutting because the oxidation reaction does not provide a significant amount of energy [13,14].

Table 6. Feasibility range of the process parameters in the case of the laser fusion cutting with the DDL.

Fusion Cutting	DDL TeraBlade			
Material	AISI 304	Al 5754	Brass C464	Copper 110
Thickness Range [mm]	1÷6	1÷6	1÷4	1÷3
Cutting Speed [m/min]	0÷35	0÷45	0÷20	0÷16
Power [W]	2000	2000	2000	2000

Assist gas pressure[bar] and type	10÷20 N_2	5÷20 N_2	5÷15 N_2	5÷15 O_2

Here an optical configuration with a smaller magnification factor, M equal to 1.25, was preferred in all the experiments in order to have a higher power density at the beam focus position (see Table 7). In fact the power density in case of fusion cutting plays a relevant role and strongly affects the cutting performances. This is particularly true in the case of thin sheets and highly reflective alloys [13,14].

A comparison with the industrial best practice of BLMGroup with the AFL source was carried out. In this case the standard configuration for the fiber laser is different since traditionally consists of a smaller delivery fiber (50 µm) and larger magnification factor (M=2). As a result the power density resulting from the configuration with the DDL source was 36% less (see Table 7).

Table 7. Optical setup used for the fusion cutting experiments in the case of DDL and AFL sources.

Fusion Cutting	DDL TeraBlade^{TM}	AFL IPG YLS
Fiber Diameter [µm]	100	50
BPP [mm*mrad]	3.9	1.7
Collimation length f_{col} [mm]	100	100
Focus length f_{col} [mm]	125	200
Magnification factor M	1.25	2
Spot Diameter [µm]	125	100
Power Density at maximum power [MW/cm^2]	16.3	25.5

2.4. Measurement equipment and procedure

At first, a characterization of the TeraDiode DDL source was performed in order to investigate the most important characteristics of the laser beam. The beam propagation caustic was measured with the power in the bucket technique by a Primes Focus MonitorFM120 system. A specific optical setup (f_{col} = 100 mm - f_{foc} = 250 mm M = 2.5) was selected to prevent damages of the instruments due to excessive power density. On the other hand the optical power was measured at the exit of the cutting head with the power meter Primes Power MonitorCPM C-9. Finally, the wall plug efficiency (WPE) of the DDL source was evaluated by means of a current clamp FLUKE 381 over all the operative range of the laser source.

Then the performance of the DDL sources were individuated by determining the limit cutting speed for each materials and conditions (as previous stated) by cutting linear (200 mm length) and prismatic samples (edge of 50 mm length).

Eventually the quality of the laser cuts was evaluated by the analysis of the edge roughness. The roughness was measured with a Mahr PGK – Mahr PCMESS 7024357 Perthometer at two different positions for each cut edge: 1/3 and 2/3 of the thickness respectively. Exceptions were the lower thicknesses (1 mm and 2 mm), measured just at ½ thickness. For each position and cutting condition, the measurements were taken on the four different sides of the prismatic samples. The values were then compared with the roughness classes defined in accordance to the standard ISO 9013:2002.

3. Results analysis

3.1. Laser source characterization

Firstly, the quality and the efficiency of the new DDL source were evaluated. As Figure 2 shows, the WPE increases when the injected current and consequent optical power increase. The TeraBlade^{TM} DDL source is of high WPE efficiency as values better than 30% are obtained for power above 550W while at the maximum power (2000 W) the WPE is 37%. As expected the TeraBlade DDL source efficiency is tuned to be the highest at the highest laser power. Moreover a strong linearity is observed between the injected diode current (in the range 10-90%) and the resulting optical power.

The quality of the TeraBlade DDL source is extraordinary high, to the point that no other commercial industrial laser sources are present with so low BBP in all the operative high power range (1000-2000 W). At the highest power the BPP measured is 3.92 mm*mrad (Figure 3) while in the range 1000-2000 W is always less than 4.0 mm*mrad.

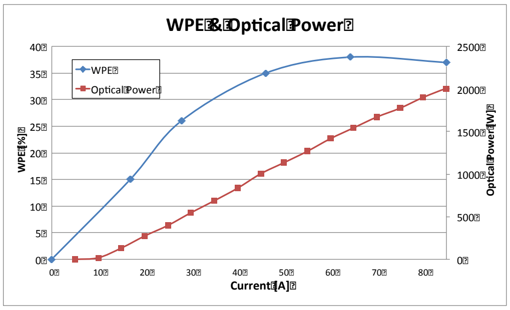


Fig. 2. Wall Plug Efficiency and Optical Power of the TeraBlade DDL source as a function of the diode current.

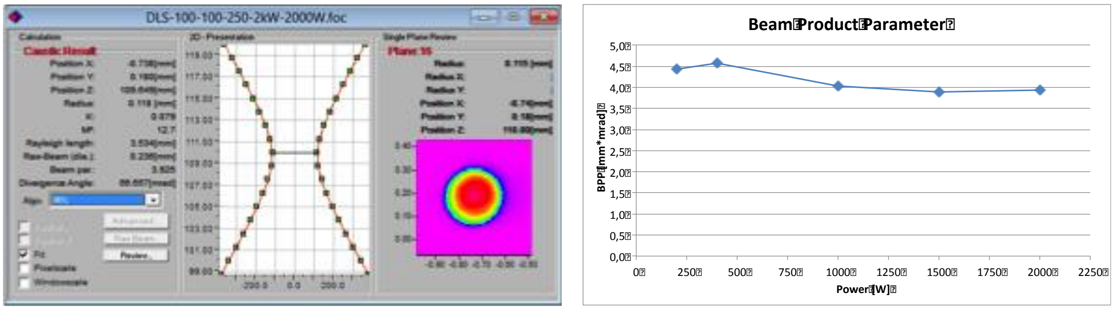


Fig. 3. Beam propagation caustic of the TeraBlade DDL source at 2000W (left) and BBP as a function of the power (right)

The DDL source is tuned to work at medium and high power as a cutting tool since the fiber diameter and beam quality are comparable with the other solid state laser sources commonly used in the cutting process.

3.2. Structural steel S235 JR

The S235 JR, representative of the structural steel category, is normally cut using low pressure oxygen as assist gas. Figure 4 compares the DDL and AFL source productivities. The DDL source allows cutting speeds aligned with the best performance obtainable in the feasibility range that BLM Group usually adopts for the AFL systems. This is particularly true in the case of the highest thickness. As known in the standard practice, regarding the oxygen gas pressure it should be mentioned that for the lower thicknesses a cutting modality with a relative high pressure was used to achieve better performances, while increasing the thickness a low pressure flow combined with higher nozzle diameter was preferable. Moreover it should be noted that in Figure 4 the cut-ability of the DDL source exceeds the 12 mm. 15 mm thickness is cut with good quality probably due to the higher BBP of the DDL source confirming that beam shape-ability is of paramount importance when a large range of thicknesses must be cut.

The surface of the S235 JR steel is smooth and shiny along all the edge up to 6 mm (see Figure 5 on the right), as confirmed by the roughness measurement that is very low and homogenous for all the thicknesses (see Figure 5 on the left). Thicker sections show the typical striations in the upper part as well as a more homogeneous and smooth surfaces at lower parts without blowouts. The surface appearance is generally very good and almost comparable with the ones at the state of art of the industrial practice.

Thickness [mm]	Pressure O_2 [bar]
1	5,5
2	5,5
3	1
4	1
5	1
6	1
8	1
10	1
12	1
15	0,8

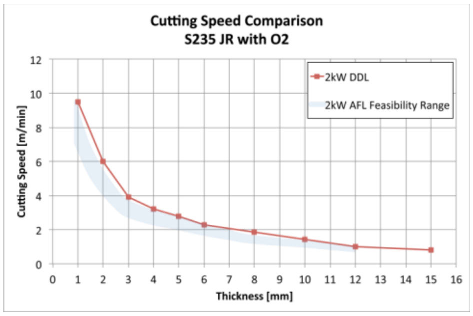
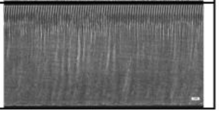


Fig. 4. Cutting speed and pressure as a function of thickness in the case of S235 JR structural steel

Thickness [mm]	Surface Edge
2	
4	
6	
10	
15	

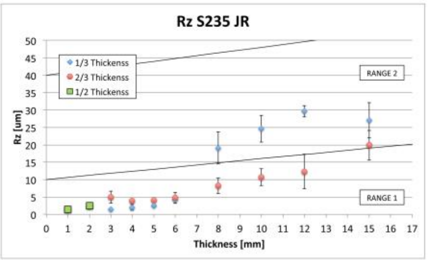


Fig. 5. Surface edge (on the left) and Rz roughness measurement (on the right) for S235 JR steel with the DDL source

3.3. Stainless steel AISI 304

As known stainless steel AISI 304 is preferably cut by nitrogen inert gas since the chromium readily forms oxides and limits the exothermic reaction [13,14]. Therefore high pressure nitrogen assist gas was used (see Figure 6). Since the contribution of the oxidation reaction is absent, the laser cutting feed rate of the AISI 304 steel will depend on power density. In our tests due to the difference between the delivery fiber and choice of available optics (see Table 7) the power density of TeraBlade DDL source is 36% lower at the work piece compared to the AFL source. Despite this significant difference the DDL source performances are only slightly lower in cutting of thinner (1mm) than the ones obtainable in the feasibility range of the AFL source. On the other hand at higher thicknesses the cutting speeds are comparable indicating that in this case a larger beam diameter and a higher BPP may in fact help to improve the performances.

The edge quality (see Figure 7 on the left) is the typical one resulting from inert gas laser cutting characterised by a rough and striated surface, that is also confirmed by the roughness measurement (see Figure 7 on the right). As known in the case of stainless steels laser cutting by laser sources with almost 1 micron wavelength, due to the high surface tension and viscosity of the molten material, the edges are quite coarse. On the other hand no dross is observed on the bottom. This is particularly true for the lower part of the surfaces at higher thicknesses.Thus roughness values increase with the thickness as exptected.

Thickness [mm]	Pressure N_2 [bar]
1	18
2	18
3	16
4	16
5	17
6	18

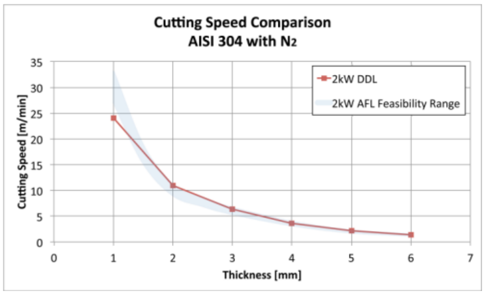


Fig. 6. Cutting speed and pressure as a function of thickness in the case of AISI 304 stainless steel

Thickness [mm]	Surface Edge
2	
4	
6	

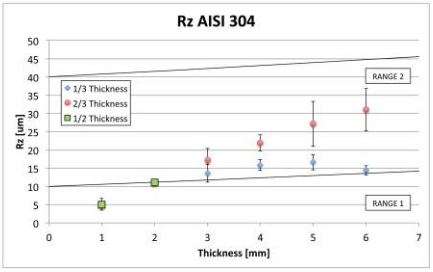


Fig. 7. Surface edge (on the left) and Rz roughness measurement (on the right) for AISI 304 stainless steel with the DDL source

3.4. Aluminum-magnesium Al 5754

Also in the case of laser cutting of Al 5754 sheet the lower power density obtainable due to the difference in delivery fiber with the DDL source explains the lower cutting speed at 1 mm thickness (see Figure 8). Again at higher thicknesses the performances of the two DDL and AFL sources are comparable despite 36% lower power density due to a larger spot size.

Thickness [mm]	Pressure N_2 [bar]
1	13
2	12
3	16
4	18
5	16
6	15

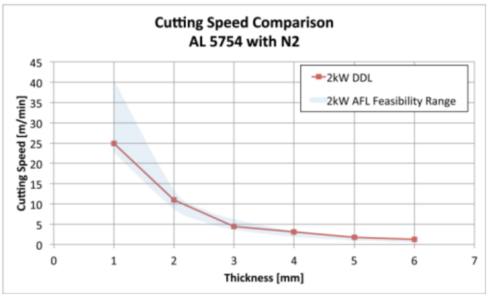
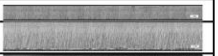


Fig. 8. Cutting speed and pressure as a function of thickness in the case of Al 5754 aluminium alloy

Thickness [mm]	Surface Edge
2	
4	
6	

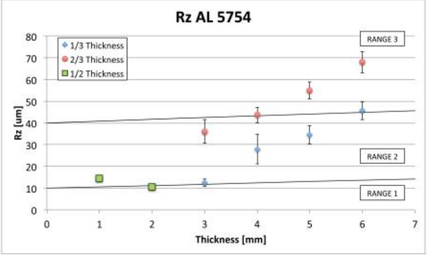


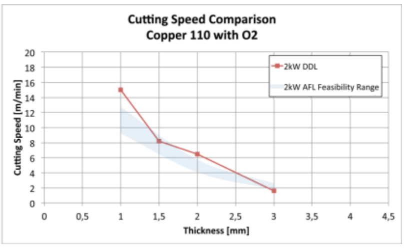
Fig. 9. Surface edge (on the left) and Rz roughness measurement (on the right) for Al 5754 aluminium alloy with the DDL source

The quality of the cutting edge in the case of Al5754 alloy is comparable with the one at the state of art of the industrial practice (see Figure 9 on the left); being characterized by a quite rough surface and higher roughness values that belong almost to the second and third ranges of the standard as shown in Figure 9 on the right (compared to the one shown in previous Figures 5 and 6). Moreover, a light and easy to be removed dross remains attached to the edge of thicknesses higher than 3 mm.

3.5. Copper 110 and Brass C464

Oxygen-assisted cutting at high pressure of the Cu 110 copper based alloys was advantageous since the oxide at the cutting edges improves laser beam absorption, although the oxidation reaction does not significantly contribute to the energy delivery [14]. That's why despite oxygen gas was used, the gas pressures were high, as in the inert gas cutting. Brass C464 was cut using the standard methodology for fusion cutting using nitrogen at high pressure. Despite the lower power density the results of the DDL source were even superior or equivalent to the ones obtainable with the AFL source in the case of Cu 110 and C464 alloys respectively (see Figures 10). Very promising performances at lower thickness in the case of Copper 110 were obtained that require further investigation.

Thickness [mm]	Pressure O_2 [bar]
1	10
1,5	13
2	13
3	13



Thickness [mm]	Pressure N_2 [bar]
1	10
1,5	13
2	13
3	13
4	17

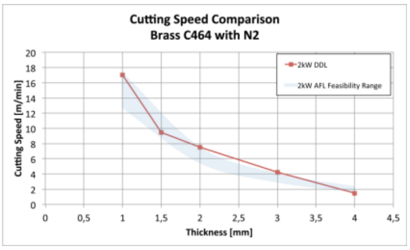


Fig. 10. Cutting speed and pressure as a function of thickness in the case of Copper 110 (left) and Brass C464 (right)

The copper and brass high-reflective materials were cut without any problems regarding the back-reflection. The surface edge of the brass shows the common striations of fusion cutting without changes in the shiny finishing of the material. On the other hand, the copper edges present the typical lightly dark surface as darker as the thickness increases.

Thickness [mm]	Surface Edge
1,5	
2	
3	

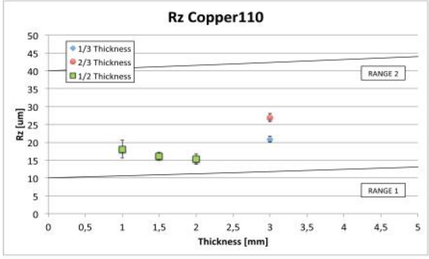


Fig. 11. Surface edge (on the left) and Rz roughness measurement (on the right) for 110 copper alloy with the DDL source

Thickness [mm]	Surface Edge
1,5	
2	
3	

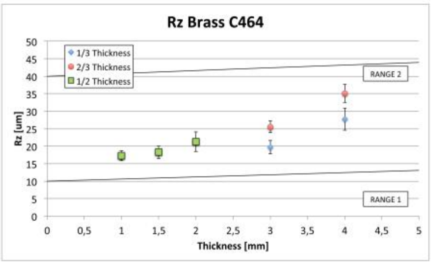


Fig. 12. Surface edge (on the left) and Rz roughness measurement (on the right) for C464 brass alloy with the DDL source

4. Conclusions

The performance and efficiency of a new industrial direct diode laser source with an extremely low BPP are investigated when iron-based and high reflective metallic alloys are laser cut. The results confirm the industrial feasibility and robustness of the direct diode laser source as tool for laser processes. Moreover they put such a kind of source among the ones transmitted by a fiber (i.e. active fiber and disk sources) that can be used as cutting tool. Eventually the comparable quality and performances of the direct diode laser source with the active fiber and disk sources open to further investigations. The peculiarity of the direct diode laser source that can be tailored in two directions: wavelengths and power density distribution, could be two distinctive key points in the future development of actively adaptable new diode laser sources.

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