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Laser Cutting of MMC Castings – Preliminary Selection of Process Parameters

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Abstract

Composite materials gain more and more applications thanks to their specific properties and possibilities of shaping of products made out of them. One of the product forming technologies is cutting. Although most metal matrix composites are ready for use after volume shaping e.g. by casting, it is worth to define also possibilities of processing these materials also by this technology. This paper presents possibilities of cutting metal matrix composites and compares existing methods and their application range. The laser cutting of metal matrix composites reinforced with hard ceramic fiber was of particular interest in this work. Preliminary process parameters were determined and quality of obtained cut edges was compared with basic material of the aluminum matrix. This comparison proved that presence of reinforcement negatively affects the quality of the cut surface. However, the laser cutting process is efficient and it allows elastic shaping of metal matrix composites reinforced with hard ceramics.

Keywords: Metal matrix composite castings, Laser cutting

1. Introduction

Main purpose of development of construction materials is improvement of their properties. Thanks to their unique qualities, composites are becoming a solution to increasing need for materials with better operational and constructional indexes [1,2]. High strength of these materials comes in a pair with a low density, which allows to obtain construction elements of small weight.

Such properties give lots of opportunities and that is why composites are becoming a main build material e.g. for sport equipment [3]. They have also found a wide application range in space technology, aeronautics, medicine, military equipment production and in automotive industry [4].

One of the most important qualities of these materials is almost unlimited possibility of shaping of manufactured products. However, there are some problems in this field, especially regarding possibility of cutting of materials reinforced with hard ceramics. This paper deals with these problems, in particular with issues related to laser cutting of metal matrix composites formed by casting, reinforced with short unordered ceramic aluminosilicate fiber.

2. Cutting of composite materials

Cutting is an operation aimed at separation of the material into at least two distinct parts. During an ideal cutting process, separation of atomic bonds occurs along a defined line, without affecting the physical state of the material [5]. Various cutting methods can be classified by values of the following features:

a) amount of energy used during the process,
b) cutting velocity,
c) amount of material losses,
d) amount of heat absorbed by cut material,
e) surface quality of edges after cutting.

Selection of an appropriate cutting method is dependent on type of the cut material, its thickness, required quality and accuracy of cutting line positioning, velocity, price of the cutting device and costs of the process itself. Cutting of sheet metal with variable, often very large thickness, is a considerable challenge for most production companies. Mechanical cutting or possibly drawing is good for thin sheets of metal and is mostly used for straight cutting lines. For thicker sheets, there are various technologies of thermal and water cutting available nowadays.

Possibilities of composite materials cutting are variable. A question needs to be asked every time: which method will be the most beneficial, meaning cheap, quick and ensuring the best quality of the cut edge. Applied methods have different parameters, possibilities and limitations, which may rule them out of a specific process realization. The cutting can be:

- mechanical,
- by plastic forming,
- with water jet,
- thermal.

One of the simplest methods of mechanical cutting is cutting with teethed saws (circular or band-saws) or with abrasive saws [5,6]. These methods are characterized by a large losses of material, dependent on thickness of the blade or band. They have some applications though, especially when high material smoothness after cutting is not required, as the edge after cutting is usually severely torn and needs further treatment. This group of cutting methods has its advantages: the operator does not need to have high qualifications and for traditional materials, e.g. wood, carbon steel, aluminum or acid-resistant steel, there is no need for high expenses on the device or its operation. Cutting accuracy is highly dependent on manual skills of the operator and on efficiency and degree of wear of the saw. Cutting of small parts is a problem, as they cannot be properly fixed. During cutting, the elements may easily pull themselves out of the fixtures. Cutting along an arc or a curved line is also a problem. The saw allows to cut any material with lower hardness than the blade or the band, that is why there is a possibility of cutting composites reinforced with hard ceramics. Diamond blades are used for cutting in such case, but this process is expensive because of rapid wear and tear of the blades and low efficiency of the process.

Cutting methods belonging to plastic forming technologies consist in separating one portion of material from another without any material loss in form of chips, combustion or fusion products [5,7]. For the cutting process, a local state of stress is created, with a magnitude causing the material to fracture. Plastic forming cutting methods are based mostly on the drawing operation and they can be divided into: cutting out, shearing, holing, trimming and incising. These operations are performed using cutting edges of a tool on presses or guillotine shears, rotary or alligator. Cutting on presses with blanking tools is also used, but it requires considerable expenditures for die and punches manufacturing, that is why it is mostly used in mass production. It is possible only to cut the parts out of the metal in form of a sheet or band. Therefore these methods are not suitable for cutting composites. Not only the material thickness is a problem here, but primarily its structure. Composites are composed at least of two materials, in which the fracture occurs as a result of applying forces of different values. It may result with pulling out the reinforcement out of the metal matrix.

Water jet cutting process is performed in low temperature and it consists in propulsion of water or mixture of water and an abrasive material under a very high pressure (above 400 MPa) through a hole of a small diameter [5,8]. In consequence, a very high energy concentration in a small area is achieved. Big advantage of this method is that is does not leave torn edges and it does not require using any chemical agents. As opposed to laser or plasma treatment, water jet cutting does not supply the material with additional heat, so there are no structural changes, local hardening, internal stresses or micro-fractures. Water jet cutting is an universal method and it is used for cutting of practically all materials – steel alloys, non-ferrous metals – aluminum, magnesium and non-metal materials – glass, rubber, composites, stone and even frozen meat. Cutting thickness range is also very broad, it is possible to cut any part of thickness up to 200 mm. It should be taken into account that increase in thickness causes a significant increase in cutting time. Accuracy of the water jet cutting is up to 0,1 mm. Despite of so many advantages, this method is not as frequently used as, for instance, the laser cutting. It is a consequence of very high costs of the device.

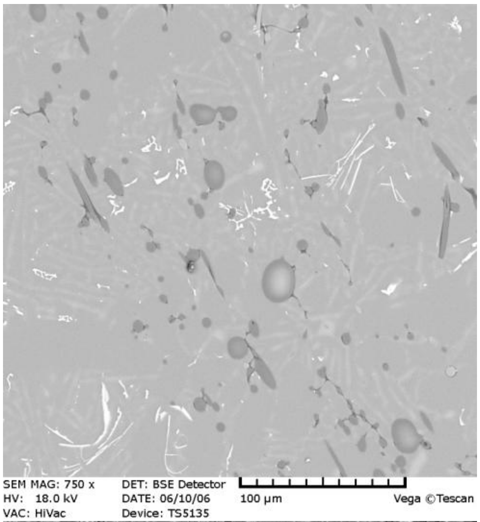
Thermal cutting consists in local oxidation, burning out or fusing out a gap in high temperature, appropriate for the cut material. Methods can be divided concerning the predominant portion of burning, fusion or sublimation processes in the main process. In practice, used methods usually join several processes [5,8,9]. Metal is usually a material subjected to cutting. Basic technologies of thermal cutting are: oxy-fuel cutting, plasma and laser cutting. Selection of a proper method of thermal cutting is usually dependent on fusion temperature of the cut material. Therefore, for materials of lower fusion temperature, like low-carbon steel, the oxy-fuel cutting can be used, while materials of higher fusion temperature, like alloy steels or ceramics, require application of plasma or laser. Both plasma and laser cutting, besides possibility of shaping any material, have a number of advantages, such as: high cutting precision, narrow gap – low volume of material loss, considerable velocity and elasticity of the process. Out of these two, the laser cutting is more advantageous, as it produces lesser amount of gases and fumes and the device generates less noise. That is why it was decided to focus on possibility of cutting of metal matrix composites reinforced with hard ceramic parts using specifically the laser cutting method.

2. Subject of the research

Criteria of evaluation of the laser cutting quality are described in the PN-EN ISO 9013 standard and they are considered as preliminary conditions of assessment of quality of the laser cutting process quality. Quality of cut edges and surfaces of various materials is determined on the basis of a geometrical measurement of the shape of the edge and the surface, mechanical and metallurgic tests [10]. However, mentioned standard does not define values of deviations for cutting aluminum, which is a matrix material for the ceramic reinforcement. Despite of this, in the presented paper an attempt was made at determination of the cut surface and edge quality on the basis of its comparison with cut surface of the matrix material and determination of the heat-affected zone.

Analysis of possibility of laser cutting was conducted on composite samples (fig. 1a), with reinforcement in form of short aluminosilicate fibers (fig. 1b, table 1) and AlSi12(b) aluminum alloy as a matrix. The samples were casted using an industrial, high-pressure machine.

a)



b)

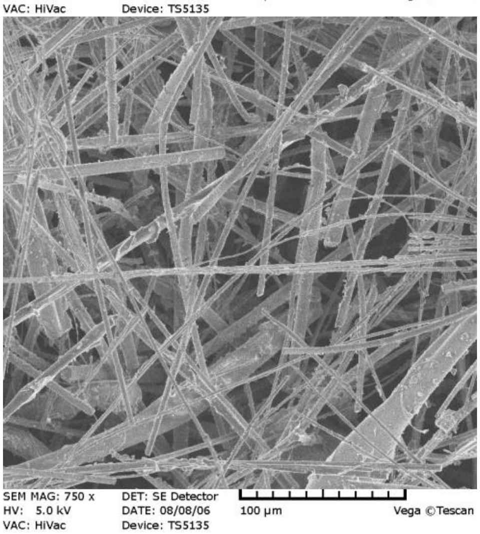


Fig. 1. Structure of the: a) composite casting of matrix out of the AlSi12(b) alloy, reinforced with b) short unordered aluminosilicate fiber [11]

Table 1.
Properties of reinforcing preforms made out of pressed, short unordered fibers (producer data) [12]

Chemical constitution	Al_2O_3 45-48% SiO_2 51-54%
Mass density	2770 kg/m^3
Apparent density	370 kg/m^3
Porosity	86,66%
Fusion temperature	1400°C

As a material for comparison, samples made out of pure (not reinforced) aluminum alloy AlSi12(b) used for composite saturation were used.

Cutting process was conducted using laser cutting machine of company Trumpf, model Trumatic L6050 of 6000W of maximum power. For cutting of samples with thickness 5 and 10 mm, automatic programs for aluminum (Alumi) and steel (INOX) cutting were used (table 2), along with corrected programs (Sibral). Sets of parameters of corrected programs, for which the most significant changes were achieved, are presented in the tables 3 and 4.

Table 2.
Parameters of cutting machine for selected automatic programs – Alumi and INOX

Program / **Parameters**	**Alumi 5.0**	**INOX 5.0**	**Alumi 10.0**	**INOX 10.0**
Sample thickness [mm]	5	5	10	10
Machine head [inch]	7,5	7,5	10	10
Type of cutting gas	Azot	Azot	Azot	Azot
Gas pressure [bar]	18	18	14,5	20
Autolas setting [mm]*	-5	-5	-25	-18
Nozzle diameter [mm]	1,7	2,0	2,0	2,7
Machine velocity [%]	80	80	80	80
Velocity [m/min]	3	3	0,90	0,90

* point of focus of the laser beam ray, reference value measured from the material surface.

Table 3.
Parameters of cutting machine for selected corrected program Sibral; composite samples with 5 mm thickness

Program / **Parameters**	**Sibral 5.0 O2**	**Sibral 5.0.1**	**Sibral 5.0.2**	**Sibral 5.0.3**	**Sibral 5.0.4**
Sample thickness [mm]	5	5	5	5	5
Machine head [inch]	7,5	7,5	7,5	7,5	7,5
Type of cutting gas	Tlen	Azot	Azot	Azot	Azot
Gas pressure [bar]	0,6	10	10	18	10
Autolas setting [mm]*	-2	10	10	-10	-20
Nozzle diameter [mm]	2,0	1,4	1,4	1,7	2,0
Machine velocity [%]	60	120	50	80	50
Velocity [m/min]	2,85	3,3	2,8	3	2,8

* point of focus of the laser beam ray, reference value measured from the material surface.

Table 4.
Parameters of cutting machine for selected corrected program Sibral; composite samples 10 mm thickness

Program / **Parameters**	**Sibral 10.1**	**Sibral 10.2**
Sample thickness [mm]	10	10
Machine head [inch]	10	10
Type of cutting gas	Azot	Azot
Gas pressure [bar]	10	20
Autolas setting [mm]*	-25	-18
Nozzle diameter [mm]	2,0	2,0
Machine velocity [%]	80	80
Velocity [m/min]	0,90	0,90

* point of focus of the laser beam ray, reference value measured from the material surface.

In next and final step, a surface roughness measurement (parameter R_a) was conducted on cut surfaces, in half of the sample height. Hommel Tester T500 profilometer was used for this measurement, with length of the measuring line equal to 4,8 mm. Results are presented as an average of at least 5 measurements.

3. Research results

Figure 2 presents a photography of cut surface of samples made out of pure AlSi12(b) alloy. Tables 5 and 6 present cut surfaces of composite samples obtained using programs dedicated for aluminum and steel cutting. Tables 7 and 8 present samples obtained using corrected programs, for certain values of the process parameters.

Because of large amount of the after-cut waste present on the bottom surface, the samples were turned by 180 degrees. On cut surface of most of the studied samples, a zone of laser fusing into sample can be observed. This zone has significantly worse quality.

Ra=5,92
σ=0,47

a)

Ra=4,98
σ=0,58

b)

Fig. 2. View of the AlSi12(b) samples of 5 mm (a) and 10 mm (b) thickness after laser cutting with automatic programs, Alumi 5.0 (a) and Alumi 10.0 (b)

Table 5
Composite samples with 5 mm thickness after laser cutting performed using automatic programs

Program	View of the composite after cutting	Ra [μm]
Alumi 5.0		Ra=17,15 σ=1,65
INOX 5.0		Ra=7,02 σ=1,09

Surface roughness of both the AlSi12(b) samples and the composite samples exceeds is significant – R_a > 4,98, it is also inhomogeneous – σ=2,72. Comparison of studied samples has proven, that presence of ceramic reinforcement is a significant factor towards decrease of cut surface quality of investigated materials. In all composite samples, in the cut edge, much larger amounts of combustion products were accumulated than in the pure alloy. Still, they were brittle and easy to remove.

Table 6
Composite samples with 10 mm thickness after laser cutting performed using automatic programs

Program	View of the composite after cutting	Ra [μm]
Alumi 10.0		Ra=9,76 σ=0,35
INOX 10.0		Ra=9,43 σ=0,8

Table 7
Composite samples with 5 mm thickness after laser cutting performed using corrected programs

Program	View of the composite after cutting	Ra [μm]
Sibral 5.0.1		no fusion
Sibral 5.0 O2		out of range
Sibral 5.0.1		Ra=9,96 σ=0,71
Sibral 5.0.3		Ra=7,10 σ=0,47
Sibral 5.0.4		Ra=6,31 σ=2,72

Table 8
Composite samples with 10 mm thickness after laser cutting performed using corrected programs

Program	View of the composite after cutting	Ra [μm]
Sibral 10.0.1		Ra=9,01 σ=1,38
Sibral 10.0.2		Ra=8,04 σ=1,86

Correction of automatic programs conducted as a part of research has also shown that:

- cutting with high velocity is not possible (Sibral 5.0.1 – velocity 120%, 3,3 m/min; Sibral 5.0.2 – velocity 50%, 2,8 m/min),
- change of gas type from nitrogen to oxygen (INOX 5.0 – nitrogen; Sibral 5.0 O2 – oxygen) affects the cut edge quality in a negative way; increase of the gas pressure may also worsen the quality (Sibral 10.1 – 10 bar pressure, Sibral 10.2 – 20 bar pressure),
- smaller Autolas setting (Alumi 5.0 – Autolas 5,5; Sibral 5.0.3 – Autolas 10) and greater diameter of the nozzle (Inox 10 – 2,0 mm nozzle, Sibral 10.2 – 2,7 nozzle) may positively affect the cut edge quality.

In order to determine the heat-affected zone (SWC), polished sections were prepared, with section plane located perpendicularly to the cut edge. Exemplary structures are shown in the fig. 3.

On the basis of conducted microscopic analysis, the heat-affected zone size was determined. These observations bring a conclusion, that depending on the program type and size of the cut sample, a heat zone of various thickness 0-500μm (fig. 3A i 3B) and varied arrangement is formed in the cut area. Apart from this zone, internal structure of the sample remains unchanged (fig. 3C i 3D). In case of samples with 10 mm thickness, it was observed that lower focusing of the beam with higher gas pressure in the Alumi 10.0 program causes the heat-affected zone to be the broadest in the upper part of the sample, while in the lower part of the sample it remains almost invisible. Higher Autolas setting, even with the higher gas pressure (INOX 10.0 program) makes the heat zone the broadest in the lower part of the sample.

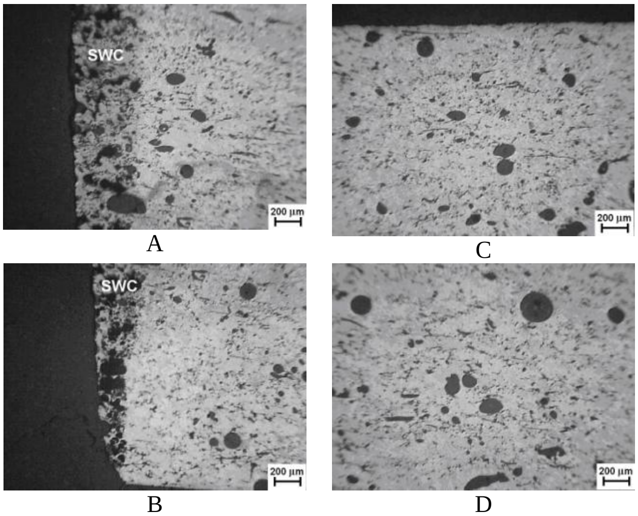


Fig. 3. Internal structure of composite samples with 5 mm thickness, cut from above using the laser and INOX 5.0 program; cut edge: A – upper and B – lower part of the sample; interior of the sample, depth 4 mm from the cut edge: C – upper, D – lower part of the sample

4. Conclusions

1. Thanks to performed preliminary tests, it was proven that it is possible to effectively cut the metal matrix composites with ceramic reinforcement using the laser beam. Analysis of the cut surfaces and edges allows to conclude that reinforcing an aluminum alloy with ceramic fibers affects the cut surface quality in an negative way. Nevertheless, obtaining a satisfying quality is possible (program Sibral 5.0.4, Ra=6,31).
2. Based on the conducted tests of cutting the composite of aluminum alloy matrix reinforced with ceramic aluminosilicate fiber, it was stated that the better quality of the cut edge can be obtained using programs created for steel cutting (INOX), not aluminum cutting (Alumi).
3. During tests of cutting of studied materials using corrected programs, significance of analyzed parameters was determined – the most important parameters were found. The quality of the cut surface and edge is influenced most significantly by a proper selection of the machine parameters: nozzle diameter [mm], autolas setting [mm] and gas pressure [bar]. The research proved that even a minor change of value of one of these parameters can result in considerable changes in quality of the cut surface.

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