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ORIGINAL ARTICLE

Effect of LBM and large-area EBM finishing on micro-injection moulding surfaces

António Selada · Ana Manaia · Maria Teresa Vieira · António Sérgio Pouzada

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Abstract Micro-injection moulding is an efficient process for large series production of thermoplastic polymer micro-parts. The moulding surface quality in the moulds is important and determines the manufacturing specifications for a given micro-engineering component. In this study, melting and vaporisation removal technologies were analysed: laser beam machining (LBM) as the material removal technique and electron beam machining (EBM) as the finishing process. Stainless steel DIN X42Cr13 was used for machining 10×10 mm^2 flat surfaces. LBM parameters, namely intensity, frequency, cutting depth, scanning speed and hatching, and EBM conditions, as energy density, number of irradiation and frequency, were varied. The surface topography and integrity and the micro-structure were characterised by optical and electronic microscopy, roughness profilometry, X-ray spectroscopy and micro- and ultrahardness tests. It was shown that the combination of LBM and large-area EBM is an interesting alternative to polishing by hand lapping of moulding surfaces for micro-moulding, improving surface roughness and surface integrity without cracks and smaller HAZ. The morphology analysis demonstrated that EBM finishing improves corrosion and oxidation resistance compared with conventional heat-treated surfaces.

Keywords Laser machining · Electron beam machining · Roughness · Surface integrity

A. Selada
ESTG, Polytechnic Institute of Leiria,
Leiria, Portugal

A. Manaia · M. T. Vieira
CEMUC—Grupo de Materiais,
Departamento de Engenharia Mecânica,
Faculdade de Ciências e Tecnologia, Universidade de Coimbra,
Coimbra, Portugal

A. S. Pouzada (✉)
Institute for Polymers and Composites/I3N, University of Minho,
Guimarães, Portugal
e-mail: asp@dep.uminho.pt

1 Introduction

The successful development of new micro-devices depends on manufacturing systems that can economically produce micro-parts in large quantities with high reproducibility. In this context, micro-injection moulding of polymeric materials is one of the key technologies for mass production of micro-components [1]. Due to the steadily increasing demand for complex micro-parts, techniques capable of replicating their features have been growing in importance. However, some of these micro-technologies lack the ability to produce complex 3-dimensional shapes with high-quality surface finishing. These limitations are set by the critical dimensions up to which the parts can be manufactured with good performance.

The quality of moulded micro-parts is important and determines the manufacturing requirements of the process and the combination of materials required to produce the moulding blocks of the injection moulds. Thus, the factors affecting the quality of the micro-parts produced by injection moulding, like the finishing quality of the moulding surfaces, must be considered. In addition, the creation of 3-D micro-details with large aspect ratio, the achievable accuracy, the ability to get a suitable surface pattern and the guarantee of the tool integrity are current challenges in micro-machining. The aspect ratios achievable in replicating micro-features constitute a major manufacturing constraint in applying injection moulding in a range of micro-engineering applications [1]. Frequently many factors interact, and their combination determines the limits of the process [2].

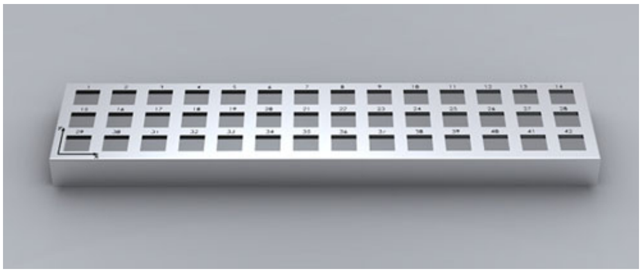

Fig. 1 Testing sample with different laser conditions

Table 1 Laser parameters

Hatching (μm)	Cutting depth (μm)	Frequency (kHz)	Scanning speed (mm/s)
5	2	30	300/400/500
10	2	30/35/40	250/300/400/500
	3		300/400/500
	4		250/300/400/500
15	2	30/35/40	300/400/500
20	2	30	

Laser beam machining (LBM) is used for producing very small features with great accuracy, without side effects like tool wear or a residual stress state in the tool surface [3]. In the state-of-the-art LBM, two laser systems are identified at the forefront of industrial integration: excimer and Nd:YAG lasers. Their applications in micro-machining have reached a high level of production maturity [4]. In recent years, ways of improving the quality of cutting, drilling and micro-machining of different materials (metals, alloys, ceramics and composites) using Nd:YAG lasers have been explored [5]. One major advantage is their capability of processing various materials which are increasingly needed for manufacturing micro-products [6].

When using Nd:YAG lasers, the material removal process depends primarily on the material itself, pulse duration, wavelength and laser fluence (pulse energy/focal spot area). In order to maintain a high degree of accuracy and a small heat-affected zone, the laser fluence for the machining of metals should be limited to 100 kJ m^{-2} (or 10 J cm^{-2}). At this level, the material removal rate (MRR) for stainless steel is around 1 μm per pulse [7].

The laser removal of metals is basically a thermal process involving fast melting and evaporation. The molten material is ejected, some debris are produced and the surface roughness decreases [8]. The material that is not removed from the machined cavity is resolidified in layers on the side walls and at the bottom of the cavity. This zone, known as heat-affected zone (HAZ), has properties that are different from the original material because the thermal energy input produced modification of micro-structure. Some authors consider that it is convenient to remove or minimise the HAZ [9]. The characteristics of the material layer under the surface determine the fatigue strength, the resistance to corrosion and the tool service life. Major causes of problems associated to the HAZ include craters, metallurgical transformation, stress-induced plastic deformation and residual stress [10].

The surface quality is critical in many components and is relatable to the roughness of the moulding surface. Laser milling with long pulses is generally associated with high-surface roughness as observed by Petkov et al. [11]. When LBM started being used, several laser parameters were identified as having influence on the surface quality and on the performance of the micro-machining process, namely the wavelength, spot size, average beam intensity, depth of focus and laser pulse duration [12]. The current state of the art indicates that besides the pulse duration the most important parameters which affect the surface quality are pulse energy, pulse

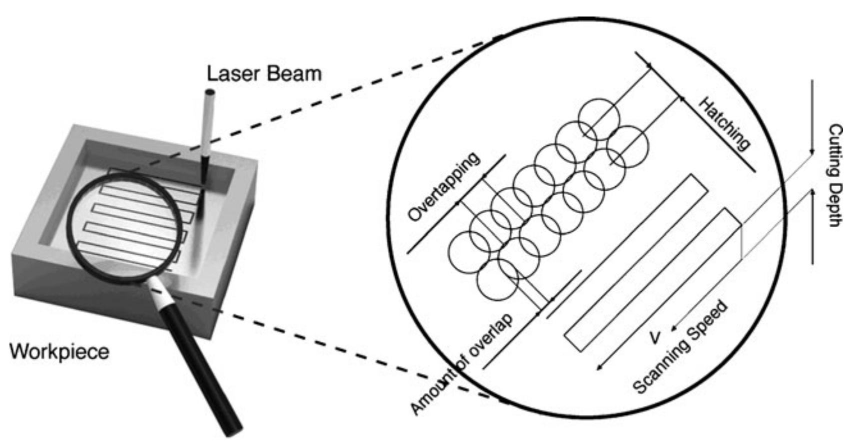

Fig. 2 Processing parameters in laser machining

Table 2 EB irradiation conditions

Parameter	Unit	Range
Energy density, *Ed*	J cm^{-2}	<10
Pulse frequency, *Fp*	Hz	*<0.2*
Number of irradiation shots, *N*		1–50
Pulse duration, *tp*	μs	2–3
Acceleration voltage, *V*	kV	30
Argon pressure	MPa	0.35–0.65
Beam diameter, *Db*	mm	60

and line distance or hatching [13]. Overlapping is reported as a parameter determinant in the roughness and the MRR by Campanelli and co-workers who also observed that frequency and scanning strategy also affect the surface roughness [2]. These many parameters are the reason why it is difficult to exactly determine the surface finish and tolerances that can be obtained with LBM. Regardless of the material, surface roughness usually deteriorates upon increasing laser pulse duration and laser intensity [7, 13]. Other findings indicate that lower laser pulse frequency is more appropriate when the surface quality is an issue [14]. The laser intensity, or peak power divided by the focal spot area, has a crucial effect on the time it takes the beam to melt the material. With I=109 W cm^{-2} on steel, for example, 300 ns are needed to reach the melting point [15].

Normally, the surface of metal moulds is finished by hand lapping after milling, laser or EDM, in order to improve shape accuracy, surface roughness and integrity of the surface, i.e., surface without cracks and reduced HAZ. This process takes time and requires special technical skills. Recently, the technique of large-area electron beam irradiation (EBM) has been proposed as a new polishing method for moulding surfaces [16]. During smoothing by EBM, the material was removed by melting, the evaporation remains on the surface and a resolidified layer is not formed. The roughness of the surface decreases is controlled by the beam energy density and the number of pulses. Furthermore, this finishing technique has the advantage of greatly improving the corrosion resistance of the mould surface [17].

The increasing use of LBM in micro-machining makes it important to study the influence of laser parameters on the surface texture and micro-structure that determines the integrity of moulding blocks. In this study, the influence of main parameters involved in the LBM ablation process, as cutting depth, scanning speeds, hatching, overlapping, frequency and laser intensity are assessed. However, there is a drawback in LBM associated to the effect of the re-melted material remaining at the edges of the machined area. This effect leads to a poor dimensional accuracy of the machined features. The problem is commonly overcome in the cases of the top surface of a microdetail or mould parting line of micro moulds, by grinding, micromilling or microEDM provided additional thickness is allowed to be removed together with the re-melted material. Moreover, the surface finishing using EBM is analysed when using a typical tool steel used in micro-injection moulds.

2 Experimental

2.1 Testing samples

Stainless steel DIN X42Cr13, after quenching and tempering, was used for machining 10×10 mm^2 flat surfaces using various laser conditions (Fig. 1).

2.2 Machining techniques

2.2.1 Laser beam machining

In this study, a DML 40 SI laser ablation equipment (Deckel Maho, Germany) with 100 W Nd:YAG-type pulsed

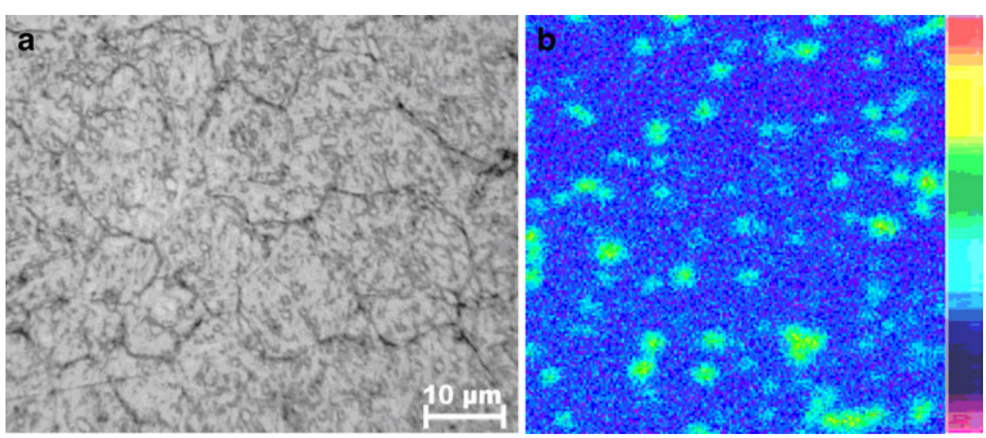

Fig. 3 **a** Micro-graph of quenched and tempered X42Cr13 (WS) and **b** chromium distribution in the matrix and in the chromium carbides

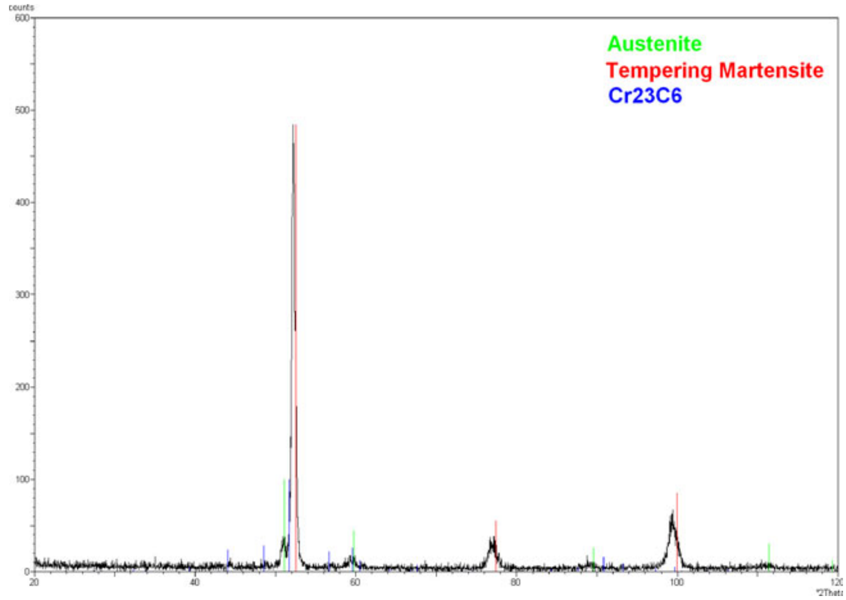

Fig. 4 X-ray diffractogram of X42Cr13 steel after quenching and tempering (*green* austenite; *red* tempering martensite; *blue* $Cr_{23}C_6$)

laser with wavelength of 1064 nm was used. Several parameters can be considered when machining complex geometries. With this specific equipment, in industrial environment, it is possible to change peak power, pulse frequency, scan speed, overlapping, machining strategy, cutting depth and hatching. Some of these parameters are illustrated in Fig. 2.

The ranges of machining parameters chosen in this study were those reportedly in the literature as more influent. Nevertheless, preliminary tests also showed that meaningful results could be obtained when the focus diameter and the pulse duration were kept constant at 30 µm and 10 ns, respectively. A small mode aperture leads to a smaller laser spot (about 30 µm), this being particularly suited for high surface quality of small parts or parts with filigree structure. Conversely, a big aperture mode with focus diameter between 80 and 100 µm is recommended if particularly high cutting rates are required and a high surface quality is not of priority. The frequency depends on the material to be machined. For steel, preliminaries tests with the Deckel Maho equipment suggested a range between 25 and 45 kHz. The feed rate that depends on the frequency should ensure an overlap of two consecutive pulses of 200 to 600 mm/s. The layer thickness depends on the required geometry and machining rate and available power. In general, a layer thickness between 1 and 5 µm produces good results.

The field of variation of the settings was made within the limits shown in Table 1. For each machining condition, the laser power was adjusted to achieve the required depth.

The specimens produced with the various laser parameters referred to in Table 1 will be identified here on using a numeric code (e.g., [10.2.40.300]) where the consecutive numbers correspond respectively to the hatching distance

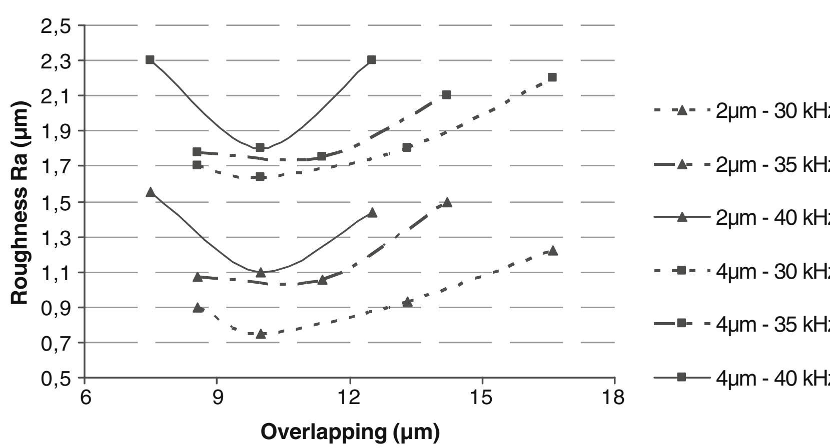

Fig. 5 Effect on the surface roughness of overlapping and laser frequency with hatching of 10 µm

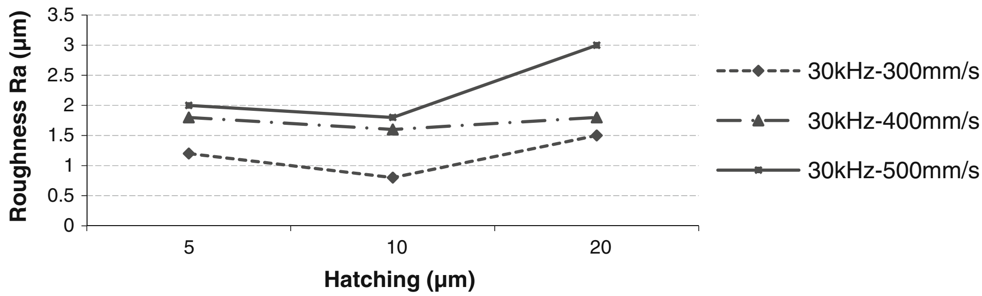

Fig. 6 Hatching: influence on roughness using cutting depth of 2 µm

(micrometres), cutting depth (micrometres), laser frequency (kilohertz) and laser scanning speed (millimetre per second).

2.2.2 Electron beam machining

A PIKA electron beam surface finishing machine (Sodick, Japan) was used in the finishing of the surfaces produced by LBM. In this finishing process for metal moulds by wide-area electron beam irradiation, the procedure used by Uno et al. [17] was followed. As opposed to using EBM in a vacuum, argon gas was used in the chamber instead. An electron beam with a maximum diameter of 60 mm was used for melting the metal surface. The electron beam parameters used are summarised in Table 2.

2.3 Materials

All tests were performed on stainless steel DIN X42Cr13 after quenching and tempering to a hardness of 490±9 (HV0.01). This 13% chromium stainless steel is used in moulds for plastics where high hardness upon heat treatment and good polishing are required. The original surface roughness (ground surface) was of Ra 0.2 µm.

2.4 Characterisation techniques

2.4.1 Physical properties

The characterisation of the textured surfaces was done by tactile roughness profilometry using a Perthometer M1 roughness tester (Mahr, Germany) with resolution of 10 nm. The measurements followed the ISO 4287 standard. The parameter used to evaluate the surface roughness was the arithmetic mean roughness (Ra) as relative heights in micro-topographies are more representative, especially when measuring flat surfaces.

In order to evaluate any micro-structural changes in the material and the extension of the HAZ, hardness measurements were performed using a Shimadzu HMV-2 equipment (Shimadzu, Japan) with a Vickers indenter and load of 0.01 mg (HV 0.01). The tests were conducted on the polished surface of specimens obtained under the various laser conditions.

2.4.2 Microscopy

The metallography routine was performed to analyse the microstructural features on prepared surfaces. The preparation of metallographic specimens involved five major operations: specimens were sectioned using wire EDM, mounted in a cold epoxy resin, ground using SiC grit, polished using a 1-µm diamond suspension and etched with

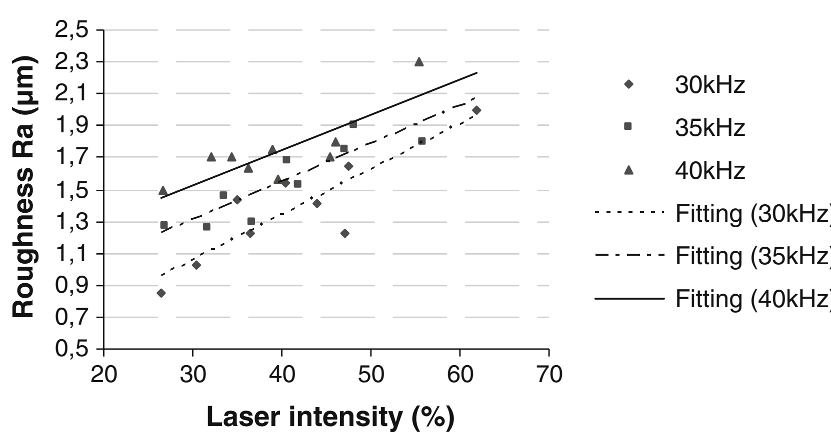

Fig. 7 Influence of laser intensity and frequency on roughness—the scanning speed varies between 300 and 500 mm/s and the cutting depth between 2 and 4 µm

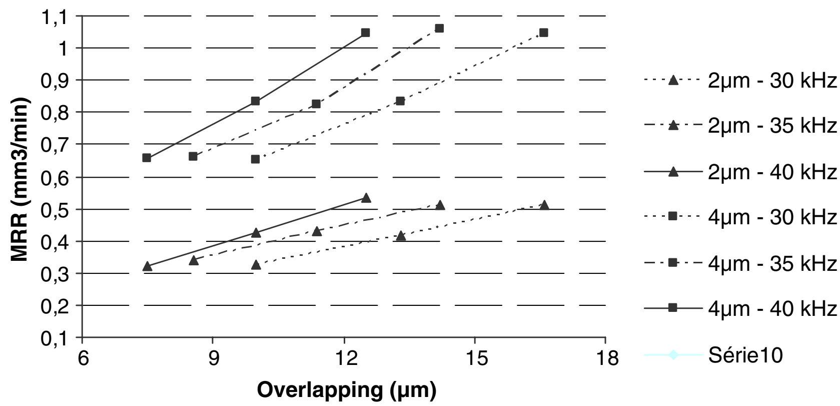

Fig. 8 Overlapping and material removal rate for hatching of 10 µm

2% Nital solution. The microscopic examination was performed using a Nikon Optiphot II (Nikon Instruments, Japan) with a digital camera.

The topography evaluation of the surfaces was done by scanning electron microscopy using JEOL JSM-5310 equipment (JEOL, Japan).

2.4.3 Elemental analysis

X-ray diffraction measurements using Co Kα radiation were carried out in a Philips diffractometer X'Pert with Bragg-Brentano geometry (PANalytical, The Netherlands) for phase identification.

3 Results and discussion

3.1 Material structure

The stainless steel DIN X42Cr13 used in this study was characterised before machining by LBM. In particular, the distribution of chromium and chromium carbides was analysed. The micrographies in Fig. 3 show an homogenous distribution of chromium carbides dispersed in a matrix of iron (a, b) with some chromium in solid solution (b).

The analysis by X-ray diffractography reveals a tempering martensite with some residual austenite and carbide $Cr_{23}C_6$ (Fig. 4).

3.2 Surface roughness

The surface roughness is an attribute that may represent the quality of a machined surface on metal moulding blocks. In LBM, overlapping is a control parameter of the laser process, defined as the ratio between the laser speed and the pulse frequency or distance between pulses. The amount of overlap, as a percentage, is given by

$$O_a = \left(1 - \frac{v}{f \times D}\right) \times 100\% \qquad (1)$$

where O_a is the amount of overlap (percent), v is the scanning speed (millimetres per second), f is the frequency

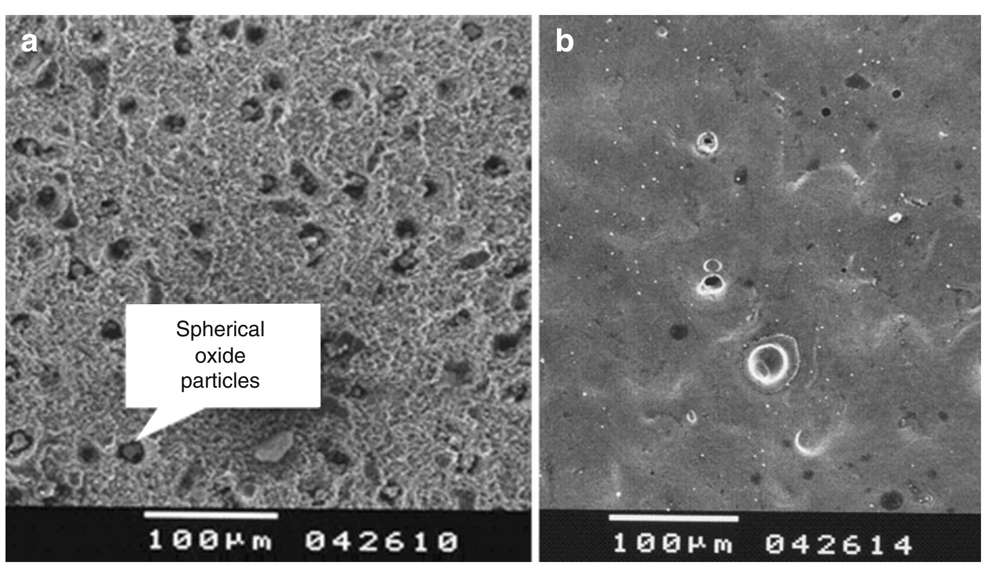

Fig. 9 **a** Micro-graph (SEM) of the bottom of a rectangular groove with laser machining [10.3.40.300] and **b** with EB polishing

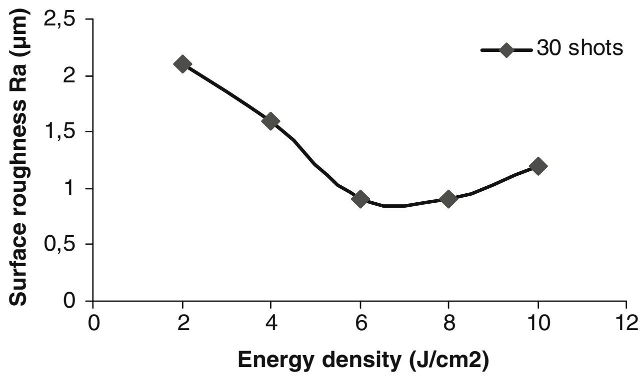

Fig. 10 Influence on surface roughness of energy density—the number of irradiations is set to 30 shots

(kilohertz), $v/f = O$ is the overlapping (micrometres) and D is the laser spot diameter (micrometres).

The roughness is mainly influenced by cutting depth, hatching and frequency. When the cutting depth is increased, the larger power required leads to higher temperature that results in degradation of the surface. The overlapping integrates the other factors that influence the surface roughness. Typically, the recommended O_a is about 70% for good surface quality, which using a spot diameter of 30 µm corresponds to overlapping of 10 µm. The final roughness also depends on the ratio between the hatching and the runway width. For a given erosion track width, there is a hatching setting that ensures an ideal overlap for the new path of the laser beam to more effectively cancel the concave surface created by the previous path.

Thus, in general, the roughness improves when the overlapping and the hatching decrease. However, at smaller values, the heating causes thermal degradation that results in increased roughness. These effects are observable in the data in Fig. 5 showing that the roughness increases with the cutting depth and the frequency. It is also observed the effect of reducing the overlapping for the same depth and scanning speed below a critical value, when thermal heating increases and surface degradation determines an increase of the roughness. For this material, the minimum roughness was obtained with 2 µm cutting depth and 30 kHz when setting an overlap of 10 µm.

The surface roughness depending on the scanning speed and hatching is shown in Fig. 6 for a constant frequency of 30 kHz.

There is a tendency for the average surface roughness to increase with scanning speed. For a laser spot beam diameter of 30 µm, it appears that hatching of 10 µm is the setting that ensures the lowest roughness. The explanation for this behaviour is based on the fact that the final roughness depends on the ratio between the hatching and the runway width. For a given erosion track width, there is a hatching setting that ensures an "ideal" level of overlap for the new path of the laser beam to more effectively cancel the concave surface created by the previous path.

Figure 7 shows that roughness increases considerably and almost linearly with laser intensity for various frequencies, as observed by other authors [13].

Besides the pulse duration, the most important parameters which affect the surface roughness in laser micromachining are the laser intensity, frequency, pulse and line distance (overlapping and hatching). The roughness Ra of a laser-machined surface, for any parameter combination used, is typically above 1 µm. This roughness is inappropriate as a moulding surface.

3.3 Material removal rate

Within this work, the processing window by LBM for stainless steel mould material X42Cr13 was also analysed in terms of the performance of the process. This is assessed by examining the material removal rate resulting from the variation of the processing parameters.

The MRR can be calculated as

$$\mathrm{MRR} = \frac{\mathrm{ht} \times \mathrm{ap} \times v}{1000^2}\,\mathrm{mm}^3\,\mathrm{s}^{-1} \tag{2}$$

where v is the scanning speed (millimetres per second), ap is the cutting depth (micrometres) and ht is the hatching (micrometres).

The scanning speed is calculated as the product between the overlap and the laser frequency ($O \times f$); thus, the MRR is a linear function of each of these variables. The data in the Fig. 8 not only confirm this assumption but also suggest that for a given cutting depth, the influence of the frequency is negligible when the scanning speed is constant, and consequently, the overlapping decreases. However, keeping the overlapping constant value causes the MRR to increase with frequency. Moreover, it was also observed that the

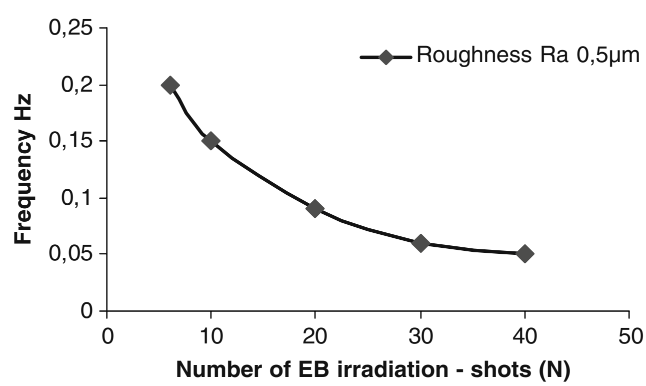

Fig. 11 Variations of frequency with number of irradiation for a constant roughness and energy density (6 J cm^{-2})

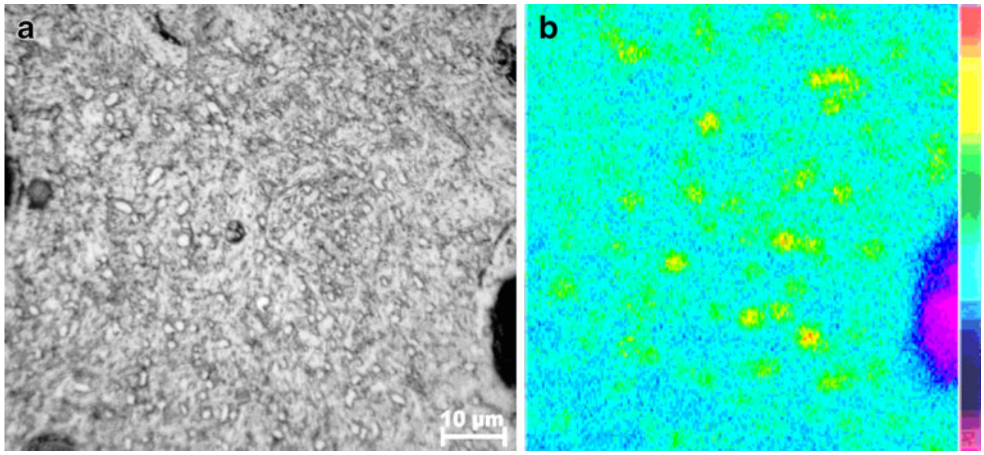

Fig. 12 Micro-graph of surface laser machining (**a**); and the chromium distribution (**b**)

material removal rate increases with overlapping, mainly at the expense of scanning speed.

The material removal rate is determined by the cutting depth hatching and scanning speed. However, it is possible to regulate the frequency and scanning speed to achieve the required combination of roughness and material removal rate. In any case, it appears that the use of high frequencies does not improve the process. The best results are obtained for the lower pulse frequencies, and there is, therefore, a tendency for the highest-scanning speed to ensure better efficiency.

3.4 Finishing using large-area EBM

After machining the surfaces by LBM, these were subjected to large-area EBM irradiation for final polishing. The irradiation was performed in argon atmosphere. This study involved changing the beam energy, the frequency, and the number of EB irradiations (shots).

When a surface is polished by large-area EBM, the roughness is substantially reduced to Ra=0.9 μm as it is exemplified in the Fig. 9 for the case of the laser machined sample [10.3.40.300] with Ra=2.1 μm. The resolidified material was not fully removed after polishing, and some particles remain clearly visible at the bottom of cavities.

The study on the effect of the EBM parameter variation showed that when small energy density (about 2.1 J cm^{-2}) is used some melting occurred at some places on the surface. Upon using larger energy conditions, the topography of surface improves substantially. The surface roughness reduces with the increasing energy density until this reaches a minimum between 6 and 8 J cm^{-2}, as shown in the Fig. 10. Using larger energy density with this stainless steel results in a noticeable deterioration in the quality of the surface.

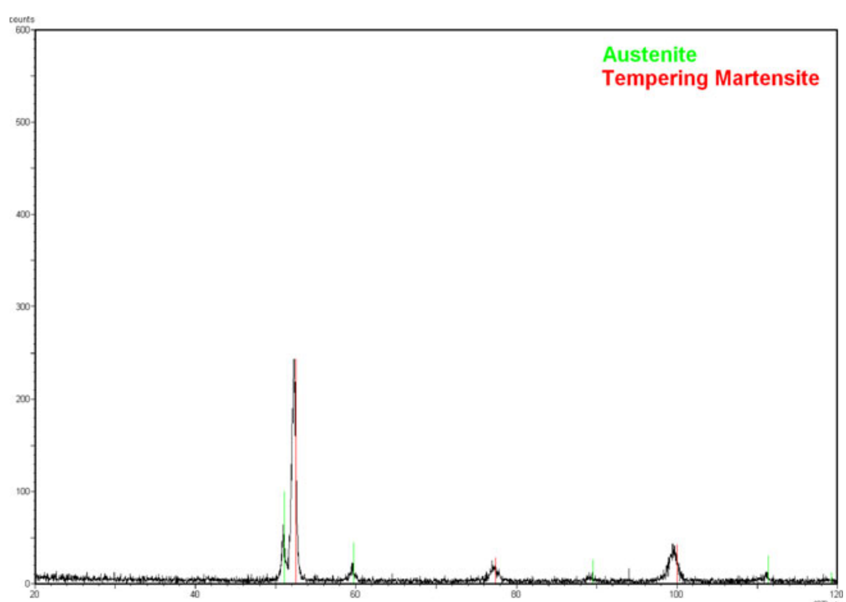

Fig. 13 X-ray diffractogram of X42Cr13 steel after LBM [10.4.30.300]

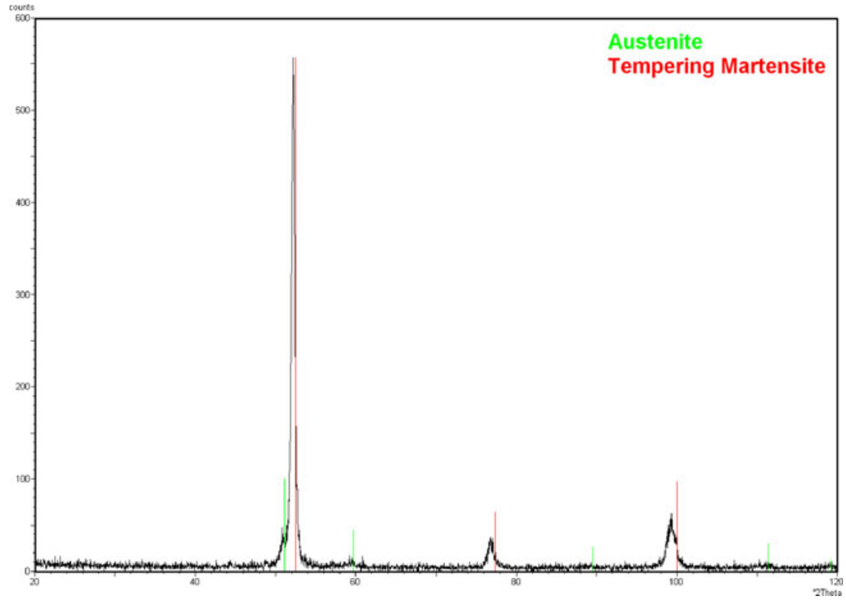

Fig. 14 X-ray diffractogram of X42Cr13 steel after quenching

The influence of the number EB irradiation on the surface smoothing depends on the energy density. For high-energy density conditions, of about 10 J cm^{-2}, increasing the number of irradiation shots improves the surface roughness; however, for smaller values of the energy density, the roughness is little improved above 10 shots. For a constant surface roughness after EB irradiation on the LBMed sample [10.2.40.400], Ra=0.5 µm, the data in Fig. 11 shows that the frequency must increase when the number of irradiation shots decreases.

Considering these results, it seems possible to improve the surface roughness using relatively large energy density and large number of shots with small frequency. The maximum frequency of 0.2 Hz is used only for cleaning the surface.

It was also found that for the same energy density, the surface roughness improves with increasing argon gas pressure and for smaller tilting angles.

Table 3 Hardness after laser machining

Specimen	Power (W)	Spot diameter (µm)	Hardness HV0.01(±30)
10.2.30.500	36.4	30	450
10.2.40.300	26.7	30	483
10.2.40.500	34.0	30	451
10.4.30.300	40.3	30	420
10.4.35.300	40.7	30	489
10.4.40.300	39.0	30	484
10.4.40.500	55.5	30	461

The optimal conditions were investigated to maintain the dimensional and geometrical tolerances of the micro-structures and to ensure that the edges are not bevelled.

We verified that the increase of the energy density leads to a greater chamfer of the edges and that for the same energy density, the frequency increase leads to the same effect. It was also verified that to have the requested quality of most microstructures of moulding inserts of high accuracy, it is recommendable to work with lower energy density (2 to 4 J cm^{-2}) and frequency of about 0.07 Hz with a high-level EB irradiations. Under these conditions, an edge will not chamfer more than 7 to 8 µm and the dimensions vary from 3 to 4 µm for the quenched and tempered steel X42Cr13.

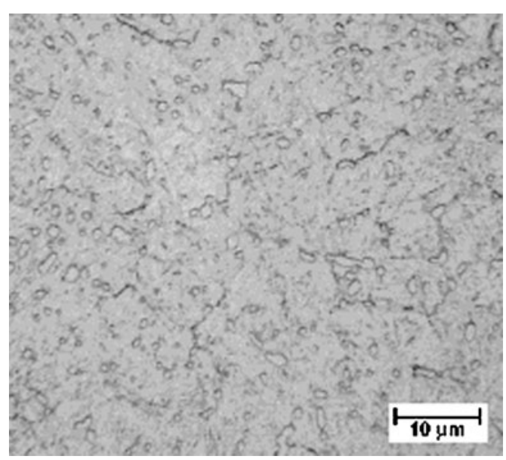

Fig. 15 Micro-graph of the specimen [10.2.40.500] after EBM finishing

Table 4 Hardness after EB irradiation

Specimen	Hardness HV0.01(±30)
10.2.40.500	512
10.4.30.300	513
10.3.30.400	485
10.3.30.500	522
10.4.35.300	530

3.5 Structural analysis and hardness evaluation

3.5.1 Laser beam machined surfaces

The HAZ of the stainless steel surface generated by laser machining was analysed concerning micro-structure and micro-hardness. The changing of metallurgical characteristics of laser-machined workpieces, being mainly governed by the HAZ, makes it necessary to minimise it during LBM. Decreasing power and increasing feed rate generally lead to a decrease in the HAZ [9]. The heat-affected area is reduced when the laser scanning speed increases, the faster scanning the less is the time, to conduct heat into the workpiece. Consequently, the HAZ is substantially restricted. However, the need to maintain cutting depth compels to the use of higher laser power densities which can lead to other effects.

After laser machining, the presence of remelted material on the surface of workpieces (Fig. 12) suggests that some micro-structural modifications might have occurred during the machining. The chemical homogeneity and micro-structural differences in the material are shown in the Fig. 12a and b. It is evident that the matrix has higher chromium content in solid solution than before LBM (quenching and tempering). Moreover, the number of areas with high concentration of chromium (yellow) has increased significantly. In fact, the laser beam interaction has promoted deficient dissolution of some chromium carbide (primary) but has contributed efficiently for the dissolution of small carbides (secondary and/or from tempering) responsible by the significant decrease of chromium in the tempered matrix (Fig. 3). In Figs. 3 and 12, there are two colours reported with abnormal concentration of chromium, one yellow corresponding to the presence of the highest concentration of this element, which means chromium carbide surrounded by green colour representing a lower concentration of chromium yet significant have in mind the matrix concentration in this element. The last one is characteristics of the processes where there is not enough time or temperature to promote chromium diffusion.

Concerning the X-ray diffractogram (Fig. 13), it is clear that the main difference concerns the relation martensite/austenite peak intensities. The laser machining surfaces present the highest rapport comparing with same steel quenched (Fig. 14) or quenched and tempered (Fig. 4).

The effect of different laser parameters are highlighted using micro-hardness values (Table 3) conducted on specimens prepared using a variety of laser conditions (cf.2.2).

In conclusion, all machined specimens have a hardness lower than steel before laser beam machining. By comparing specimen [10.2.30.500] with [10.2.40.300], it appears that high power intensity will promote lower hardness. The specimens [10.4.40.300] and [10.4.40.500] show that an increase in the scanning speed from 300 to 500 mm s^{-1} results in lower hardness. This means that with the same cutting depth, hatching and frequency, there is a softening when overlapping is greater.

3.5.2 Large-area EBM finished surfaces

A typical structure of a specimen after EBM finishing is shown in Fig. 15 for the case of the specimen

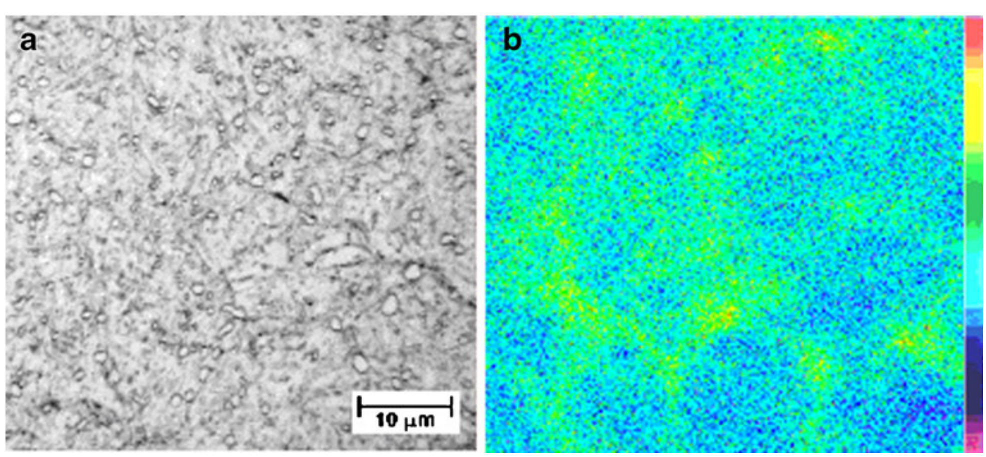

Fig. 16 Micro-graph of the specimen [10.4.30.300] after EBM finishing and the chromium distribution

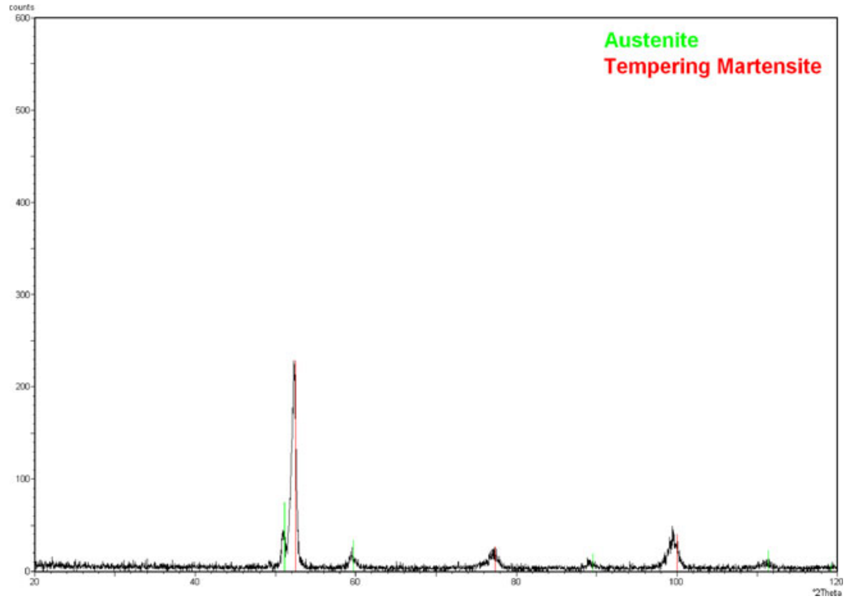

Fig. 17 X-ray diffractogram of X42Cr13 steel after EBM treatment [10.4.30.300]

[10.2.40.500]. The structure and the hardness are similar to those of heat-treated steel.

In fact, after large-area EBM, the specimen exhibits hardness values similar or slightly higher than the steel before LBM (Table 4). The maximum hardness (530 HV0.01) was attained in the specimens previously laser machined in the conditions [10.4.35.300].

After this finishing treatment, the elemental distribution of chromium (Fig. 16b) reveals an enrichment of chromium in solid solution in relation to tempered and laser treatment, assuring a high corrosion/oxidation resistance of these surfaces treated by EBM. This increase must be related to the better distribution of chromium resulting from the heating enhancing the diffusion of chromium and/or to the dissolution of some chromium carbides. The last case was responsible for the slight increase in some cases of hardness due to the carbon matrix incorporation resulting from chromium carbide dissolution.

The X-ray diffraction reveals that after finishing by EBM, a similar structure to the LBM and also a similar austenite were obtained (Fig. 17).

4 Conclusions

This study showed that the combination of LBM and large-area EBM is an interesting alternative to polishing by hand lapping of moulding surfaces for micro-moulding. This combination enables improved surface roughness and surface integrity without cracks and smaller HAZ. Furthermore, it does not require the time and special technical skills associated to hand polishing.

For martensitic stainless steels, as X42Cr13, the surface roughness deteriorates with increasing laser intensity. The adjustment of other laser parameters carried out a significant improvement in surface finishing quality. The lowest roughness for the X42Cr13 steel is reached with hatching and overlapping of 10 µm using 30 µm spot diameter.

The roughness of large-area EBM finished surfaces is reduces with the number of irradiation shots using low frequency and high energy density. Nevertheless, a roughness minimum is reached when the energy density is between 6 and 8 J cm^{-2}.

Moreover, the EBM finishing improves significantly corrosion and oxidation resistance compared with conventional heat-treated surfaces.

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