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Novel methodology for burr extension estimation on machined SLM surfaces

GINESTRA Paola[1,a *], QUARTO Mariangela[2,b], ABENI Andrea[1,c], ATTANASIO Aldo[1,d], CERETTI Elisabetta[1,e], D'URSO Gianluca [2,f] and GIARDINI Claudio[2,g]

[1]Department of Management, Information and Production Engineering, University of Bergamo, via Pasubio 7/b, 24044 Dalmine (BG)

[2]Department of Mechanical and Industrial Engineering, University of Brescia, via Branze 38, 25123 Brescia (BS)

[a]paola.ginestra@unibs.it, [b]mariangela.quarto@unibg.it, [c]andrea.abeni@unibs.it, [d]aldo.attanasio@unibs.it, [e]elisabetta.ceretti@unibs.it, [f]gianluca.d-urso@unibg.it, [g]claudio.giardini@unibg.it

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Abstract. Additive manufacturing techniques can cover the needs of these components thanks to their high level of customization of the products and the ability to realize complex shapes without high effort. Despite the benefits derived from AM processes, these techniques are characterized by a low-quality of surface finish, one of the most important requirements for medical devices. Considering this aspect, it is important to develop a solution able to improve the surface finish in order to enjoy the low lead times and the high level of customization typical of these processes. A characteristic element of micro-machining is the presence of burrs on the machined surface which can affect the surface texture of micro-features. For this reason, a novel technique for the evaluation of burr was defined. The burrs were evaluated by means of an autofocus variation digital microscope Keyence VHX-7100, on 17-4 PH steel samples produced by laser bed fusion. A 3D reconstruction of the channels and holes surfaces was performed and through the analysis of the peaks distribution, a threshold was defined to discriminate between the original surface of the part and the burrs. In this way, it was possible to estimate and approximate the value of the extension of the burrs in terms of volume and area, where the area is referred to the projected area. Specifically, in micro-machining, not only the extension of the burrs is significant, but also the variability is particularly high, preventing a priori consideration of the defect.

Introduction

Laser bed fusion technologies are widely used to produce complex metal parts not obtainable with traditional and conventional machining processes. Selective Laser Melting (SLM) is a popular and suitable technique for the production of metal components from powder melting by the passage of a laser source in a controlled atmosphere. This technology has been highlighted for the acceptable structural integrity (i.e. density) of the produced parts and the wide range of materials available for this process [1]. On the contrary, such technology, as all the powder bed processes, suffers from an inadequate final surface finishing that is often characterized by high variability affecting the dimensional accuracy of the specimens.

The poor surface quality derived by powder bed fusion is influencing the technical properties of the parts and compromising their tolerances, leading to a limited range of applicability, extremely related to the post-processing requirements [2]. Other defects, such uncontrolled internal porosities, are deeply under study, to exploit the possible applications of these products. The high surface roughness reached by the final parts produced with SLM is easily explained by the presence of partially melted powder and layer thickness requirements typical of the building process.

The surface finishing and mechanical properties of the metal 3D printed parts are highly related and therefore, an adequate post-processing technique needs to be identified and applied. Among the wide range of traditional processes used for high precision surface finishing, considering the final applications of 3D components that can require low roughness values (i.e. biomedical applications where the surface roughness can influence bacterial adhesion), micro milling is the most convenient manufacturing process when considering the volume and cost ratio [3,4].

Micro-size features of considerable complexity can be obtained by the mechanical removal of material using micro tools on a variety of substrates and materials. Micro milling is a high efficiency process but requires an extended selection of tools and part miniaturization as well as an optimal process optimization before being applied to complex parts especially 3D printed ones. Before considering the usage of this technology on a SLM sample, the micro milling forces and chip thickness formation have to be analyzed and optimized to avoid any material removal behavior that could decrease the precision of the technique [5]. Specifically, the cutting energy and forces are highly influenced by the undeformed chip thickness causing side effects. When the uncut chip thickness is too low, the cutting process is not anymore guided by an elastic deformation (shearing) but by a ploughing regime, which is an elasto-plastic deformation that causes an incorrect chip formation.

The undeformed chip thickness has been identified as one of the causes of the burrs formation during micro milling operations, affecting the quality of the product and the specified dimensional accuracy [6]. Burrs removal is often cost and time consuming since it is extremely difficult on small size components and rarely performed by conventional processes [7]. Therefore, the controls on burrs formation has assumed a lot of importance for a lot of applications, especially in the biomedical field that requires burrs free components.

For this reason, numerous studies focus on the timely and direct characterization of the burrs to provide prompt feedback on the process. Most of the optical systems used for burrs estimation are not able to provide accurate information on geometry or surface roughness and thus specific additional systems are often required to access this information (profilometers, micro-probes or SEM) [8]. Usually, studies on obtaining burrs data by SEM images are conducted manually, meaning that time and practice are required [9].

In this work, a prior evaluation of the machinability and material removal behavior on 17-4PH steel SLM samples has been performed, and a fast and user-friendly solution for measuring burr formation at the micro-scale requiring only one image as input, is proposed. The use of the data acquired through the optical profilometer allows a geometrical characterization of the machined sample with high accuracy, including the burrs geometrical characteristics in terms of morphology and volume evaluation.

Materials and Methods

Micromilling assessment

17-4 PH samples were produced by the laser powder bed fusion machine ProX 100 (© 3D Systems, Rock Hill, South Carolina, United States) as 25x25x5 mm^3 square samples, with four holes on the corners for the micro milling machine positioning.

The process parameters were: 50W of laser power, 30 microns of layer thickness and 300 m/s of scan speed. The samples were micro-machined by using the five axes Nano Precision Machining Center Kern Pyramid Nano (© Kern Microtechnik GmbH, 82438 Eschenlohe, Germany). The machining tests consist in channel fabrication with a single tool pass from the outer to the center of the sample at a constant depth (a_p) of 200 μm (Fig.1).

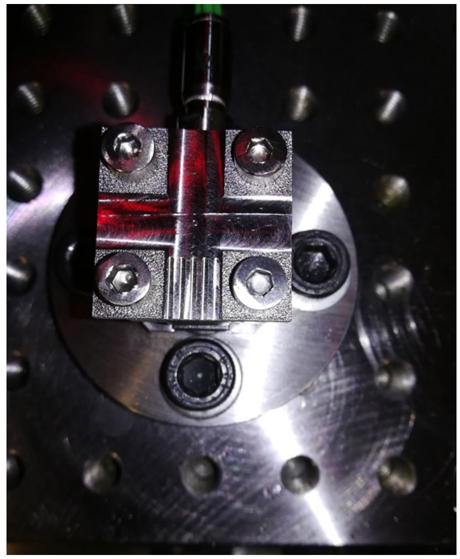

Fig. 1. Reference picture of the machining setup.

Tests can be grouped in two different categories: (i) micro machining at constant cutting speed and different feed per tooth (f_z) values as reported elsewhere [10]; (ii) micro machining with a constant feed rate and three different cutting speeds in order to evaluate the dynamic effects on the burrs developing.

In the first group of tests, a cutting speed (v_c) of 40 m/min was kept constant for each cut. Twenty micro channels were machined by using twenty feed per tooth values ranging between 10 µm and 0.5 µm. The microchannels were produced using a coated two flutes micro mill with a nominal diameter of 0.8 mm.

These tests were designed to identify the MUCT as a function of the feed per tooth. A Labview code was implemented to calculate the cutting force by the cutting load components and the signal was filtered in order to identify the cutting force maximum peak on the flutes (z=2) for each rotation.

The tool run-out has been taken into account when normalizing the cutting force: with two flutes (A and B), the maximum chip thickness for one flute (h_{Amax}) will be different than the thickness for the other flute (h_{Bmax}). This asymmetric condition causes two cutting force peaks (F_{c_maxA}; F_{c_maxB}) which should be normalized by considering the effective thickness (for further details please refer to [10]). The second group of channels were fabricated with a constant depth of cut and by changing the cutting speed on three different levels. It is well known that the cutting speed has a major effect on the size of the burrs in micromachining [11,12].

The tests were finalized to evaluate the burrs formation on the inner and outer side of the channel. Two different dimensional scales were investigated by using a coated two flutes micro mill with a nominal diameter of 0.8 mm and a coated two flutes micro mill with a nominal diameter of 0.2 mm. Two sizes were tested in order to verify the procedure to estimate the burr dimensions at different dimensional scales. With the 0.2 mm micro mill a feed per tooth of 1 µm/tooth and cutting speed of 18, 22 and 26 m/min were tested, while with the 0.8 mm micro mill was chosen a feed per tooth of 3 µm/tooth and cutting speed of 30, 40 and 50 m/min. Each test was repeated three times to statistically validate the results.

Burrs estimation methodology

The new developed method assumes that it is possible to extract more information from surface topography. Specifically, the purpose is to define a method able to quantify burrs extensions exploiting the capabilities of an optical profilometer.

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The use of this instrument enables a complete characterization of the machined micro-channels, since the data acquired on the bottom part of the channels can be used for the surface texture evaluation (roughness and amplitude parameters), profiles on different sections can be used for the geometrical characterization of the channels, the data acquired on the top part can be used for the burrs evaluation.

In this paper the focus is on this last point. Since the burrs have complex and irregular geometry, their surface results are difficult to be measured with direct measurement techniques. The proposed method for burrs evaluation leverages the 3D topography enabling the evaluation of burrs volume and projected area. The process flow-chart describing the proposed methodology is reported in Fig. 2.

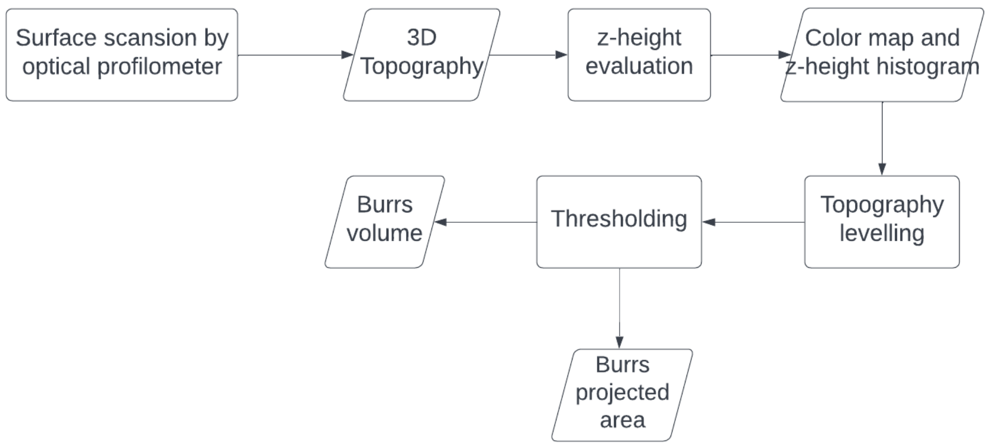

Fig. 2. Flow-chart of proposed method.

The optical profilometer (Sensofar S-neox© Copyright 2021 by Sensofar, Barcelona, Spain) allows the acquisition of a points cloud containing spatial distribution of the scanned points along the 3 main directions (x,y,z). An example of the 3D topography of a micro-machined channel is reported in Fig. 3 where it is possible to distinguish two main regions: the bottom of the channel and the top plane which indicate the rough surface.

The top region is used for the 3D alignment procedure. A roto-translation matrix is determined by applying a least-square algorithm between the top region points and a plane. A linear least-square fitting is applied, using a polynomial plane equation. The coefficients of the equation are then used for the matrix creation, referring to the x-y plane. The obtained matrix is then applied to the entire point cloud along the three main directions x,y,z. The alignment of the top plane is necessary for the thresholding procedure. This step is applied on the height map in order to exclude all the points below the top plane.

The thresholding criterion is based on the points height distribution around the fitted plane, specifically, the limits of the threshold was set in correspondence of the starting point of the positive queue of the z-height distribution which allows to identified only the points characterized by a z-height higher than the as-built surface.

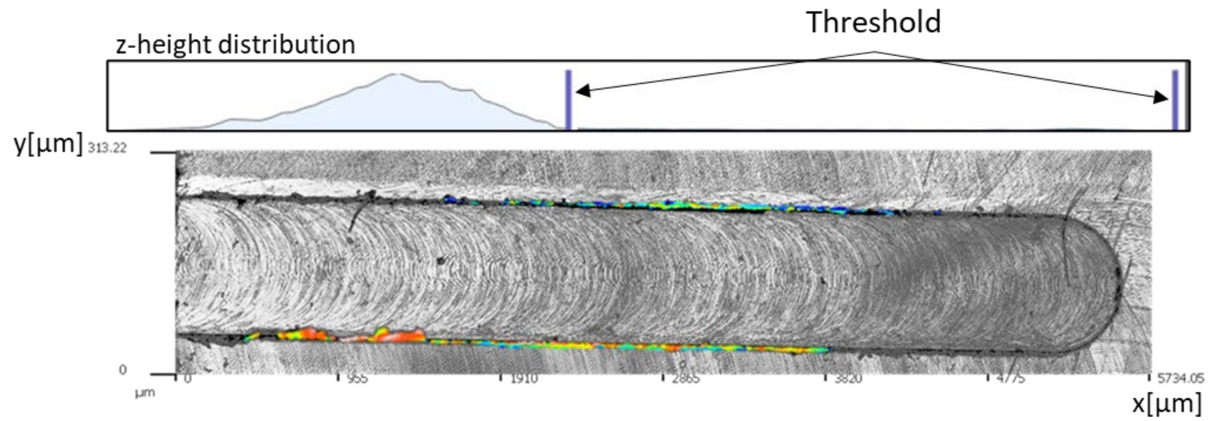

Fig. 3. Portion of burrs identification on the 3D reconstructed machined samples.

Results and Discussion

Identification of the MUCT

As shown in Fig. 4 with a feed per tooth equal or lower than 2 microns, the difference between the cutting force peaks of the two flutes increases. This behavior can be related to a ploughing condition involving flute B that causes an increment of the undeformed depth of cut for flute A. The normalization performed on the resulting cutting force values allowed us to investigate the cutting regime of the material by making the tool run out effects negligible.

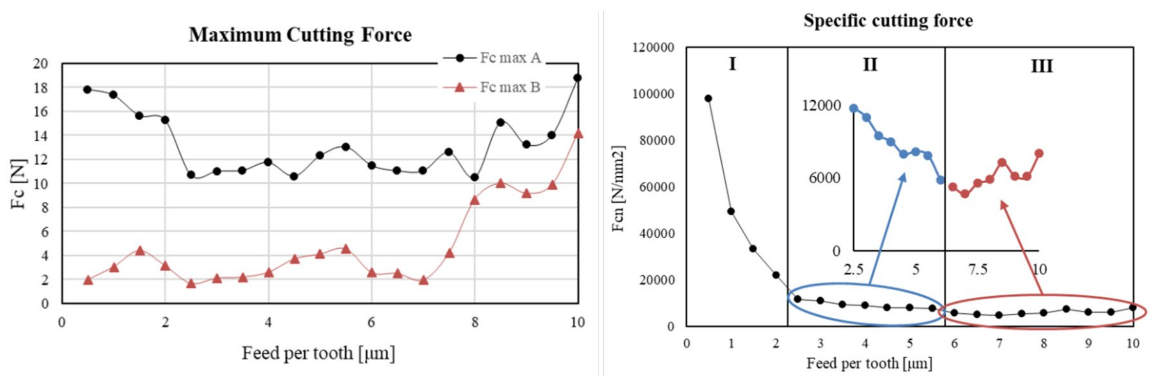

Fig. 4. Cutting force peaks as a function of the feed per tooth (left) and Specific cutting force maximum values for different feed rates (right).

Furthermore, from Fig. 4 it is evident that the specific cutting force changes during the process due to different deformation regimes. Below a f_z of 2.5 µm/tooth, the normalized cutting force increases significantly. For this reason, the MUCT for this analysis was set at 2.5 µm, which falls within the range of the 20-40% of the cutting-edge radius of the tool (0.8 mm). In fact, the region I reported in Fig. 4 is indicating a ploughing deformation region.

The region II instead, is a transition region between the deformation mechanism where the ploughing is progressively substituted by the shearing regime of region III, characterized by the independence of the cutting force in relation to the feed per tooth values.

Influence of cutting speed on burr formation

An overview of the machined channels is reported in Fig. 5, specifically Fig. 5(a) reports the 0.2 mm micro-channels, whilst the Fig. 5(b) shows the 0.8 mm micro-channels.

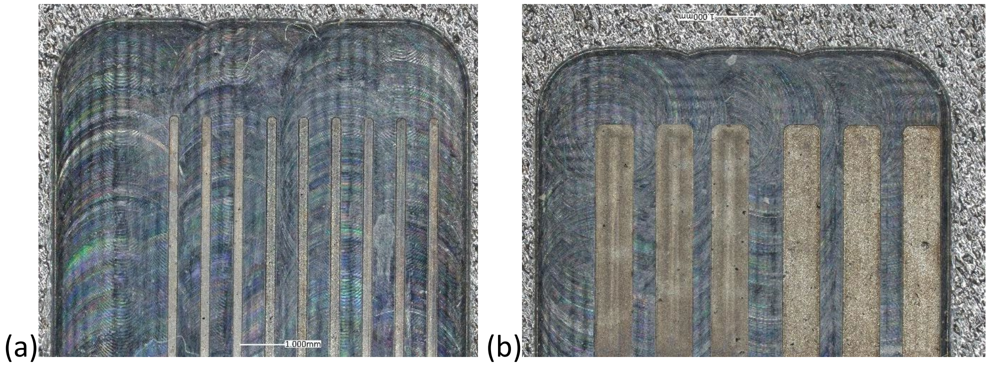

Fig. 5. Reference image of the burrs on the machined samples with 0.2 mm (left) and 0.8 mm (right) tools.

As reported in Fig. 6 the extension of the burrs for this micro milling operation is significant, and the variability between the measured values is particularly high, preventing a priori consideration of the defect.

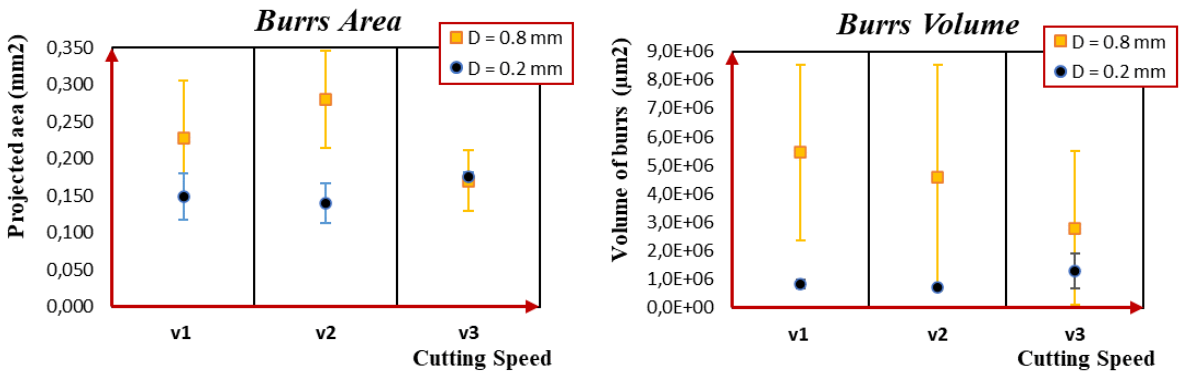

Fig. 6. Burrs Area (left) and volume (right) reported as a function of the cutting speed values for the two used tools.

As visible in Fig. 6, the burrs area on 0.8 mm channels is higher than the 0.2 mm channels, except with the higher cutting speed when it is comparable. There is not a significant dependence of burrs area on cutting speed. The variability of data is calculated as the standard deviation of the measurements, and it resulted lower with 0.2 mm channels. About the volume, the gap between the burrs on 0.2- and 0.8-mm channels increases. The data show a great variability with the 0.8 mm channels and a decrease of the average volume as cutting speed increases. Higher cutting speeds promote higher deformation rates, with a consequent work-hardening of the material. The resulting decrease of the workpiece ductility facilitates the chip evacuation with a consequent reduction of burrs. With 0.2 mm channels, the volume of burrs is almost constant, and it does not depend on cutting speed because on the micro scale, other phenomena are prominent, such as the development of undesired cutting regimes.

The ratio between the burrs area and cross section of the channels (*ratio A*), and the ratio between the burrs volume and the channel volume (*ratio V*), were calculated in order to compare the dimensions of the burrs on channels with different diameters.

$$Ratio\ A = \frac{Burrs\ Area}{D * a_p} \tag{1}$$

$$Ratio\ V = \frac{Burrs\ Volume}{D*a_p*L_C} \quad (2)$$

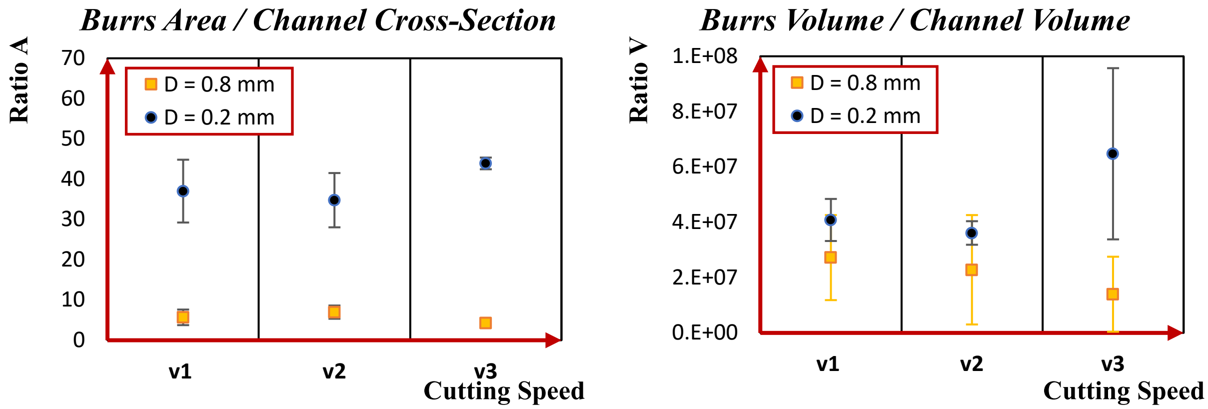

Fig. 7. Ratio A (left) and Ratio V (right) reported as a function of the cutting speed values for the two used tools.

As visible in Fig. 7, the coefficients *A* and *V* are higher for the 0.2 mm channels if compared with 0.8 mm channels. It means that the relative dimension of the burrs is higher with the channels machined with 0.2 mm micro-mill. The miniaturization of the machined features determines a worsening of the surface integrity due to the size effect. It is related to the promotion of negative rake angles due to the decrease of the ratio between the chip thickness and the cutting-edge radius. The compression of the material, known as ploughing, avoids the correct chip formation with a consequent increasement of the materials collected on both sides of the channels. The size effect has more impact on the ratio *A* then the ration *V*. It means that the morphology of burrs strictly depends on the size of the machining process. With the 0.2 mm diameter micro-mill, the burrs are more developed on the xy plane (see Fig. 3), while they are less developed on the z-direction. On the other hand, as the size increases, the burr are more developed in the z-direction. Each micro-mill has the same helix angle, consequently this trend can be related with the compression of the material in ploughing regime.

Summary

This paper deals with the micro milling of a 3D printed stainless steel material for the post-processing of poorly finished samples. Moreover, this paper introduces an easy-to-handle and time efficient procedure for the burrs identification and characterization after micro milling. From the reported results on the micro milling process, it was possible to notice the occurrence of two deformation regimes as a function of the feed per tooth values. Specifically, at low fz, ploughing dominates the material removal behavior while at higher feed rates, the shearing deformation regime becomes predominant. As a result, the cutting forces during shearing are ten times lower than the forces calculated during ploughing.

Moreover, during shearing the cutting force is not related to the feed per tooth values. The measured transition corresponds to a MUCT of 2.5 microns which is 30-35% of the actual tool edge radius, according to literature [13]. The optimal feed rates have been highlighted to reduce the cutting forces and reduce the tool damage, which causes severe tool wear. We moved beyond the state of the art by introducing a quick and easy-to-handle method for burrs estimation on micro-machined samples. Specifically, a threshold has been established and the software automatically selected the volume and the projected areas based on the z-height of the samples.

Moreover, our method avoids the binary transformation of the values and the consequent projection of the area, which leads to an approximation of the area extension in relation to the projection. Therefore, we based our work on the estimation of the burrs 3D extension and not only the burrs 2D dimension.

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