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Computational-experimental investigation of milling porous aluminium

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ABSTRACT

Porous materials are increasingly incorporated in light-weight structures and although they are near-net-shape fabricated, a finishing step is required to achieve the desired tolerances. Herein, a computational-experimental framework is proposed to investigate milling of porous aluminium. A FEM model was built, for the first time recorded in the literature, to simulate the milling process of the 3D closed-cell porous geometry, reconstructed by a Voronoi-based CAD algorithm. The chip evolution, traced by the developed FEM model, reveals interesting deformation mechanisms, while the chip fragmentations lead to multiple force fluctuations in a single cut, offering a good agreement with the measured forces.

1. Introduction

Porous metals are among the most promising materials to use in advanced industrial applications and structures, like aerospace, medicine, automotive etc. [1–3]. This trend arises from the interesting combination of characteristics and the ease of adjusting their properties to meet the desired needs by tailoring porosity characteristics [4]. Even though porous metals are usually near-net-shape fabricated, they often require a finishing machining stage. Due to the thin walls of the porous structure, they often yield to burr formation, which in some cases may be a critical issue [5]. Cryogenic cutting seems to be a working solution for controlling ductility of porous metals [6]. However, machining of porous materials has been rarely investigated [7,8] and even more modelling of the machining process, especially in milling, seems to be an unexploited area.

The present work aims to investigate the milling of porous aluminium by computational investigations coupled with cutting force measurements. A 3D FEM model of the cutting process was established, enabling the monitoring of the chip evolution and the forces developed in milling. Some of the major challenges encountered when building the FEM model refer to the workpiece geometry complexity, which makes difficult the establishment of tool-workpiece contact, along with the simulation during densification of the porous structure and the self-contact at the workpiece. The 3D geometry of the porous structure was reconstructed employing a Voronoi-based tessellation algorithm developed for this purpose [9]. The results show a good correlation between experimental and computational findings, revealing that the cutting forces are fluctuating according to the pores located underneath the tool. These fluctuations of the cutting force may imply a premature fatigue damage of the tool, given that the tool is loaded multiple times per cut chip, which intensifies the fatigue initiation and fracture. The chip thickness h is pivotal in producing continuous (non-fragmented) chips and was varied to avoid burr formation and pore closures through permanent deformations of the workpiece.

2. Materials and methods

2.1. Tool and cutting details

Grade K05-K20 cemented carbides, supplied by KENNAMETAL and deposited with a 5 μm-thick diamond coating by CEMECON AG [10], were applied in the milling investigations. Fig. 1 shows the cutting strategy and the experimental setup employed for measuring the cutting forces. Down milling was selected with both the radial a_e and axial a_p depths of cut set to 2 mm. Chip thickness h was varying from 0.2 to 0.5 mm by adjusting the feedrate, while cutting speed v_c was set to 600 m/min. A KINSTLER type 9257A 3-axis piezoelectric force measurement device was engaged, supported by three signal amplifiers Kistler Type 5011 (one per axis) and a National Instruments data acquisition card NI PCI-6024E. Labview SignalExpress software package offered the platform for data acquisition. The cutting forces measured in the stationary coordinate (F_x, F_y, F_z) were then translated into the rotating cutting tool coordinate system (F_c, $F_{\kappa n}$, $F_{\kappa t}$).

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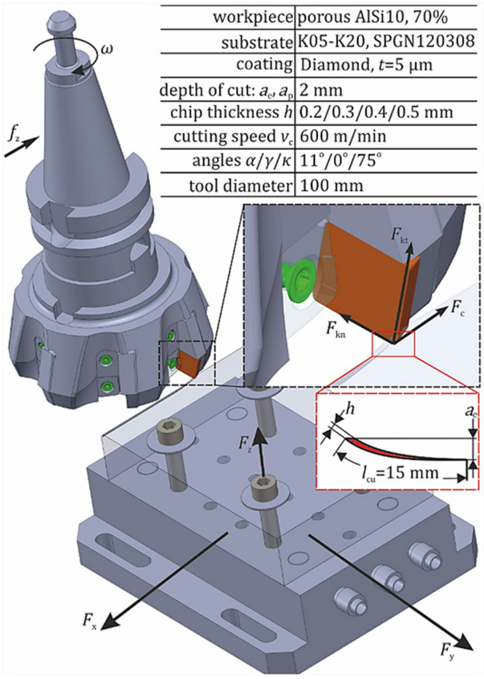

Fig. 1. Cutting strategy and experimental setup for measuring the cutting forces in down milling of porous aluminium.

2.2. Porous aluminium macro- and micro-structure and 3D geometry reconstruction

The porous aluminium work material employed in the cutting investigations was fabricated through liquid metallurgy using AlSi10 as matrix, by adding 1.3 wt.% Ca (to enhance the viscosity) and 2 wt.% TiH_2 particles (as foaming agent) and stirring the melt at 620–650 °C [9]. From the obtained Al-foam with an average porosity of about 70%, plates were manufactured to a thickness of 30 mm. Fig. 2 presents images from optical and scanning electron microscopes of the produced foam, revealing both its micro- and macro-structure, respectively, after a careful grinding-polishing procedure to avoid damage of the cells. At macro scale level, pores are ellipsoidal forming a closed-cell structure with almost no interconnection with each other. At micro scale level (see detail of the cell microstructure), dendrites of primary solid solution α-Al grains and eutectic structure mainly found in the dendritic interspaces are evident. The eutectic consists of relatively coarse silicon plates dispersed in an Al-matrix (α phase). The Ti that is released from the foaming agent, as well as the Ca, remain in the Al-Si melt, forming Al_4Ca and $TiAl_3$ precipitates (not shown in the micrograph). There is no evidence that the precipitates are concentrated on or near the pore surface area, so they are considered as homogeneously dispersed all over the volume of the porous metal.

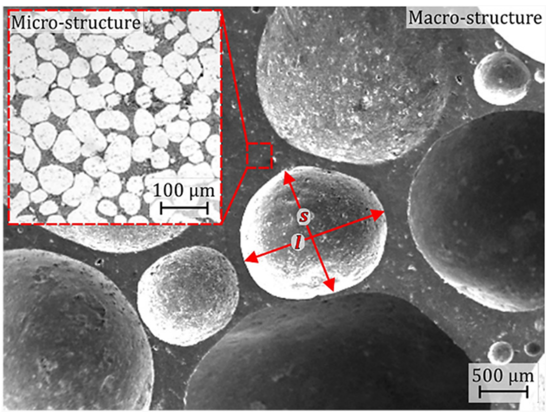

Fig. 2. Macro- and micro-structure of the produced porous Al.

The reconstruction of the porous geometry was realized employing Rhino software in combination with Grasshopper add-in, following the procedure described in [9]. Fig. 3a shows the main steps followed, involving: (i) Polyhedra generation by applying the Voronoi tessellation algorithm based on random points created inside a solid cube with an edge length of 30 mm. (ii) Scaling down of the polyhedra with respect to their centroid to create an empty space, which then is used to form the walls between the cells and smoothing to match the shape of the pores, which could be characterized as ellipsoid. (iii) A Boolean operation was performed to subtract the smoothed polyhedra from the initial cube to create the porous structure. (iv) Creation of the final geometry considering the cutting tool first cut, by removing the volume which is formed from the intersection of the workpiece with the tool when rotated and moving on the path of the feed. The porosity of the modelled structure was adjusted to approximate one of the produced foam, by tuning the number of generated polyhedra and scale ratio. A total number of 1070 polyhedra combined with a scale ratio of 0.9 resulted to a structure having a porosity of approximately 70%. To further investigate the porous macro-structure (cell size, cell shape and anisotropy) of the produced Al-foam, five cross-sections with dimensions of 30 mm × 30 mm were cut employing a precision diamond saw to minimize the cell damage. A quantitative image analysis was then performed based on approximately 200 pores. The images of the cross-sections went through various preparation steps including: converting the image to black and white, enhancing the contrast and brightness, and adaptive thresholding to specified areas of interest for highlighting the pores. Once the cross-sectional images were segmented, each pore was replaced by the best fitting ellipse of the same area, orientation and centroid as the original pore, by applying an appropriate algorithm. The ratio of the smallest pore axis s divided by its largest l and the mean pore

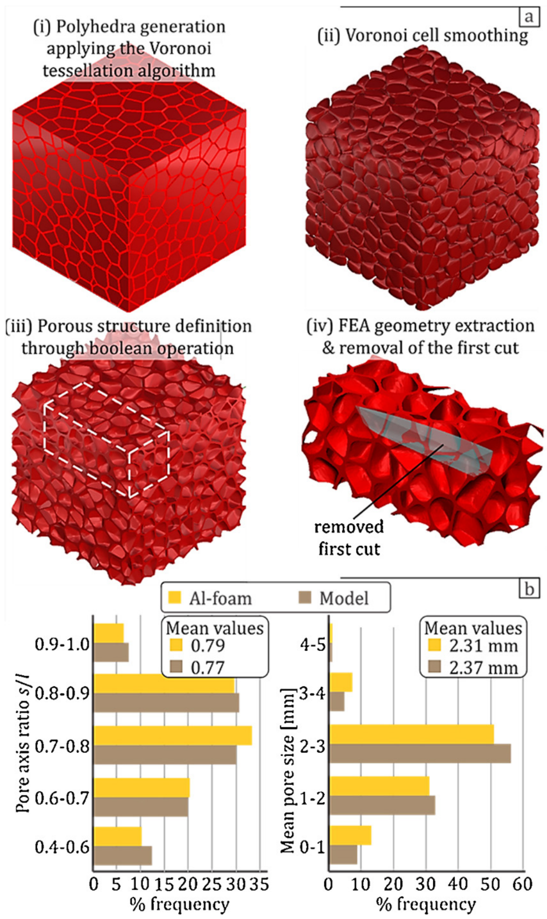

Fig. 3. (a) Reconstruction of the 3D porous geometry by the developed Voronoi-based tessellation algorithm and (b) comparison of its pore characteristics with the real foam.

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