Micromilling of metallic feedstock produced by extrusion additive manufacturing

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Abstract

Greenstate micromilling is a very promising method that can be integrated in to the 3D printing of metallic micro components using feedstock, for compensating the lack of micro reachability that typical extrusion-based additive manufacturing (AM) method cannot deal with. This integration can aid manufacturing of complex geometries, generation of good surface quality and can provide exceptional flexibility to new product shapes. In this machinability study, the effects of workpiece temperature on green machining is studied, in addition to the micromilling parameters such as cutting speed, feed per tooth, axial depth of cut and air supply for feedstock components produced by extrusion-based AM. Edge integrity and surface roughness of the machined slots are analysed using 3D microscopy and acquired cutting force signals are analysed for each micromilling condition. The micromilling of workpiece at hot temperature (45°C) with an air supply for debris removal showed the best surface quality with least surface roughness value. The micromilling parameters at lower levels seemed to be appropriate for the greenstate micromilling of extrusion additive manufactured parts. This study confirms the possibility of implementing micromilling into extrusion-based 3D printing manufacturing cycles of metallic feedstock.

Keywords: micromilling, extrusion, additive manufacturing, 3D printing, surface quality, feedstock.

1. Introduction

The extrusion-based methods for AM of metallic components are increasing in popularity because of the recent advancement in the feedstock preparation, ease and low cost of production system, capability of producing parts with unique properties achievable by multiple materials and the small extent of material wasted during processing. Use of feedstock for extrusion avoids the incapability of direct metal extrusion for AM because of the problems due to the very high temperature, low viscosity and the surface tension of the molten metal [1]. The initial step in the process chain of the extrusion-based AM (extrusion-based 3D printing) which is based on powder metallurgical principle is that extrusion and deposition of metal polymer feedstock micro filaments, layer by layer in the required geometry to produce a 3D part in greenstate. This is followed by debinding of the part using solvent or thermal methodology to eliminate the binder and then sintering of the debounded part to acquire the required final properties [2,3]. The final metal parts produced by extrusion-based AM could require final finishing operation due to the shrinkage and defects caused by debinding and sintering operations [4,5] but geometry correction of the part could also be very effective in the greenstate because of the material hardness and because of part and features accessibility.

Micromilling can then be efficiently adopted on greenstate material in order to compensate geometrical inaccuracy of the layer deposition, to increase surface finish, or to obtain microfeatures (such as microcavities and microchannels) which cannot be obtain with the deposition process [5]. For example, some internal surfaces could be milled before becoming inaccessible because of the following material deposition. Previous micromilling studies by the authors [6] in hot-pressed AISI316L green feedstock showed that force generated during micromilling in green state is very less. Then, machining the feedstock in green state is easier and cost effective and gives better machinability because of low mechanical strength [7]. Integrity of the slot upper borders were influenced by cutting conditions and this accomplishes that right parameters and their level selection is very significant for the successful integration of micromilling into the process chain [6]. By studying machinability of feedstock components produced by extrusion-based AM at greenstate, this study extends what has been done by the authors in the previous study. Effect of workpiece temperature on green machining is studied exclusively in addition to the micromilling parameters such as cutting speed (vc), feed per tooth (fz), axial depth of cut (ap) and air supply.

2. Materials and method

2.1 Material

The feedstock material selected for experimental investigation is AISI316L with a polymeric binder (Embemould K83). AISI316L feedstock is produced in house with a percentage weight of 92.25% of metal particle based on our previous experimental study in ratio with polymeric binder and with average particle size lower than 16 µm with water soluble binder

2.2 3D printed specimen preparation

Greenstate workpieces used for experimental investigation were feedstock blocks produced by 3D printing using an Efesto prototype machine developed in house [8].

Fig 1. a) Strategy used for 3D printing, b) Workpiece produced by 3D printing in greenstate, c) 3D printed workpiece after face milling and side macromilling operations

A block was printed in the preheated worktable by depositing continuous layers of extruded wires one above other. The strategy used for the printing was that an extruded wire boundary to the designated shape and dimension is deposited first and then hatching wire shapes are deposited to fill the boundary (see Fig. 1a).

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Then, the samples were prepared with macromilling operations with a 6 mm tool, to generate regular surfaces for testing micromilling machinability (see Fig. 1b). Bigger irregularities produced due to the deposition process were then removed on the upper face and lateral faces (see Fig. 1c).

2.3 Experimentation

Micromilling experiments were conducted on the prepared green workpieces by milling micro slots of width 1 mm and length 5 mm by using GF Mikron HPM 450U CNC machining centre (see Fig. 2). Samples were fixed on a work base, attached to a triaxial piezoelectric dynamometer Kistler 9257B. Micro flat end mills, with tapered corners, 1 mm of diameter and 2 teeth, were used for slot milling operations (producer: Sandvik Coromant 1P220-0100-XA). The experimentation was aimed to find out the factors that influence micromilling of the green samples produced by extrusion additive manufacturing by the prototype machine. Micromilled slots were analysed for edge integrity and surface roughness using 3D microscopy (Alicona G4) and optical profilometry (Mitutoyo Quick Vision Pro) and acquired cutting force signals were analysed for each micromilling condition.

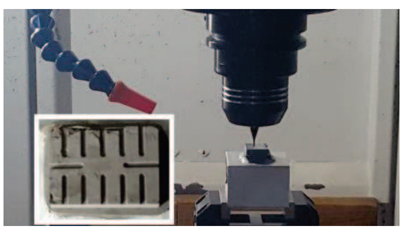

Fig 2. GF Mikron HPM 450U CNC machining centre and, in inset, 3D printed workpiece after slot milling operations

The measurement of machined micro slots provides very accurate indexes including the arithmetic mean height Sa, as indicator for quantitative roughness analysis. ANOVA analyses were then carried out to identify the influence of each parameter on the greenstate micromilling quality. The samples in each set of experiments were analysed using scanning electron microscope (SEM) to understand the effect of milling parameters in greenstate micromilling and to understand in depth the changes during debinding, pre-sintering and sintering operations.

Experiments were conducted in four sets on three workpieces which were prepared for experimental investigation. The experiments from set 1 to 3 were conducted on workpieces 1 and 2 by removing the milled surfaces after analysis, while workpiece 3 was used for understanding the effect of debinding and sintering on the micromilled extrusion 3D printed samples. Previous debinding and sintering studies of micromilled green feedstock samples had shown surface defects like cracks, air entrapments etc. The micromilling parameters and their levels are selected based on the previous micromilling studies by the authors in hot-pressed AISI316L green feedstock [6] and also based on some preliminary micromilling studies in AM samples. The positions of the slots were designed in the workpiece samples by keeping a gap of twice the width of cut between two successive slots to avoid any unwanted effects in neighbouring slot milling. In the first two experiments, the study of the influence of milling parameters such as vc, fz and ap and the effect of the refrigerated air supply (air at 5°C) on the micromilling of the 3D printed part when the workpiece was kept at 22.5°C in cold stage (room temperature) was carried out (fz=0.03 mm/tooth and ap=0.5 mm are set constant for first and second sets of experiments respectively). The third set of experiments was conducted by maintaining the workpiece at 45°C in hot stage (in order to mimic the temperature of the workpiece right after the 3D printing process). The study is expected to provide the essential information required for integrating micromilling to the extrusion-based AM process chain. A constant ap of 0.5 mm was selected for the third set of experiments. Air flow was given to the workpiece from a suitable distance not to disturb the heating plate effect and, at the same time, assuring the debris removal. Experiments were conducted in three repetitions in randomized order (see Table 1).

Table 1

Micromilling parameters and levels for experiments

Exp.	Parameter	Low	High
Set 1	Cutting speed (vc [m/min])	17.5	35
	Depth of cut (ap [mm])	0.25	0.5
Set 2	Feed per tooth (fz [mm/tooth])	0.015	0.03
	Air supply [°C]	Nil	5
Set 3	Cutting speed (vc [m/min])	17.5	35
	Feed per tooth (fz [mm/tooth])	0.015	0.03
	Air supply [°C]	Nil	22.5

The fourth set of experiments was conducted by cutting 12 slots (width 1 mm and depth 1 mm) in workpiece 3 which was at 22.5°C in cold stage by micromilling with a vc of 35 m/min, fz of 0.03 mm/tooth and ap of 0.5 mm. The sample was then debinded using water at 40°C followed by thermal debinding in H_2 atmosphere and finally pre-sintering at 680°C. This sample was sintered first in H_2 atmosphere and then in vacuum at a temperature of 1340°C.

3. Results and discussion

3.1 Part force analysis

The measured cutting force signals were acquired at a sampling frequency of 25000 Hz and compensated to filter out the pure dynamic behaviour of the sensor. The X-Y-Z components were added to get the estimation of the resultant force Fr, whose RMS value was computed using Matlab® and plotted using Minitab®. The influence of the tested cutting parameters during machining operations is analysed in terms of main and interaction effects (see Fig. 3). From the results we can see that the resultant forces remain below 2.5 N of RMS values. From the statistical perspective the ap and fz parameters show an effect (p-Value <0.05) on the force in a positive way (doubling these values means an increase of almost 40% of the force value). On the other side, the air and velocity did not affect forces significantly. This shows how green components machining generates low forces hence more desirable to work in this state than the finished state. There are no evident outliers as well. Interaction analysis shows no statistical evidence of interactions (p-Value >0.05) between the varying parameters.

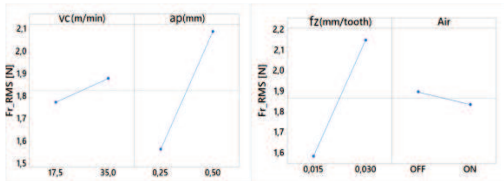

Fig 3. RMS of resultant force Fr: Main effect plot ((cutting speed vc and axial depth of cut ap, and feed per tooth fz, standard/refrigerated air)

Variation of the cutting forces with the workpiece temperature has been tested by heating up the sample at 45°C and testing the force variability in respect to ambient temperature (22.5°C). Rotational speed was 8360 rpm and ap=0.5mm. By looking at Fig.4, it is possible to see that hot conditions generate more force variability and stronger sensitivity of the forces with feed rates. However, force magnitude differences between hot and cold workpiece condition are very low.

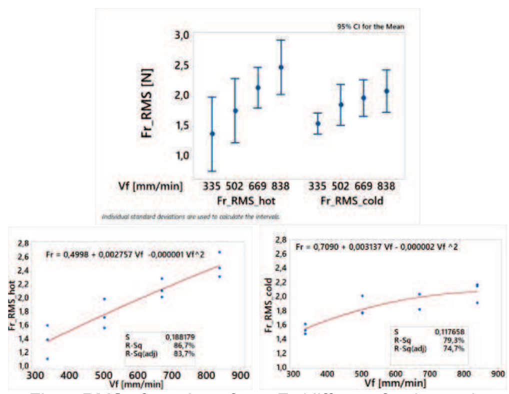

Fig 4. RMS of resultant force Fr (different feed rates in mm/min and workpiece temperature (22.5°C cold, 45°C hot)

3.2 Surface quality

The micromilling of workpieces produced by extrusion additive manufacturing showed a good machinability and thereby generally a good surface and edge quality. However, some macro defects such as large border breakage happens rarely in some cases. The reason for this large border breakage is attributed mainly to the lack of adhesion between the successive layers during 3D printing operation. Optimizing the 3D printing parameters may help to avoid this problem.

3.2.1 Surface quality of green samples

The roughness analysis of the milling experiment on workpieces at 22.5 °C temperature, slots of exp. set 1 gave a maximum value of roughness of 2.85 µm and minimum value of 1.46 µm while that of exp. set 2 gave a maximum and minimum values of 2.93 µm and 2.15 µm respectively, which were unexpectedly good values for the green state material (see Fig 5).

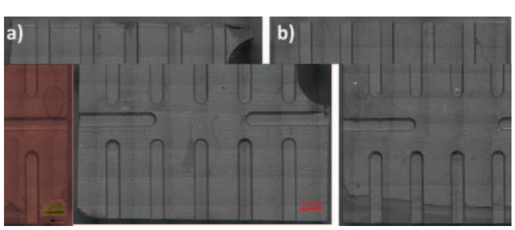

Fig 5. Mitutoyo images of exp. a) set 1 and b) set 2

However, the roughness values in both sets 1 and 2 varie only marginally with a variation of the different factors. Main effect plot showed only minor influence of fz, ap and effect of refrigerated air supply at 5°C except vc. The interaction plot denied the possible interaction between the factors. ANOVA and verification of the assumptions showed that there are neither significant factors nor the interaction which influences the surface roughness for the selected ranges and levels (p-Value <0.05).

An analysis with wider spread levels may need to be performed to understand the significance of parameter variations in case of greenstate micromilling of 3D printed workpiece at room temperature.

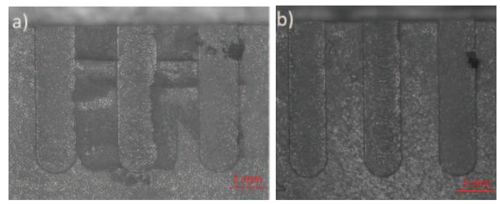

Fig 6. Mitutoyo images of slots of exp. set 3 a) exp. without air supply and b) exp. with air supply

The micromilling of the first stage of exp. set 3, without an air supply for chip removal resulted in material remachining and difficult debris evacuation from the cutting zone. Top burr formation, augmented border breakages, and debris attachments to the slot boundary (see Fig. 6a) were evidenced after cutting. This is probably caused by the augmented adhesion effect of the polymeric binder at the higher temperature. The milling experiments in the second stage of exp. set 3 were conducted with a supply of pressurized air at ambient temperature from a far distance (300 mm) in order to increase the debris removal. This condition resulted in a good surface finish (see Fig. 6b) and reduced the overall defects.

The roughness analysis of the milling experiment conducted on cold workpieces showed poorer surface quality than the hot one. Roughness was measured at entry, middle and exit of the slots (see Fig. 7). The main effect plot shows that roughness values are lower for the lower levels of vc and fz. The roughness value doesn't change significantly along the slots. fz seems to be the most significant factor (p-value<0.05) in this case.

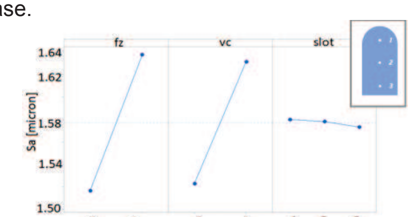

Fig 7. Main effect plot of Sa surface roughness: (fz, vc and measuring slot position)

The roughness analysis of micromilling experiments for workpiece at cold (22.5°C) and hot state (45°C) showed a decrease in roughness value with respect to increase of workpiece temperature (see Fig. 8). This attribute is probably given to the softening of the binder content at high temperature which could have supported the generation of better surface quality. This aspect will receive attention in further studies.

Fig 8. Box plots comparison of roughness analysis for milling exp. on workpiece at hot (45 °C) and cold (22.5°C) state

3.2.2 Surface quality of green, brown and sintered samples

The debinded and sintered workpiece surfaces showed nice surface quality without any cracks or air entrapment defects. The roughness analysis of the green, brown and sintered samples showed gradual increase in the mean value of roughness (see Fig. 9). The increase of roughness is caused by the binder removal by debinding and pre-sintering and the generation of voids. The sintering operation causes the diffusion of atoms and forms bonds between the metal particle by reducing the porosity inside the material (see Fig. 10).

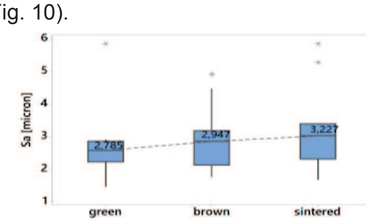

Fig 9. Interval plot and box plot comparison of roughness analysis for green, brown and sintered states

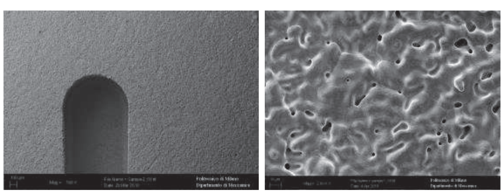

Fig 10. The SEM image of the workpiece in brown state (left) micro structure showing porosity reduction by sintering (right)

3.3 Defects and specific features on surfaces produced by micromilling

Micromilling experiments in green feedstock workpieces produced by extrusion 3D printing generally milled slots with good edge integrity and surface quality. Some of the defects observed are breakage of the edges, marks formed by milling cutter, chamfer formation and burr attachment to the edges of the milled slots (see Fig. 11).

The micromilling operations seemed to produce breakage of the slot edges. The soft nature of the feedstock in green state accounts for this problem. Feedstock with an increased binder percentage may able to solve this defect by improving the adhesion between the metal particles.

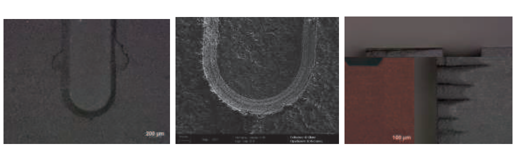

Fig 11. SEM Image of breakage of the slot edges (first) mark of cutting teeth of the micro mill on the slots (second) and cross sectional view showing chamfer formation (third)

Another feature observed during micromilling of feedstock is the left mark of cutting teeth marks of left by the micro mill, as observed in the Fig. 11. A chamfer shaped material left also can be observed at the bottom corners of the slots from the cross sectional view of the slots. The layers formed by 3D printing and surface after side milling also can be observed from the cross sectional view. The side milled surface didn't show any porosity, which means that successive layers in 3d printing were fused together in a nice manner.

4. Conclusions

Force analysis confirmed what was found on hot pressed material milling, i.e. that generated forces during greenstate micromilling of extrusion 3D printed parts is very low. Milling parameters ap and fz displayed to be the significant parameters on the force in a directly proportional way. Lower levels of ap and fz values are observed to be suitable for low force generation.

The micromilling of hot workpiece with an air supply for chip removal purposes showed the best surface quality with least surface roughness. fz seemed to be the most significant milling parameter and the lower values of fz and vc were found to be apt for the greenstate micromilling.

This micromilling study on extrusion additive manufactured samples proposed that micromilling is a suitable method to use in-line in combination with 3D printing.

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