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Cutting forces analysis in additive manufactured AISI H13 alloy

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Abstract

Combining Additive Manufacturing (AM) and traditional machining processes is essential to meet components functional requirements. However significant differences arise in machining AM and wrought parts. Previous works highlighted the increasing of tool wear and worse surface finish. In this paper cutting forces are investigated as an indicator of material machinability. Milling cutting force coefficients are identified using mechanistic approach, comparing AISI-H13 wrought and AM specimen. Cutting force behaviour was investigated for two AM technologies: laser deposition (LENS) and wire-arc additive manufacturing (WAAM). Results show a general increase of cutting forces and coefficients of both AM materials, suggesting AM parts reduced machinability. Therefore, different cutting parameters should be selected for the AM material to achieve a sustainable production.

Keywords: Machinability; Milling; Cutting; Force; Additive Manufacturing.

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1. Introduction

Additive Manufacturing (AM) technologies for the production of metal components represent one of the most relevant innovation in the manufacturing sector. Nevertheless, AM parts usually require post-process machining operations to achieve functional requirements in terms of dimensional accuracy and surface finish [1]. Therefore, assessing the machinability of AM materials is a crucial topic. Since there is not a unique indicator to define the material machinability [2], the following three aspects are usually analyzed: tool life, surface integrity and cutting forces [3]. In literature few works deal with AM materials machinability: Bordin et al. [4] compared tool life and surface integrity in turning wrought and Electron-Beam-Melting (EBM) CrCoMo alloy, highlighting an increase of tool wear and the arise of surface craters in the AM material. In a subsequent work, Bordin et al [5] compared the dry and cryogenic cutting strategies in turning operation of Ti6AlV4 alloy, analyzing wear mechanisms, tool life and surface integrity.

Previous works investigated AM material machinability for what concerns tool life and surface integrity aspects, but no analysis was carried out about the cutting forces. Indeed, this is a relevant parameter in evaluating material machinability, especially in milling operations: higher specific cutting forces (i.e., cutting coefficients) can lead to a reduced stability limit [6] and increased vibration amplitude [7] especially when flexible tooling or parts are used [8].

In this work, machinability of AM and wrought material is compared analyzing cutting forces in peripheral milling operations. The analysis was carried out for two different AM technologies:

- Laser-Engineered-Net-Shaping (LENS);
- Wire-Arc-Additive-Manufacturing (WAAM).

Both technologies are direct energy deposition processes, but using different raw material type and power sources. In

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particular, LENS is a powder-based process, using a laser power source while WAAM is a wire-based technology and process heat is provided by an electric arc [9].

The analyzed material was AISI H13, a low alloy steel usually adopted in dies and molds manufacturing, that is one of the main application of AM technologies [1].

Milling tests were carried out on wrought, LENS and WAAM specimens measuring the cutting forces with a table dynamometer. Measured cutting forces were used to compute cutting force coefficients as defined in Altintas et al. [10] mechanistic cutting force model. This step allowed having an indicator of cutting forces independent from the adopted cutting parameters.

2. Adopted Procedure

The objective of this work is providing a comparison between cutting forces in milling AM and wrought AISI H13 steel. In this section the testing procedure steps will be presented.

Before carrying out the milling tests, specimen hardness was measured in order to acquire preliminary information about the material. After this pre-test step, cutting parameters were selected according to tool manufacturer recommendations, as presented in sub-section 2.3. Finally, cutting tests were carried out measuring cutting forces and cutting coefficients were identified according to the mechanistic technique.

2.1. Experimental set-up

LENS specimen was manufactured using an OPTOMEC 850 R machine. WAAM specimen was manufactured in Tokyo University of Agriculture and Technology (TUAT) using a Daihen gas metal arc welding unit attached to a tailor-made four axis machine tool. AM and wrought specimens are shown in Fig. 1. Cutting tests on wrought and LENS samples were carried out using a DMG Mori NMV1500DCG vertical milling center in the University of Firenze laboratory. WAAM specimen was machined using a MAZAK VCN-410A vertical milling center in the TUAT.

2.2. Cutting force measurement

For both machines, cutting forces were used using a Kistler 9257 B three axial table dynamometer.

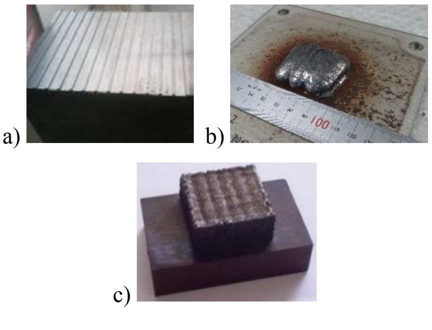

Fig. 1: Wrought (a), WAAM (b) and LENS (c) material specimens

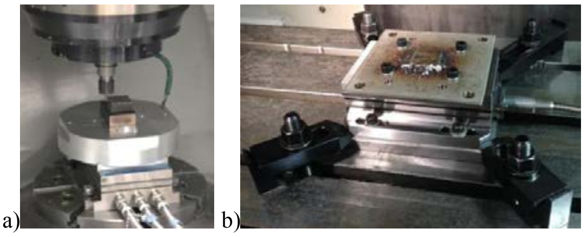

Fig. 2: LENS (a) and WAAM (b) specimen test set-up.

Cutting tests were carried out using a 4mm diameter Taegutech (HSF 2040 060 100) solid carbide end mill (sharp edge). The selected end mill is suitable for finishing operations on pre-hardened and hardened steel. Furthermore, tool has sharp edge, simplifying the cutting coefficients identification procedure [11]. Cutting tool and machines set-up conditions are shown in Fig. 2.

2.3. Hardness test

As mentioned earlier, before carrying out the cutting tests material hardness was measured for all the specimens. Rockwell testing (Type C) was selected using a 30 kg load. Results are presented in Table 1.

Table 1: Rockwell C hardness measuring results.

	Wrought	LENS	WAAM
HRC	19	59	55

Hardness testing highlight that both AM materials experience a significant increase in material hardness. The supplied powder or wire metal is melted and then solidified in both AM processes. In this process martensitic transformation is caused by rapid temperature decrease, then the hardness increases, as presented in previous works [12]. Based on such results, an increase of cutting forces is expected on the wrought material with respect to the wrought one.

2.4. Cutting coefficients identification procedure

Cutting force model proposed in [10] was used for the evaluation of cutting forces coefficients. This model computes the force components (tangential, radial and axial) by means of six coefficients as expressed in eq. 1, where db is chip width, dl is the engaged cutting edge length and t_n the chip thickness for an infinitesimal section of the chip.

$$\begin{aligned} dF_t &= K_{tc} t_n db + K_{te} dl \\ dF_r &= K_{rc} t_n db + K_{re} dl \\ dF_a &= K_{ac} t_n db + K_{ae} dl \end{aligned} \tag{1}$$

Cutting force coefficients were computed according to the mechanistic identification procedure, used by authors in [11]. In such a technique a series of peripheral milling tests must be carried out at different feed per tooth but with fixed depth of cut, radial engagement and cutting speed. Cutting forces are measured in X, Y and Z directions. Force time series are then post-processed to identify average forces per cutter revolution. According to the cutting force model described in eq.1, a linear relation exists between average cutting forces and feed per tooth. Therefore, performing a linear regression of average forces, cutting coefficients can be computed from linear regression coefficients. One of the main advantages in using average forces instead of instantaneous values is that mean value is not affected by errors induced by dynamometer and machine tool vibration [13].

In this work only radial and tangential coefficients are presented, since these are the most significant one in determining tool vibration [14]. In order to pursue the presented identification procedure, six different feed per tooth values were used for the cutting tests, as presented in Table 2. Usually such tests are performed in slotting, since cutting coefficients identification from linear regression data is simplified in this condition. Preliminary slotting tests were carried out in order to assess the feasibility of such approach on AM materials. Despite the fact that wrought material could be easily milled in this condition, remarkable effects of high cutting temperature were observed on the AM material, as shown in Fig. 3. This caused detrimental effects both on surface quality and on tool integrity. Indeed this aspect is particularly relevant to identify reliable cutting coefficients values: since such parameters are dependent on tool rake angles, excessive tool wear could affect the identification procedure. After the pre-test, a side milling condition was chosen over the slotting one, adopting radial engagement recommended by tool manufacturer, presented in Table 2.

Table 2: Tests cutting parameters

Feed per tooth [mm]					
0.05	0.07	0.09	0.11	0.13	0.15
Radial depth of cut [mm]	0.8				
Axial depth of cut [mm]	0.5				
Cutting velocity [m/min]	120				

All tests were carried out in down milling condition without any type of lubrication.

3. Results

In this section, cutting tests outcomes are presented. Two main results are given: average cutting forces and cutting coefficients.

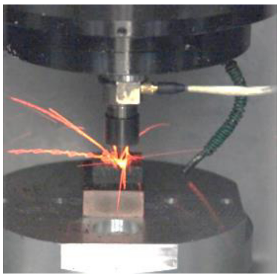

Fig. 3: Hot chip during LENS specimen slot milling.

In order to improve the robustness of the input data for cutting coefficient identification, all cutting tests were repeated twice. Average force values extracted from the tests at the same feed per tooth were then averaged, reducing the effect of casual errors, such as measurement noise. Therefore, average forces presented in this section are not related to a single test but are averaged as described above.

Average forces are given in the feed direction and in the normal direction (perpendicular to feed and tool axis directions): Fig. 4 and Fig. 5 show the comparison between average values of AM and wrought cutting forces (on both directions). Despite cutting tests were carried out for six different feed per tooth values, just the three lower values are presented. This was due to an issue concerning cutting tests on WAAM material: average forces concerning higher feed experienced a significant deviation from the regression line. Actually on larger feed per tooth value on WAAM material, remarkable tool vibrations were observed and the finished. This was compliant with a bad surface finish. Therefore, for wrought and LENS material the data form six tests were used to carry out cutting coefficients computation, while for WAAM material just the three values were used.

Results concerning cutting coefficients are presented in Table 3: radial and tangential constants values are compared between the three different specimens. Such comparison will be discussed in the following subsections.

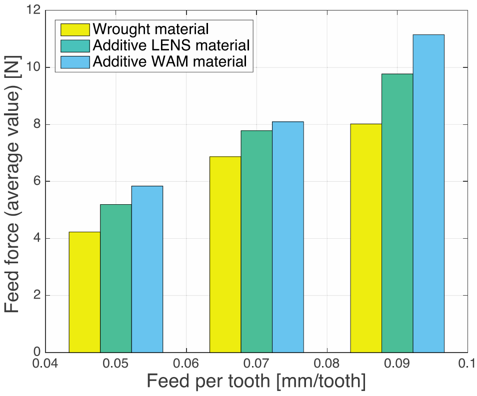

Fig. 4: Comparison of average feed force values for the different materials.

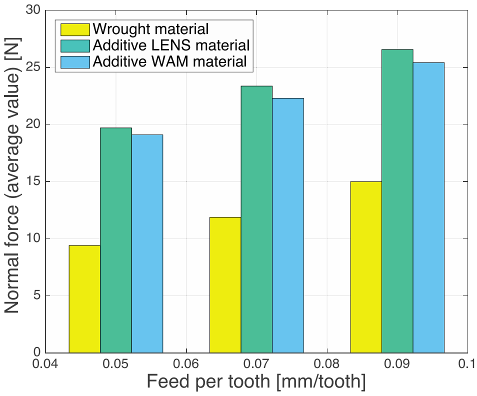

Fig. 5: Comparison of average normal force values for the different materials.

3.1. LENS material

As expected from hardness testing, cutting force values are significantly higher in LENS material. Both average forces and cutting coefficients values confirm this pattern. Indeed, as shown in Table 3, LENS material tangential cutting coefficient is about 10% higher than the wrought material one. Such difference increases to 30% for the radial cutting coefficient.

3.2. WAAM material

Cutting forces and coefficients observed on WAAM material are compliant with the LENS ones. A general increase of both average cutting forces and cutting coefficients was observed. As shown in Table 3, tangential cutting coefficients turned out to be higher on WAAM material than in the LENS one. On the other hand, the trend is opposite for the radial coefficient, higher on the LENS material.

Table 3: Cutting coefficients identification results.

Specimen	**K_{tc} [MPa]**	**K_{rc} [MPa]**	**K_{te} [N/mm]**	**K_{re} [N/mm]**
Wrought	2424	808	8	20
LENS	2721	1077	42	76
WAAM	2848	1007	40	71

4. Conclusion

In this work cutting forces in milling of additive manufactured AISI H13 steel were analyzed and compared to the standard wrought material. Proposed comparison was carried out on two different AM technologies: LENS and WAAM. Cutting coefficients, defined in Altintas et al. [10] model, were used as indicator of cutting forces independent on chip cross section. Hardness measurements outlined that both AM technologies produced materials having higher HRC values than the wrought one. Such difference turned out to be compliant with the cutting force values: cutting coefficients on both AM materials are significantly higher than the ones of wrought material.

In conclusion, this work highlights that AISI H13 AM material are harder to be machined, compared to the same material at wrought state. Indeed, results show a significant increase of cutting forces and cutting force coefficients. A specific definition of cutting parameters for milling operation of AM parts is hence required to effectively machine such materials.

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