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Machining of Additive Manufactured Metal Alloys

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Abstract. Additive Manufacturing of metal alloys offers unique advantages for producing net-shape components of complex geometries with very little waste of material. Nevertheless, machining operations may be needed on functional surfaces to get the required surface finish and geometrical tolerances. This poses challenging issues since the microstructural features characterizing the AM alloys are drastically different from those of the wrought alloys of the same chemical composition, which, in turn, may affect the mechanical and machining response to a great extent. This paper shows that both the machined surface integrity and tool wear are greatly affected by the microstructural features induced by the previous AM process as well as by the build-up orientation.

Introduction

Additive Manufacturing (AM) processes of metal alloys, introduced first in the nineties, have gained more and more popularity within the manufacturing industry community thanks to the advantages they offer over conventional subtractive processes [1]. Complex-shaped parts with negligible material waste can be fabricated, which are exploited especially in added-value sectors, like the aerospace and biomedical ones. When processing metal alloys, Powder Bed Fusion (PBF) and Direct Energy Deposition (DED) processes are the most employed according to the ASTM F2792-12A [2] classification: the former uses either a laser or an electron beam to melt the metal powders on the powder bed to fabricate a dense part layer-by-layer, while the latter uses a laser beam to melt the metal powders but on a metal substrate surface. DED processes can be used to fabricate dense parts as well as to repair or modify the surface of existing ones.

Regardless of the approach used to fabricate them, as-built AM metal parts usually show very rough surfaces, with values of average roughness even up to 50 μm, as well as low geometrical tolerances. This can be ascribed to various factors, especially the layer-by-layer nature of the process, namely the smallest built element, which affects the part resolution and is influenced by the deposition parameters and the characteristics of the feedstock material, the defects that can arise as a consequence of the material deposition and fusion, like partially fused powders, balling effect,... In both PBF and DED, the part resolution is given by the melt-pool geometry, which, in turn, depends on the laser power, scanning velocity, hatch spacing, and layer thickness. In DED, the feedstock material delivery defines the process resolution. Besides them, also the design of the part to be fabricated can play a role, such as its orientation with respect to the building direction. Nonetheless, regardless of the source of the geometrical inaccuracies, in order to meet the required design criteria in terms of surface finish and geometrical tolerances on functional surfaces and/or guarantee those specific characteristics that are affected by the surface finish, such as corrosion, wear and fatigue resistances, subtractive post-processing operations may become mandatory on AM parts.

As AM processes are able to assure the fabrication of near-net-shape parts, subtractive operations to be carried out on these parts can be classified as finishing ones, and their typology primarily depends on the geometrical complexity of the surface to be finished. Conventional machining operations with either a tool of defined geometry or abrasive grains of undefined geometry are the most widespread to finish AM parts, even if they may not be suitable for finishing hidden zones, enclosed features, very small corners, or lattice structures. Finishing operations on AM metal parts are also classified on the basis of the mechanisms employed to remove material, namely: (i) mechanical processes, i.e. machining and grinding; (ii) thermal processes, i.e. laser and electron beam melting; (iii) chemical and electrochemical processes, i.e. etching and electropolishing.

For the sake of clarity and brevity, the present paper restricts its survey to the most interesting features of post-AM conventional machining processes that make use of cutting tools with a defined geometry. In this framework, one of the key issues is related to the different response an AM metal can show when subjected to machining operations compared to the one exhibited by the wrought metal of the same nominal chemical composition. This is the consequence of the complex thermal evolution experienced by the metal during AM, which produces microstructural features, and thus mechanical characteristics, which can substantially vary from those of conventionally fabricated metals. This can lead to a very different machining response in terms of cutting forces and power consumption, tool wear, chip morphology, surface finish and integrity. The evaluation of the latter is also mandatory when the in-service characteristics of the AM part are to be identified. Titanium alloys (Ti6Al4V in particular), nickel-base alloys, cobalt alloys, tool steels, and titanium aluminides are the most investigated between the metal alloys fabricated through AM processes. Among conventional machining operations making use of cutting tools with defined geometry, turning is the most investigated, followed by milling and, less often, drilling.

The paper is subdivided into three chapters, where the main issues about machinability, correlation between machinability and part in-service characteristics, modelling and control of machining processes applied to AM metals are briefly discussed.

Machinability

Most of AM metal alloys are classified as difficult-to-cut alloys, therefore literature studies dealing with their machinability are mainly devoted to the evaluation of: (i) the influence of both the AM and cutting parameters on the cutting process performances, and (ii) the comparison between the performances of the AM and wrought alloys of same chemical composition. Given that the parameters of the AM process are usually optimized in studies that prescind from the machining step of the process chain, cutting parameters like cutting speed, feed, and lubrication strategy are usually varied and their effect investigated, showing that a proper choice of these can substantially enhance the AM alloy machinability. Generally speaking, the complex thermal phenomena to which an alloy is subjected during AM induce microstructural features that contribute to lower its machinability in the as-built condition compared to the one of the alloy conventionally fabricated with the same chemical composition. Nevertheless, suitable heat treatments after AM, capable to generate microstructural features similar to those of the wrought alloy, can help in even improving their machinability compared to the wrought alloy.

Ti6Al4V is one of the most investigated AM alloys in terms of machinability, being significantly exploited especially in the biomedical and aerospace sectors. Selective Laser Melted (SLM) and Electron Beam Melted (EBM) Ti6Al4V samples were finish turned in [3] and the developed tool wear was evaluated at the rake and flank tool faces: it was proved that the different response exhibited by the AM alloys in comparison with the one of the wrought Ti6Al4V could be due to the different thermal and mechanical behaviour of the investigated alloys as a consequence of their peculiar microstructural features. In [4] a novel strategy was applied to increase the tool life when cutting EBM Ti6Al4V. Samples of EBM Ti6Al4V were subjected to cryogenic cooling during turning with the twofold objective of providing a clean environment to machine biomedical components and reduce the tool wear: it was proved that cryogenic cooling could prevent the formation of the crater wear even when the most severe cutting parameters were applied.

SLM Ti6Al4V samples fabricated horizontally and vertically with respect to the building direction were end milled in [5], showing that the tool life decreased of 40% when machining the horizontally fabricated samples. This study proved the significant effect of the build-up orientation as a consequence of the different orientation angles of the alloy microstructural features with respect to the tool registration angle (see the cutting mechanisms on the left of Fig. 1). A follow-up of this study in [6] showed the effect of the AM-induced anisotropy also on the machined surface integrity, proving that samples fabricated with horizontal orientation allowed for better machinability (see for example the results about the burr height on the right of Fig. 1).

Not only PBF processes are of interest for Ti6Al4V applications, but also DED ones can be exploited, as in [7], where finish turning was carried out on Ti6Al4V samples fabricated through DED using wire feedstocks, showing that inhomogeneities or porosities had a deleterious effect on the machined surface integrity.

Besides Ti6Al4V, other AM titanium alloys are gaining attention, as is the near β alloy Ti-5553 more suitable for high load aerospace applications: the SLM Ti-5553 was proved to behave differently from the wrought metal, but it was stated that the choice of a proper heat treatment can lead to a significant improvement [8]. A gamma titanium aluminide fabricated through EBM was milled in [9] using different cutting conditions, showing that the improvement of its machinability could be obtained thanks to a proper adjustment of the cutting edge geometry. The same material was subjected to drilling in [10] stating a significant influence of the tool wear and surface integrity on the chosen cutting parameters, but with very reduced tool life compared to other similar materials.

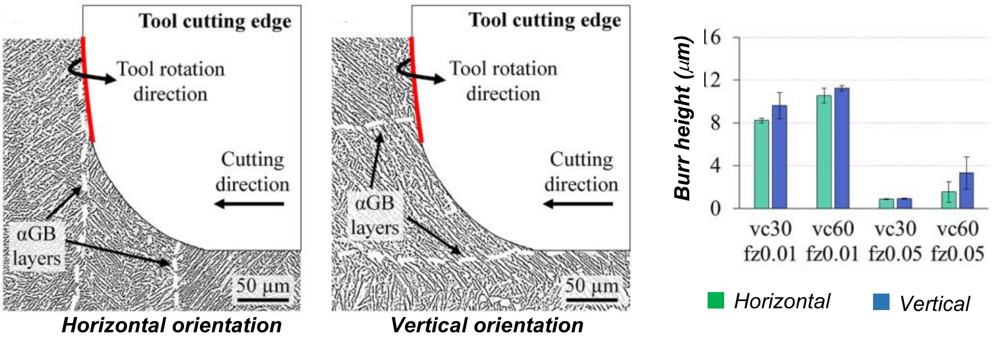


Fig. 1. Cutting mechanisms when milling horizontally and vertically oriented samples (left), and burr height as a function of the sample orientation (right) (adapted from [6]).

The machinability of nickel-based superalloys after AM has been also extensively studied in recent years, especially as regards Inconel 718. In general, the tool wear when machining AM Inconel 718 is lower than in case of machining the wrought alloy, but still depending on the sample orientation with respect to the building direction. In [11] the SLM Inconel 718 was found to have comparable machinability of the cast and wrought alloy if subjected to heat treatments capable to guarantee the same mechanical properties of the conventionally fabricated alloy and when using emulsion during milling. The role of a proper heat treatment after AM for DED Inconel 718 was also pointed out in [12], where the AM machinability after heat treatment was found to be comparable with the one of the conventionally fabricated alloy.

The machinability of SLM Inconel 718 during micromilling operations was investigated in [13] showing that the AM alloy was more difficult to machine than the conventionally fabricated one, and that the surface finish was strongly affected by AM-inherent defects, like slags and pores, which limited the effectiveness of the finishing operation. Anyway, it must be pointed out that no heat treatments were carried out on the as-built samples, witnessing that the actual machinability of the AM nickel-base alloys can be strongly affected by a post-AM heat treatment.

The degree of anisotropy induced by laser-PBF on samples of CoCrMo alloy was evaluated during slot milling in [14]: it was found that the machining force response was strongly influenced by the mechanical anisotropy of the as-built material, which, in turn, was proved to be driven by its microstructural morphology and crystallographic texture.

Tool steel inserts fabricated through AM can be used to customize dies and molds, especially for injection molding and die casting processes. In [15] a SLM and heat-treated maraging steel was milled showing that both an increased surface integrity and reduced tool wear could be obtained if the process chain parameters were properly chosen, in particular the typology of the post-AM heat treatment. In [16] layers of AISI H13 tool steel were laser cladded on a C45 substrate and their machinability during milling evaluated. Even if a reduced number of layers was shown to lead to a better quality of the claddings, their machinability was negatively affected since the higher the number of the layers the higher the cutting forces and the worse the surface integrity (see Figure 2).

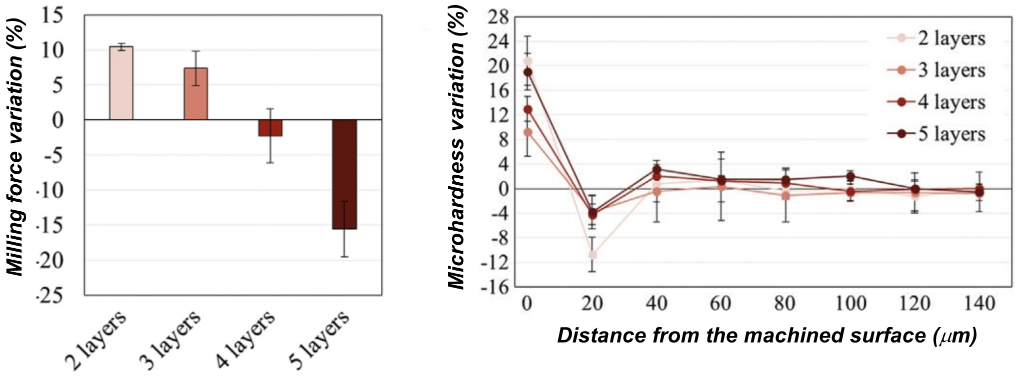


Fig. 2. Cutting force (left), and microhardness (right) when milling laser-cladded H13 layers on a C45 substrate (adapted from [16]).

Besides a proper choice of the cutting parameters, the enhancement of machinability can be fulfilled using alternative approaches to conventional cutting strategies. An example was proposed in [17], where an innovative system of high-frequency vibrations called Vibration-Assisted Drilling (VAD) was implemented in drilling Ti6Al4V samples fabricated via Laser Powder Bed Fusion (LPBF). The scheme of the process is shown in Figure 3 on the left. Tool wear was evaluated at increasing number of drilled holes and related to the hole quality. The comparison with Conventional Drilling (CD) showed that VAD not only was able to significantly reduce the tool wear compared to conventional drilling (see Figure 3 on the right), but also to improve the overall hole quality.

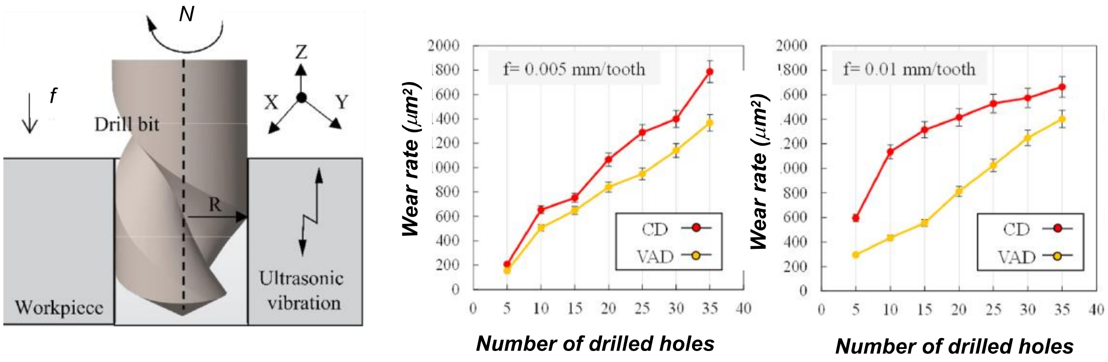


Fig. 3. Scheme of the VAD system (left), and tool wear area at varying feed and drilling strategy (right) (adapted from [17]).

Correlation between Machinability and Part In-Service Performances

The AM and subsequent machining steps of the process chain may significantly influence the part in-service performances, especially as regards fatigue and tribological characteristics.

In [18] the fatigue strength of SLM Ti6Al4V samples was evaluated in the as-built condition and after finishing machining operations, and compared with the one of conventionally fabricated Ti6Al4V samples. The AM samples showed half the fatigue resistance of the wrought ones, and none of the different machining processes that were employed were able to assure a comparable fatigue resistance (see Figure 4 on the left where the fatigue strength is reported as a function of the skewness parameter Ssk that is usually considered indicative of the functionality of a surface in terms of fatigue).

In [19], Ti6Al4V samples were fabricated through laser beam melting, annealed, hot isostatically pressed, and finally subjected to four different finishing machining methods, namely milling, blasting, vibratory grinding, and micro-machining. Even if milling was found to achieve excellent results in terms of fatigue life (see Figure 4 on the right), no direct correlation between specific roughness values and fatigue life was found.

The wear resistance of wrought and EBM Ti6Al4V cylinders after dry and cryogenic turning was investigated in [20] in reciprocating sliding motion on wrought CoCrMo plates during in-vitro wear testing using a cylinder-on-plate configuration. It was proved that the adoption of cryogenic cooling conditions during machining allowed obtaining the same wear response regardless of the Ti6Al4V as-received condition. This was due to the fact that cryogenic cooling assured a higher degree of adhesive wear rather than abrasive wear on the machined cylinders compared to dry turning (see Figure 5 where the weight increase is indicative of adhesive wear). This can limit the formation of wear debris, which are known to adversely affect the service life of biomedical components.

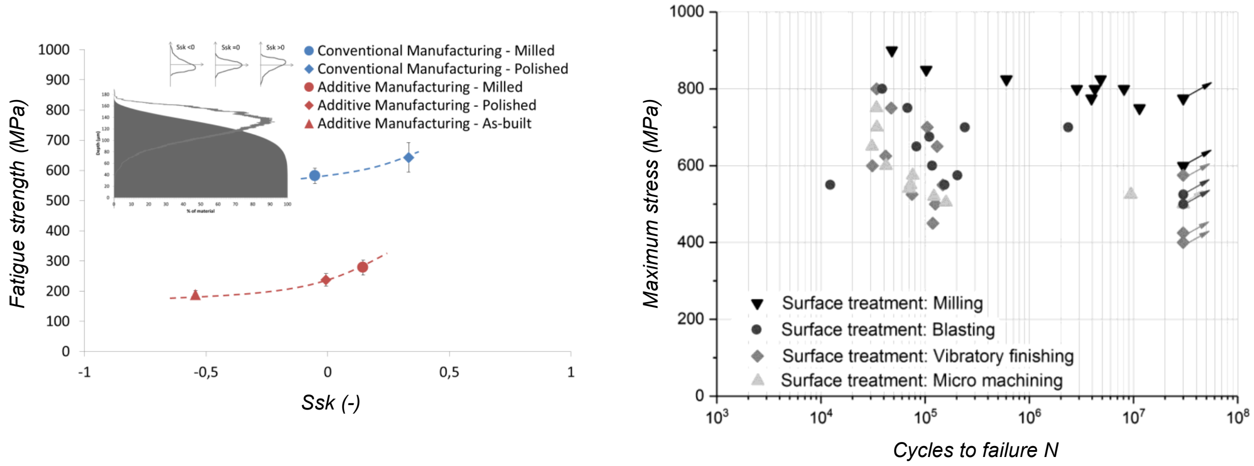


Fig. 4. Fatigue strength of AM Ti6Al4V samples finished through different post-processing operations (adapted from [18] left, and [19] right).

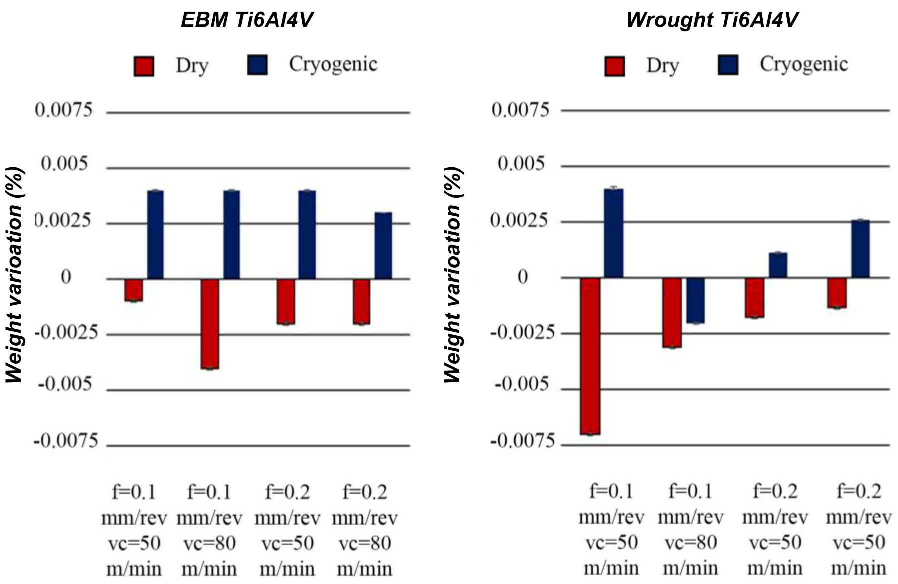


Fig. 5. Weight variation of wrought and EBM Ti6Al4V cylinders after in-vitro wear testing at varying cutting strategy (adapted from [20]).

Modelling and control of post-AM machining

For an accurate numerical simulation of machining operations on AM metals, the modelling of the peculiar microstructural features characterizing the AM metal itself is strictly mandatory. In [21] a 3D Finite Element-based model was developed to predict the surface integrity of the EBM Ti6Al4V after dry and cryogenic machining: to do that, the thickness of the alpha lamellae that characterize the microstructure of the AM metal was predicted by means of an empirical model calibrated through experimental data. It was found a good agreement between the experimental and numerical nanohardness, alpha lamellae strain and thickness, proving the model suitability to catch the AM metal peculiar behaviour during cutting (see Figure 6).

For a proper numerical modelling, the anisotropic characteristics of the AM metal must be also taken into account, as was done in [22] where orthogonal cutting experiments, carried out on SLM AlSi10Mg aluminum alloy samples, were simulated using the Hill 1948 anisotropy model. It was found that the cutting direction with respect to the building direction mostly influenced the chip geometry and chip segmentation behavior, being the largest effect in case of 45°samples. This was ascribed to the fact that the resulting microstructure of these samples aligned along the cutting direction.

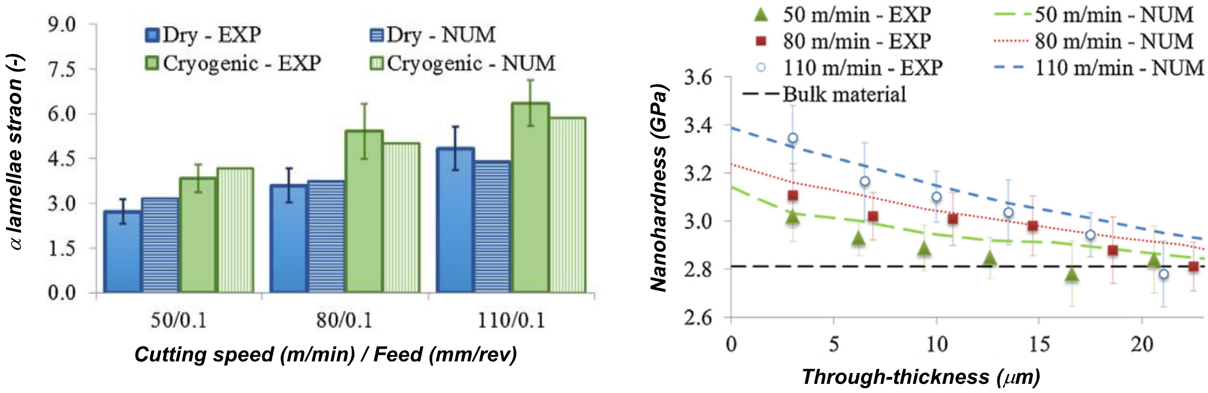
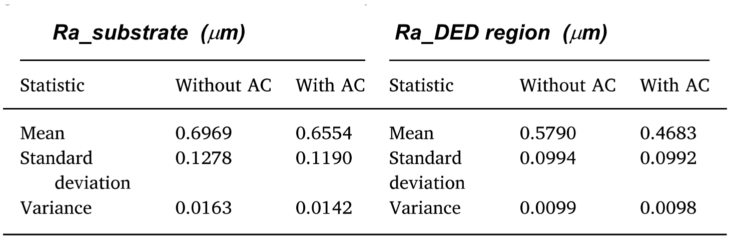


Fig. 6. Comparison between experimental and numerical outcomes when simulating turning of EBM Ti6Al4V: α-lamellae strain (left), and nanohardness under cryogenic cooling (right) (adapted from [22]).

The intrinsic anisotropy of a AM metal inevitably leads to variations in its machinability and, therefore, in the machining process outcomes. In [23] an adaptive control machining system was developed to address the microstructural alterations due to the AM-induced anisotropy on DED Ti6Al4V samples. The system was applied to both milling and drilling operations, proving that it was capable to reduce the onset and development of chatter marks on the machined surface as well as reduce the subsurface deformation. As example, the table in Figure 7 reports the values of the average roughness of both the substrate and DED region with and without the adaptive control, showing a sensible improvement of the surface finish thanks to the adaptive control.



Ra_substrate (μm)			***Ra_DED region (μm)***		
Statistic	Without AC	With AC	Statistic	Without AC	With AC
Mean	0.6969	0.6554	Mean	0.5790	0.4683
Standard deviation	0.1278	0.1190	Standard deviation	0.0994	0.0992
Variance	0.0163	0.0142	Variance	0.0099	0.0098

Fig. 7. Surface roughness improvement thanks to the application of an adaptive control machining system (adapted from [23]).

On the machine tool market, machines comprising the features of AM and machining processes are already present and emerging more and more. These machines can provide significant opportunities in the design and manufacture of finished parts, since they have the ability to both add and subtract material during the fabrication of the part, thus helping in addressing geometrical features, such as internal and overhanging features, which could not be made in the two separate steps. Furthermore, the material waste is further decreased as is the cutting tool consumption. A general architecture presented in [24] is shown on the left of Figure 8, while the right side of the same figure indicates the possible process interactions, given that the system may use an open- or a close-loop control. In case of close-loop control, metrology and sensing devices are mandatory.

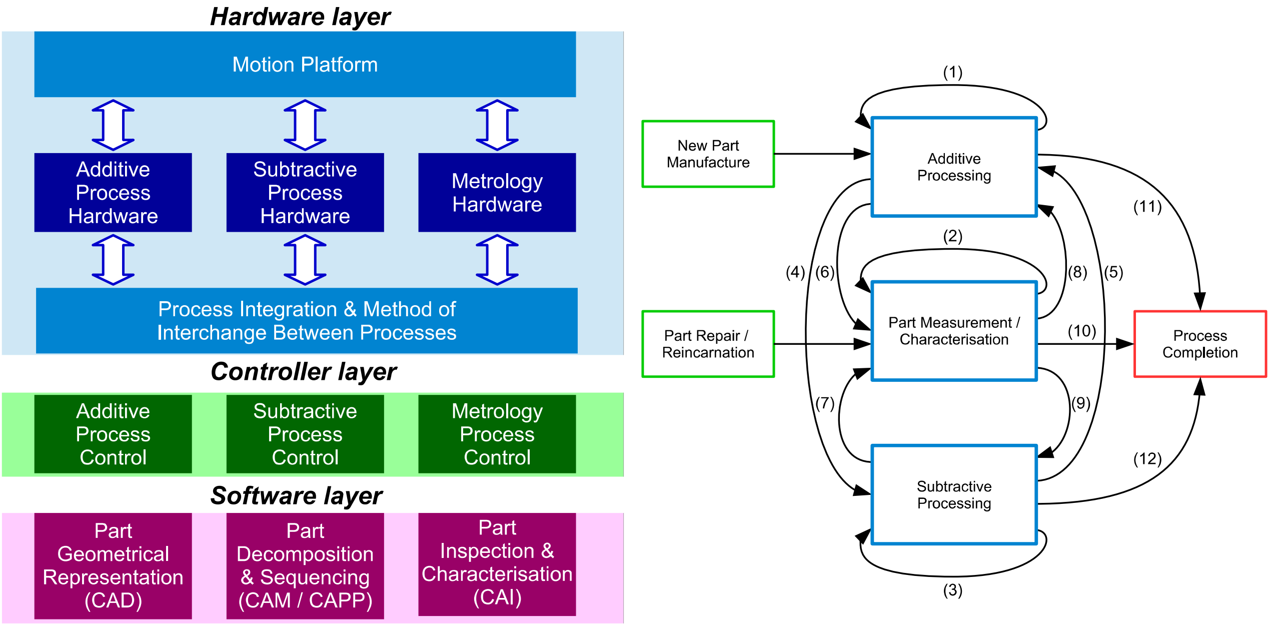


Fig. 8. General architecture of hybrid machine tools (left), and process interactions between the different components of a hybrid machine tool using open- and close-loop control (adapted from [24]).

The concept of hybridization between AM and machining was exploited in [25] where layers of Ti6Al4V were deposited through Laser Metal Deposition on substrates of the same material that were previously additive manufactured and then milled using dry, flood and cryogenic cooling with carbon dioxide. Cryogenic milling allowed for a better deposition thanks to the attainment of clean machined surfaces without organic residues that provide good metallurgical bonding with the subsequent deposits. Figure 9 shows the flow chart of the developed experimental procedure.

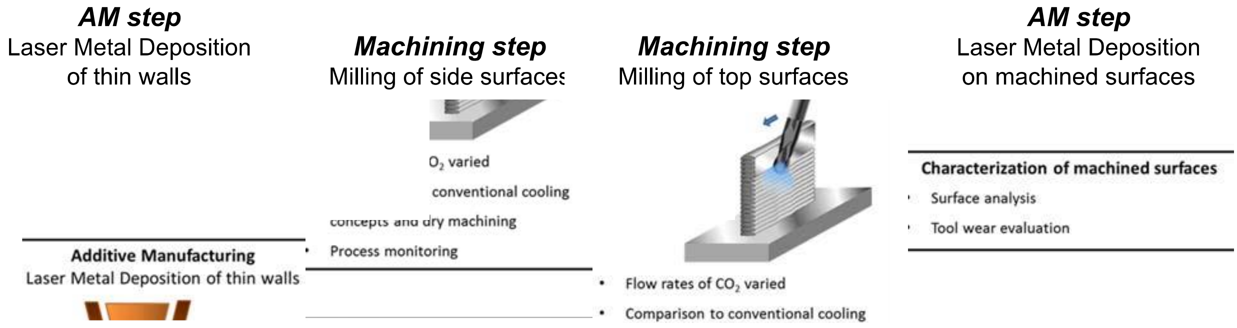


Fig. 9. Procedure of the hybrid process in developed in [25].

Summary and Perspectives

The paper has presented a brief overview of the main issues related to machining of AM metal alloys in terms of machinability, correlation with the part in-service characteristics, and modelling and control approaches. The following main conclusions can be drawn:

- Machinability of AM alloys can be quite different than that of the same conventionally fabricated alloy as a consequence of the complex thermal phenomena characterizing the deposition, melting and solidification of the metal powders, which, in turn, contribute to develop peculiar microstructural features. As a consequence of that, the choice of different sets of optimal cutting parameters may become mandatory.
- In general, as-built AM alloys show lower machinability (i.e. higher tool wear, reduced surface integrity) than the same conventionally fabricated alloys; nevertheless, the conduction of a suitable heat treatment can help in modifying the as-built microstructural

features to be more similar to those of the conventionally fabricated alloys, therefore enhancing the AM alloy machinability.
- Unconventional machining strategies may also help in enhancing the AM alloy machinability: for instance, it was proved that cryogenic cooling during cutting may help in both reducing the tool wear and improving the surface integrity.
- The AM-induced anisotropy plays a fundamental role in assessing the AM alloy machinability, especially in relation to the orientation of the tool cutting edge, regardless of the heat treatment carried out on the AM alloy itself.
- Accurate numerical modelling of post-AM machining operations must take into account the peculiar microstructural features characterizing the AM alloy as well as the AM-induced anisotropy.

Even if the scientific literature of the last years has shown a growing interest of such topics, there are still several points that can be considered of potential interest of both the academic and industrial communities.

- Robust guidelines for the choice of both the most appropriate post-processing operations and related parameters still lack. This is especially critical now that new metal alloys are emerging as candidates for AM processes, like functionally-graded metals, which require an extensive characterization of their machinability, being strictly correlated to their peculiar microstructural features.
- Design for Additive Manufacturing is nowadays quite popular when designing a metal part fabricated through AM processes; however, it must take into account also post-processing operations, as a proper design and optimization of the final machining steps have been shown to be mandatory to meet the product final requirements. In this sense, the concept of concurrent engineering is even more demanding than in case of conventionally fabricated metal parts.
- Design and optimization of the machining steps must take into account, on one side, the microstructural and mechanical features induced by the AM process, and, on the other side, the part in-service characteristics.
- The successful industrial application of the recent hybrid processes comprising AM and machining steps in the same machine tool passes through the correct understanding of the mechanisms arising when additive/subtractive steps are simultaneously carried out.

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