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NEW TRENDS IN HYBRID FINISHING PROCESSES OF METALLIC ADDITIVELY FABRICATED PARTS – A SHORT REVIEW

This comprehensive survey highlights some important finishing processes used in fabricating additively manufactured parts, mainly using SLM (Selective Laser Melting). In practice, there are applied hybrid processes which integrate additive and subtractive componential processes (AM+SM type) or additional finishing processes, mainly based on the electrochemical polishing such as ECP (Electrochemical Cavitation Polishing) and PEMEC (Electrochemical-Mechanical Polishing) ones. On the other hand, AFM (Abrasive Flow Machining) is predominantly recommended for conformal cooling (CC) channels. Some conclusions and future trends in the implementation of special hybrid finishing processes are outlined.

1. INTRODUCTION

This paper continues the discussion on the technological problems described in earlier publications [1, 2] which appear in the hybrid manufacturing processes integrating *additive manufacturing* (AM), obviously termed *3D printing,* and finishing *subtractive processes* including milling and turning operations performed on a hybrid machining platform along with automatic dimensional control. In general, due to unsatisfactory surface integrity of additively fabricated parts, additional cutting and abrasive finishing processes, as well as a special thermal treatment, in the post-processing mode, are required in order to produce an appropriate surface functionality [2, 3–5]. In particular, excessive surface roughness and tensile residual stresses produced by intensive heating of the machining zone adversely affect the thermo-mechanical fatigue life of highly loaded aerospace engine parts and injection moulds [1, 4, 6, 7].

As shown in Fig. 1a, additive machining can provide higher shape complexity but is less productive than conventional machining processes such as CNC milling. On the other hand, hybrid machining, integrating AM and SM processes, seems to be an optimal choice between higher part complexity characteristic for the additive fabrication and higher productivity characteristic for CNC machining. As a result, the demanded high quality of AM parts, for instance produced by SLM (*selective laser melting*), needs additional finishing treatments to

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be performed as *post-process* operation(s). As shown in Fig. 1b, the surface of AM part contains characteristic scallops due to the stair-case effect with the height depending on the thickness of the deposited layer [2]. It is obviously known from the tooling practice [3, 9] that the roughness of cooling channel' surfaces in the injection mould dies (also blow moulds) equipped with the conformal cooling (CC) system (see Fig. 1c) is typically higher than Ra = 10 µm but functionally required surface roughness should be decreased even down to 1 µm. This limit results not only from the surface smoothing but also generating compressive residual stress in the subsurface layer which retards the propagation of fatigue cracks [4, 7, 10, 11]. It can be seen in Fig. 1c that the edges of channels suffer from such defects as warpages and collapses. It is also important to minimize scraps which correspond to minimizing the allowance planned for finishing abrasive or hybrid operations. It is in sharp contrast with the so-called monolithic part machining performed usually in aerospace industry when large monolithic parts are shaped by removing 80–90 % material from the bulk material [12].

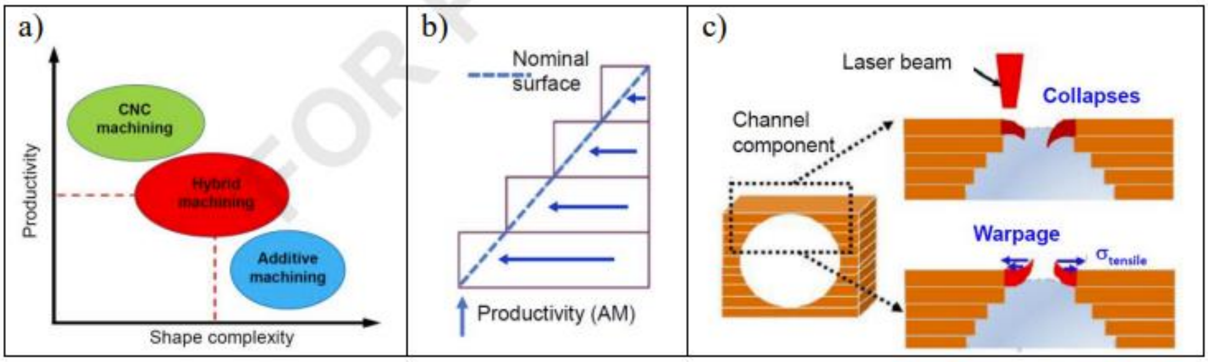

Fig. 1. Characteristic features of manufacturing processes (a), external surface state after additive shaping (b) defects in LPBF fabricating of cooling channels [1, 3, 8]

It is a great challenge, due to the rapid application of AM processes in the manufacturing industry, to concurrently develop finishing conventional processes such as turning, milling, shot blasting, lapping and mechanical polishing, and a number of unconventional/hybrid processes including chemical etching, tribo-finishing, laser polishing, electro-discharge polishing, wire electrical discharge polishing (WEDP), ultrasonic vibration assisted electrochemical polishing, magnetic field-assisted finishing, ball burnishing, etc. [3, 8, 13–18]. It is reported [3, 8, 13, 14, 19] that the existing finishing methods for AM components such as laser polishing, chemical polishing, abrasive finishing, mechanical polishing and other hybrid combinations have numerous limitations including difficulty in accessing complex part surfaces, loss of dimensional accuracy and deterioration in material surface and functional properties. Comparatively, the resultant roughness reduction obtainable for laser polishing, electrochemical, ultrasonic machining, AFF (Abrasive Flow Finishing), and MAF (Magnetic Abrasive Finishing) is shown in Fig. 2. It can be noticed that the surface smoothing effect fluctuates between 70% and 100% in comparison to the initial surface roughness and an appropriate post-processing technique can be applied to achieve desired surface roughness reduction.

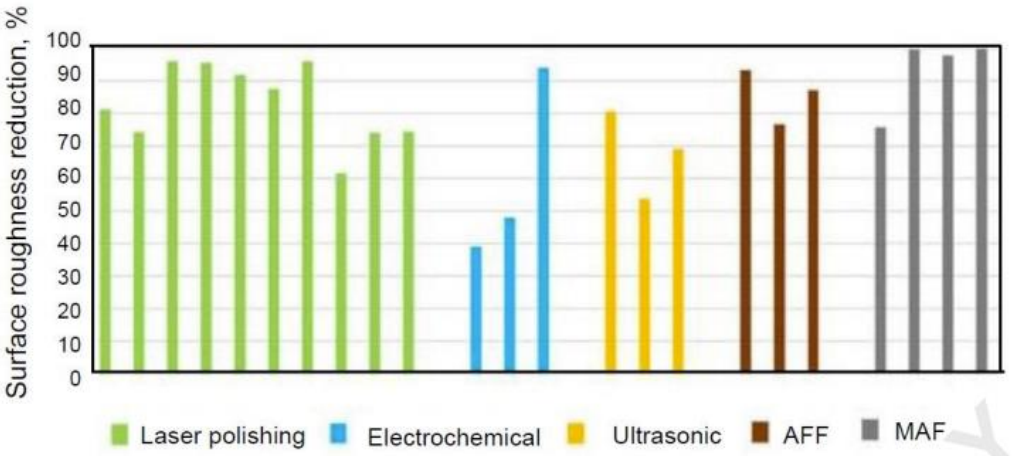

Fig. 2. Comparison of the resultant roughness reduction for different finishing processes of AM-fabricated parts [19]

In general, finishing processes performed on AM parts can be selected in terms of the part material including polymeric and metallic materials [20]. For polymeric parts, abrasive grinding, milling, and micromachining can produce a fine surface finish of nano-level roughness and these finishing methods can be frequently used alongside ultrasonic vibrations. On the other hand, chemical, electrochemical and laser post-processing can be applied for AM-fabricated metallic parts. In particular, laser polishing can reduce the surface roughness up to 95% and produce surfaces with the surface roughness as low as 790 nm, as reported in Ref. [15].

A new class of hybrid processes termed electrochemical-mechanical polishing (PEMEC), which synergistically integrates abrasive removal mechanisms characteristic for drag machining in the reservoir with chemical dissolution characteristic for (electrochemical polishing) is successfully developed now [21]. In other words, it extends and intensifies the abrasive finishing by electrochemical assistance as a secondary process. Because the above-mentioned finishing methods are limited to external surfaces, the next technological challenge appears to adopt effective methods suitable for finish internal surface including CC channels and various cavities. It was proven that *abrasive flow machining* (AFM) can be the first choice [3, 9]. In this survey, the focus will be made on the ECP and PEMEC processes related to finishing external surfaces of AM parts and AFM process for finishing conformal cooling channels in injection mould dies fabricated mainly by SLM technique. Other conventional and hybrid finishing processes are described in books [2, 11, 12] and journal papers [3, 9, 10, 21].

The main objective of this survey is to highlight and characterize new trends in the development of hybrid finishing processes devoted to AM-fabricated parts made of stainless and ageing steels which can be applicable to free-form external surfaces and optimized flow abrasive processes which, on the other hand, would be effectively applied to complex internal surfaces. Hence, the scope of this paper is to overview some important achievements in the hybrid finishing processes which can overcome the above-mentioned limitations for producing AM-fabricated parts with desirable surface finish and operational functionalities.

2. FINISHING OF EXTERNAL SURFACES USING US VIBRATION-ASSISTED ELECTROCHEMICAL POLISHING (ECP/USAECP) AND ELECTROCHEMICAL-MECHANICAL POLISHING (PEMEC)

The principle and kinematics of PEMEC process, and the set-up applied in the experiments, are shown in Fig. 3a-c. In the tested equipment, being a *drag finishing* machine (called also *mass finishing*) presented in Fig. 3b, the process container (work bowl) filled with the mixture of abrasive stones and electrolyte rotates with the angular velocity of ω_1, whereas the vertical spindle with the clamped workpiece, fully immersed in the working medium, rotates in the same direction with the angular velocity of ω_2 (corresponding rotating velocities are equal to 0.5 and approximately 500 1/min). As a result, a high sliding velocity of the working mixture in relation to the workpiece surface is generated. The constant "rubbing" of media on parts over a certain period of time is producing the desired surface finish. Preliminarily, the process was tested for plane and cylindrical parts but it will be extended to free-form parts. Abrasive stones of a pyramidal shape and a 2 mm in size were made of Al_2O_3 ceramics (Fig. 3c). The electrolyte was composed as the mixture of phosphoric acid H_3PO_4 at 85 wt.% and deionised water. The specimens made of 316L stainless steel were initially milled and sandblasted and the surface roughness Sa of about 11 μm was obtained. Characteristic surface profiles recorded after both componential processes, i.e. after drag machining and electrochemical process, as well after the PEMEC hybrid process are successively presented in Figs. 4a and 4b.

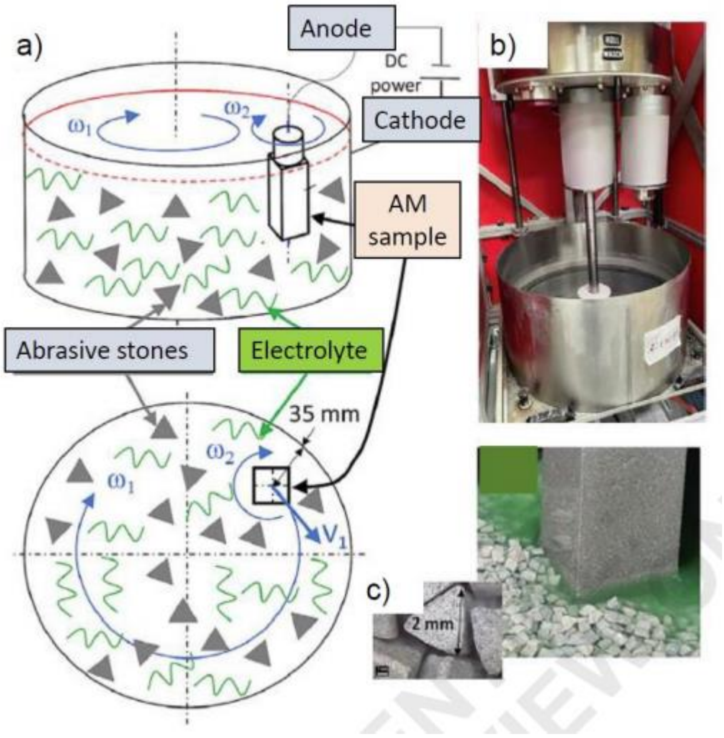

Fig. 3. Kinematics of PEMEC process (a), the experimental set-up (b), view of the machining zone consisting of abrasive media and electrolyte (c) [21]

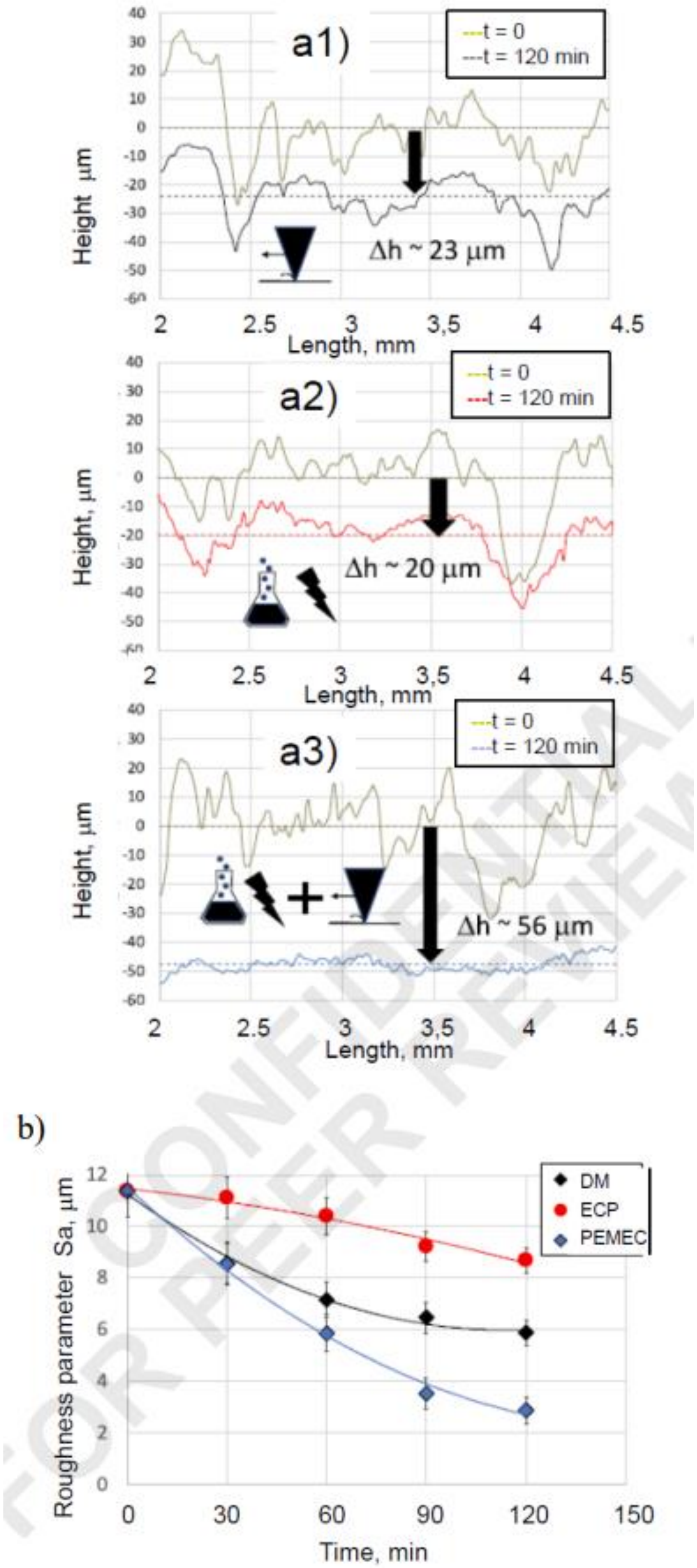

Fig. 4. Schematic illustration of the evolution of reference surface profiles after 120 min finishing using conventional processes (a1 and a2) and hybrid process (a3) and corresponding roughness parameter Sa (b) [21]. Symbols: a1) drag finishing, a2) ECP, a3) PEMEC

It can be depicted in Fig. 4b that the surface roughness parameter Sa measured on the surface subjected to PEMEC finishing decreases down to 3 µm, whereas after individual/componential processes, i.e. drag finishing and ECP, it is reduced to 6 and 8.7 µm respectively. It should be noted that in the hybrid PEMEC process (denoted by (a3)) all excessive surface irregularities generated during initial processes are removed. As a result, the total height of the surface profile is reduced after 120 min by $\Delta h \approx 56$ µm.

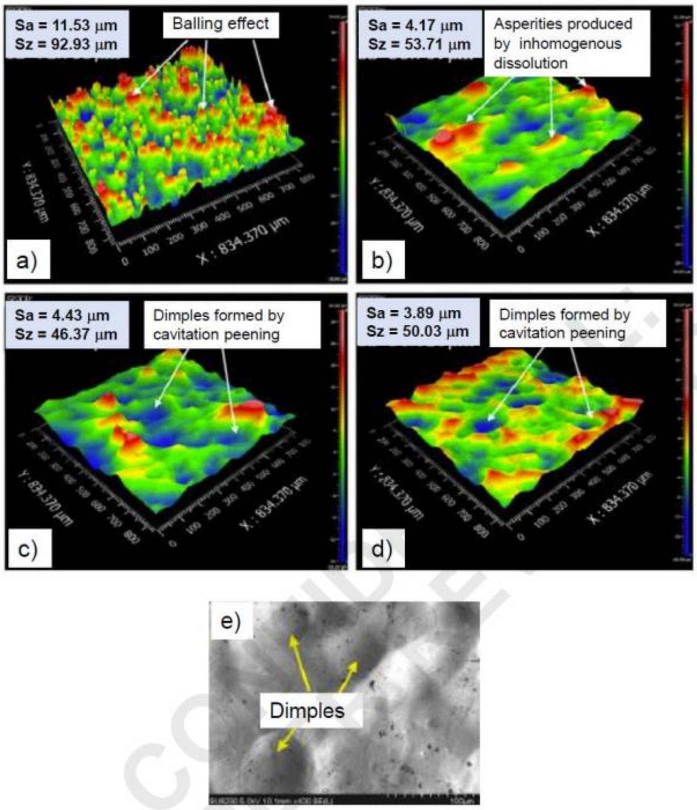

Fig. 5. Changes in surface topography before and after post-processing: (a) as-built surface, (b) treated by ECP for 10 min, (c) treated by sequential process including ECP and cavitation peening for 10 min each, and (d) treated by hybrid process for 10 min, (e) SME image of the real surface visualized in Fig. 5d with magnification 10^4×, US amplitude 56 µm [13]

In the case of ECP (*electrochemical cavitation peening*) described in details in Ref. [13] additional ultrasonic vibrations causing the dynamic cavitation effect, termed the *cavitation peening*, resulting in the local strain-hardening effect, are generated. A similar surficial effect can be obtained by the hydrodynamic action when using a high-pressure water jet. According to the hybridization rule this process can also by termed *ultrasonically assisted electrochemical polishing* and denoted by symbol USAECP [2]. As a consequence, as shown in Fig. 5c, the surface roughness decreases and values of Sa and Sz areal parameters measured on the additively fabricated specimens made of 316L AM steel after the hybrid process decrease from initial values of 11.5 and 92.9 µm to 3.9 and 50 µm [13]. However, in comparison to PEMEC process, a large number of small dimples produced by US-generated cavitation remain on the surface.

3. FINISHING OF INTERNAL SURFACES USING ABRASIVE FLOW MACHINING (AFM)

A classical example of the effective applications of abrasive flow machining process are so-called conformal cooling systems, i.e. in which cooling channels are accurately adjusted to the shapes of die cavity and the core, consisting of a system of very complex channels of different shapes of cross-sections. It is very important design trend because during the injection moulding process, the cooling time accounts for up to 70–80% of the entire cycle time because the temperature of the melted plastic of typically 200–300ºC needs to be reduced by cooling below the release temperature of 80ºC generally [8]. Therefore, the cooling rate is crucial for improving production efficiency of injected plastic parts.

As shown in Fig. 1c and 6a and 6b, the structure of such a system consists of straight parts, often with 2 or 3 branchings, and helical/spiral with different lead angle and scale/pitch (Fig. 6d). As reported, fabricating conformal cooling systems by means of 3D printing allows increasing the productivity throughput of the injection mould dies for plastics by 30–50% in comparison to traditional drilling and milling operations. Moreover, the cooling performance is enhanced. As a result, benefits resulting from the application of printed CC cooling system in the mould die for the car reflector headlight shown in Fig. 6c are as follows [22]:

- reduction of cycle time by 17% (from 40.3 sec to 33.4 sec),
- reduction of warpages by 62%,
- reduction of temperature deviation on the part’s surface by 73% (Fig. 6c),
- reduction of sink mark affected areas on the part’s surface by 50%.

In addition, residual stresses of injection-moulded parts with variable thickness, large size and/or complex shape are reduced (see for instance Fig. 1c).

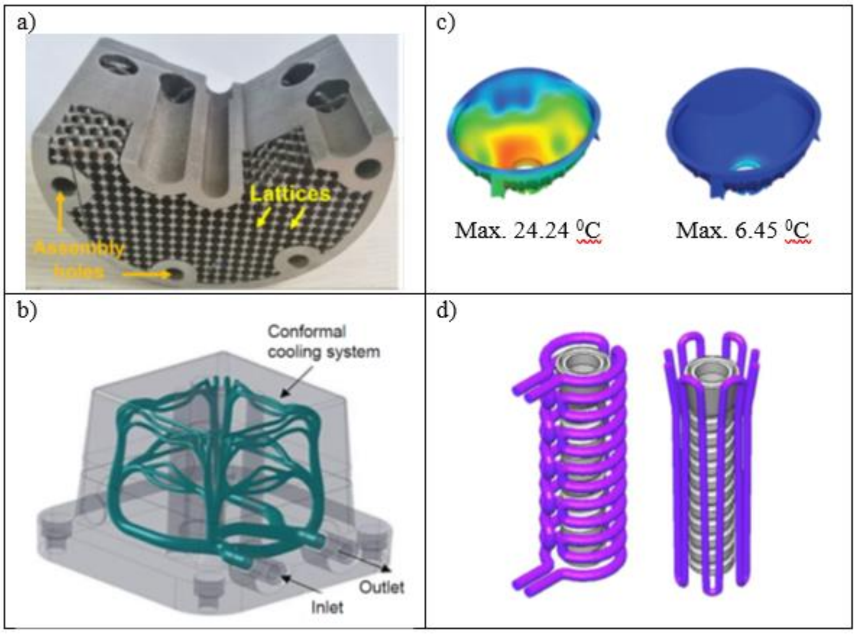

Fig. 6. Examples of injection moulds with conformal cooling channels: a) a flow mixing part, b) visualization of the cooling system, c) part temperature deviation, d) examples of channel shapes- zigzag systems [8, 22, 23]

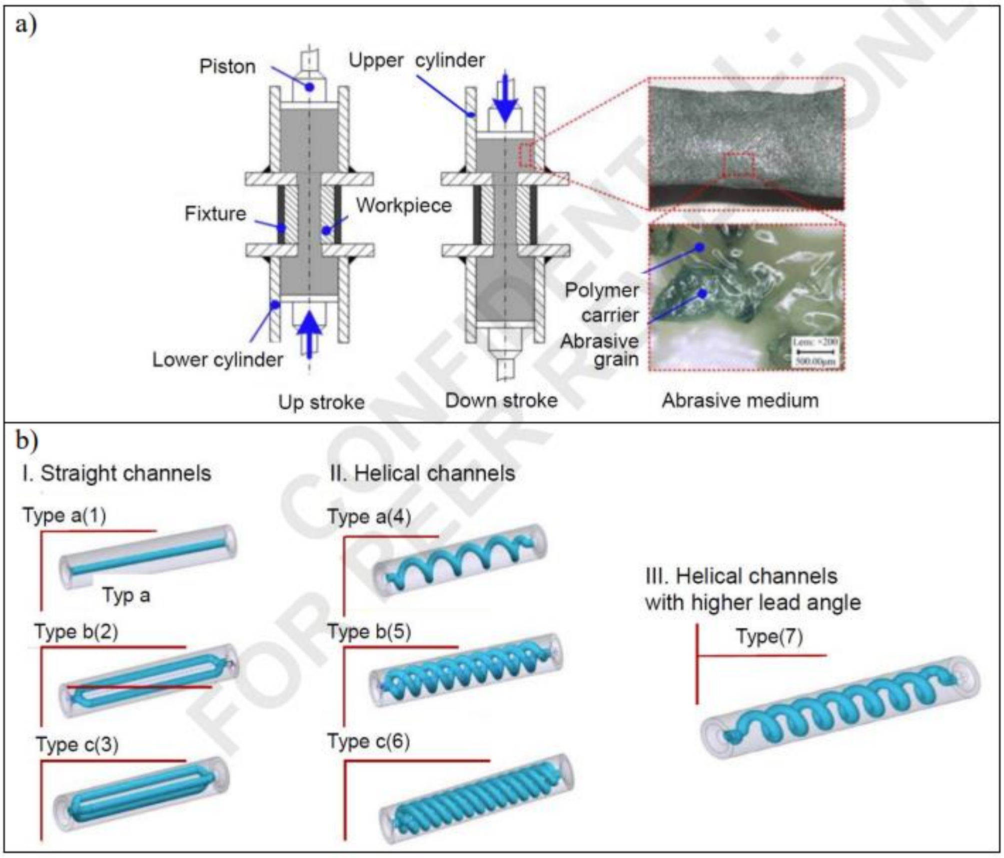

Fig. 7. A scheme of a two-way (up- and down-stroke) AFM equipment (a) and CAD models of various types of cooling channels tested (b) [3, 9, 24]

Experimental studies [3, 9] were performed using an extrusion machine of a two-way model produced by Extrude Hone Corp. (this company produces such equipment since 1960) presented schematically in Fig. 7a. Seven different configurations of straight and helical cooling channels, each of 3 mm in diameter, were tested. Their CAD models are presented in Fig. 7b. Specimens made of an aged Maraging 300 steel were fabricated by means of SLM technique. As the AFM medium (denoted by ULV50%-54 symbol) a mix of silicon carbon (SiC) abrasive grits of 54 μm in size with abrasive concentration of 50 wt.% and polyboroxane polymer carrier of ultra-low viscosity (ULV) was applied. AFM finishing of each type of conformal channels was performed for 10 cycles including one up-stroke and one down-stroke. It was proven, based on measurements of the selected surface topographies, that AFM finishing influenced such areal roughness parameters as Sa/Sz, the RMS gradient Sdq, the developed interfacial area of a surface Sdr (expressed in %), the reduced peak height Spk and the skewness Ssk. Some important measurement results are presented in Figs. 8a and 8b.

General conclusion concerning the observed trends in changing roughness parameters resulting from AFM finishing is that higher changes are termed for straight channels resulting from higher velocities of the extrusion of AFM media. It was documented that the velocities of a AFM flow in one helical channel with large and small lead angle are 26% and 46% lower than that in one straight channel [3]. For instance, for the case of one straight channel (case Ia in Fig. 7b) the value of the Sa parameter decreases from 7.6 μm down to 1.3 μm [9].

Consequently to the medium flow rule, for one helical channel (case IIc in Fig. 7b) Sa parameter decreases from about 9 µm down to about 3 µm. On the other hand, the reduction of the Sz parameter results mainly from the corresponding reduction of the Spk parameter (Sz is the sum of Spk and Svk parameters), as illustrated in Fig. 8a. This reduction of sharp peaks indicates that a "*plateau*" surface (close to a flat surface) with Sdr value of 2% is produced. In turn, this effect causes that the skewness Ssk changes its sign from positive (about 1 before AFM finishing) to negative (about 0.5–1.5) after AFM finishing). As shown in Fig. 8b, a distinct reduction of the Sdr parameter indicates that a surface with a higher value of Sdq parameter is generated after AFM finishing.

The evolution of Spk/Svk, Sdq and Sdr areal roughness parameters is schematically illustrated in Fig. 9.

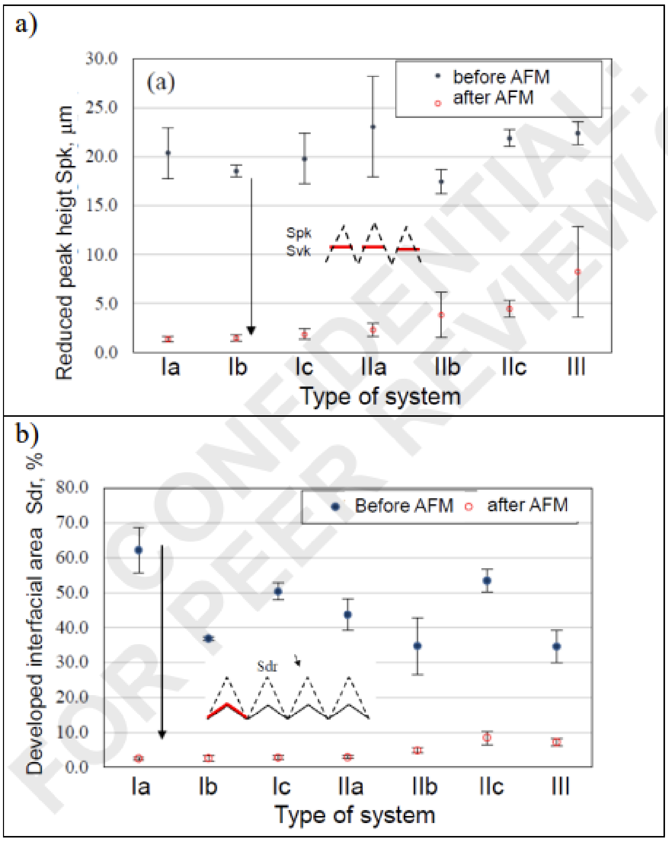

Fig. 8. Changes of Sdq (a) and Sdr (b) areal roughness parameters for different types and configurations of SLM conformal cooling channels [9]

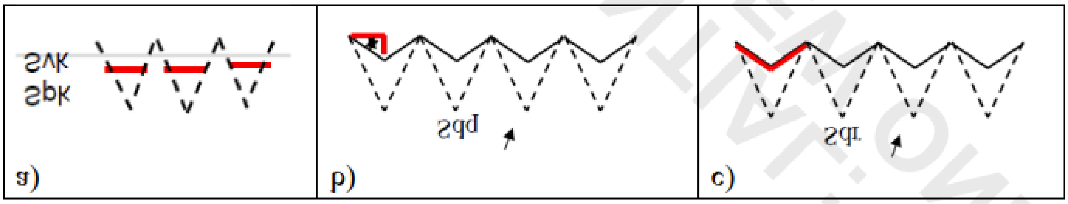

Fig. 9. Schematic illustration of the evolution of Spk (a), Sdq (b) and Sdr (c) areal roughness parameters resulting from SLM finishing of conformal cooling channels [3]

Because additively produced parts are subjected to the heat treatment, it is important to find its possible influence on the final surface finish, mechanical properties and the stress state in the subsurface layer [3]. For this purpose, a Maraging 300 steel was aged using the heat treatment cycle consisting of heating to 490°C, holding at this temperature during 3 hrs and then cooling. It was documented that values of Sa and Sq roughness parameters are distinctly reduced when the number of AFM media flows increases and their minimum values (Sa = 3 μm and Sq = 3.5 μm respectively) are obtained after 150 cycles. Better results are recorded for polymeric carrier with medium viscosity (MV) and higher concentration of abrasive grains (65%). For these AFM conditions the highest values of compressive residual stresses measured in the directions perpendicular and parallel to the AFM medium flow are recorded.

4. MAIN CONCLUSIONS

The following conclusions can be formulated based on this literature review:

- Machine parts fabricated by means of additive methods, e.g. SLM (*Selective Laser Melting*) or DED (*Directed Energy Deposition*) demand finishing processes in order to reduce the initial surface roughness Ra (Sa) to about 1 μm and/or to generate compressive residual stresses in the subsurface layer. In general, it is possible to apply both conventional and unconventional, as well as hybrid finishing processes.
- Among the possible spectrum of finishing processes for external surfaces, most promising seem to be hybrid polishing ECP and PEMEC processes which use electrochemical polishing as a primary process and mechanical polishing or ultrasonic (US) vibrations as secondary processes. However, it is necessary to extend their effective application to the free 3D/sculptured surfaces.
- The performance of surface finishing using ultrasonically vibration-assisted electrochemical polishing (ECP/USAECP) and electrochemical-mechanical polishing (PEMEC) results in a substantial smoothing of the initial surface profile leading to reduction of the Sa parameter down to about 3(4) μm.
- On the other hand, finishing of internal surfaces, as for instance cooling channels in conformal cooling systems in injection mould dies for polymeric materials, seems to be most effective when using abrasive flow machining (AFM). However, it is necessary to perform a deep analysis of the flow conditions of AFM medium due to its slows-down (the velocity of AFM flow is lower) in helical channels in order to obtain the required surface roughness.
- The primary effect resulting from the application of AFM process is a distinct reduction of the Sdr parameter down to 2%, which means that practically flat surfaces with a higher value of the asperity slope (Sdq) parameter are generated. Moreover, typical defects such as warpages, collapses and shape deviations are practically eliminated.
- The post-treatment of additively fabricated parts does not distinctly influence the surface roughness (assessed by Sa and Sq parameters) and values of the induced residual stresses. In this case, the set of influencing factors covers the number of extrusion cycles, the viscosity of polymer carrier and the concentration of abrasive particles in the AFM medium [9].

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