Available online at www.sciencedirect.com

ScienceDirect

Procedia Computer Science 180 (2021) 358–365

Procedia Computer Science

www.elsevier.com/locate/procedia

International Conference on Industry 4.0 and Smart Manufacturing

Functionalized additively manufactured parts for the manufacturing of the future

Michela Sanguedolce[a]*, Giovanna Rotella[b], Maria Rosaria Saffioti[a], Luigino Filice[a]

[a] *Department of Mechanical, Energy and Management Engineering, University of Calabria, Rende, 87036 CS, Italy*
[b] *Department of Engineering for Innovation, University of Salento, Via per Monteroni, 73100 LE, Italy*

Abstract

Innovation technology is giving the opportunity to fabricate products and parts in alternative ways and with special characteristics, which do not strictly depend on the primary manufacturing process. In particular, smart manufacturing seeks for flexible systems and customizable products, recognizing additive manufacturing (AM) processes as a key element. To successfully integrate AM into the production chain it is necessary to overcome its limitations in terms of final product quality and reliability, wisely choosing post-processing operations. This work outlines how it is possible to significantly improve AM product performance using an environment friendly process, such as burnishing, coupled with a numerical simulation model encouraging customer integration and developing a flexible manufacturing process capable to conform with the main idea behind Industry 4.0.

Keywords: Smart Manufacturing; Burnishing; Additive Manufacturing; Simulation; Sustainability.

1. Introduction

The initiation of the process of digital transformation, as a part of Industry 4.0 framework, is giving to manufacturers the opportunity to find a trade-off between product personalization, process flexibility and competitiveness on the market. Continuous changes in industrial manufacturing have occurred over time. At the beginning, there was the craft (customer) production (CP) paradigm where a small range of products was fabricated

* Michela Sanguedolce. Tel.: 390984494637
E-mail address: michela.sanguedolce@unical.it

10.1016/j.procs.2021.01.174

at high cost according to customer specifications. Afterwards, the mass production (MP) was introduced based on large scale manufacturing systems, creating low cost goods, still with a very restricted portfolio. Thus, in order to extend the variety of products required by customers, the mass customization production (MCP) paradigm emerged. It involved the adoption of automation, information and computer technology leading to a wide range of products by means of faster and computerized processes, flexibility, high productivity and cost reduction [1]. Nowadays, the focus of companies is changing again, adding the customer integration to the maximization of the returns, defining the mass personalization production (MPP) paradigm. Consequently, as it happens for the supplier, the customers play an active role into the production process by building their own products according to their specific needs [2].

A fairly new technology, Additive Manufacturing (AM), is emerging as one of the pillars of the 4th Industrial Revolution, promoting proactive flexibility strategies [3]. Additive manufacturing can be defined as the process of depositing and joining material to create 3D objects, differently from conventional manufacturing (CM), which usually involves material removal processes in order to achieve a desired shape. Born as a technology to manufacture pieces to be used in the internal product development process (rapid prototyping), AM technologies have been then intensively developed to meet the requirements of the industrial production. In fact, such technology suits the challenge to make individualized products at an affordable cost but, to effectively enable the production of a variety of individualized products, it is necessary to integrate the AM machines into a manufacturing system containing other operations. Anyway, it is essential to ensure that the efficiency of the production is not affected by the cycle time variation [4].

If conventional subtractive manufacturing (SM) is still preferred for a mass production of low-complexity products, additive manufacturing systems can guarantee a cost drop when high-complexity goods need to be produced. Therefore, a comparison based only on production volumes is inadequate to exhaustively represent the boundary between AM and SM in terms of cost-effectiveness. In this regard, Fera et al. [5] presented a methodology to assess the suitability of using AM with reference to the product features, drawing a convenience diagram based on a complexity index definition.

One of the main advantages attributed to AM processes is the possibility to fabricate a final product in a single step while CM requires multiple stages and processes, implying the relocation of semi-finished product from a machine to another [6]. However, the reliability of the AM products can suffer from poor surface quality, porosity, anisotropy, lack of precision and accuracy, etc., consequently requiring additional post-processing and heat treatments [7, 8]. In fact, the above issues need to be overcome when manufacturing components for critical applications (e.g. aerospace and biomedical), involving high resistance to fatigue loads and extreme working conditions.

The benefits related to finishing processes span from improved fatigue life to higher corrosion resistance and strength enhancement. In this regard, burnishing process can successfully replace other surface finishing processes like honing, grinding and superfinishing [9, 10] and recent developments concern the possibility to machine complex-shaped parts [11].

Burnishing is a chipless severe plastic deformation (SPD) process able to modify the surface characteristics. More in detail, it increases the product performance by smoothing the roughness through depressing the asperities and removing microcracks as well as voids resulting from previous production processes.

In this work, burnishing has been selected as a suitable post-process able to fit the Smart Manufacturing principles. An experimental campaign was performed in order to assess the capability of the process to enhance surface integrity and high cycle fatigue life of additively manufactured samples. Furthermore, a finite element model has been developed in order to describe the process and predict its influence on the overall product quality. Such methodology successfully replaces additional expensive tests representing a further pillar of Industry 4.0. In fact, with reference to the above-mentioned mass personalization production paradigm, process simulation allows to optimize the analysed process in terms of working parameters and lubrication, further contributing to the manufacturing of customized products at a reasonable cost and paving the way for the development of a process digital twin.

From a managerial point of view, the use of secondary operations enlarges the research space to optimize the manufacturing process. In other words, the need of special component behaviours requires a redesign of the manufacturing sequence. Flexibility, in this case, is suitable allowing an improved process effectiveness which can become a competitive advantage for the industry. In fact, real companies working in the manufacturing area could adopt this kind of technologies opening a new scenario with respect to the use of proper processes and machines able to manufacture ready-to-use components but at a higher cost.

2. Materials and Methods

2.1. Experimental procedure

The experimental campaign [12] has been carried out on Stainless Steel GP1 samples obtained by laser powder bed fusion (L-PBF) process. Standard building parameters optimized by EOS GmbH have been used. The additively manufactured samples had the shape of dog bone (Figure 1 and Figure 2).

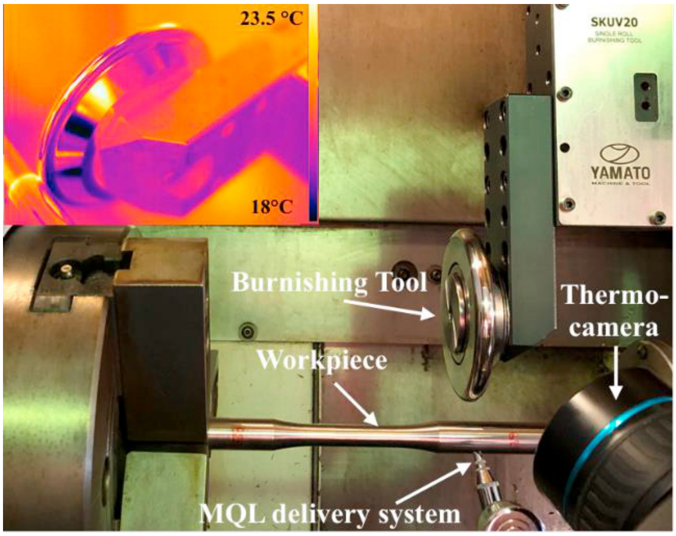

Fig. 1. Experimental set-up for burnishing tests.

The as printed (AP) samples have been thermally treated to reduce the porosity and release the residual stresses. After that, the specimens have been machined at standard finishing parameters in order to remove the unmelted powder residues and to achieve reasonable surface finish. After the turning process, the burnishing tests have been performed using a commercial roller-burnishing tool equipped with a spring-based force regulation system and under minimum quantity of lubrication (MQL) conditions, using a biodegradable oil.

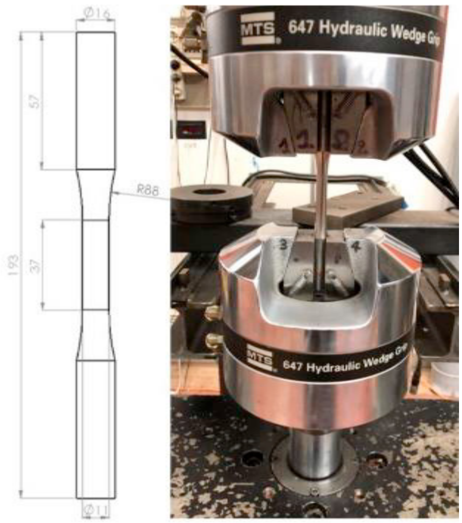

Fig. 2. Fatigue sample specifications and set-up.

Concerning lubrication in severe plastic deformation (SPD) processes, it is worth considering their related environmental issues such as the indiscriminate use of metalworking fluids (MWFs) and generated waste. Coolants and lubricants have been synonymous with metal manufacturing for centuries, while nowadays the first necessary step for making a more sustainable process is to eliminate the MFW since it is not embodied in final product. However, the total absence of cooling/lubrication may result in accelerated tool wear, undesirable residual stresses and poor surface finish. Thus, it is important to make products using more sustainable methods and processes, minimizing the use of coolants/lubricants. One of the most commonly used methods to limit these issues is MQL. It represents an alternative where dry processes are not applicable, guaranteeing the same product performance, providing a healthy and safe working environment. In MQL-assisted processes, a lubricant is sprayed at the tool-workpiece interface in very small quantities and, penetrating into the contact zone, it supplies lubrication and cooling effects. Such configuration avoids the undesired formation of aerosols arising during flood cooling leading to serious health issues as well as the generation of waste to be treated and disposed.

High cycle fatigue life tests have been performed (Figure 2) in order to verify the capability of burnishing process to improve the quality of the additively manufactured products and to obtain the fatigue limit at given numbers of cycles.

2.2. Simulations

A numerical 3D model of roller burnishing process was developed using the software SFTC DEFORM© to allow thorough understanding and optimization of the real system, subject of the experimental campaign. In particular, the main aim was to investigate the effect of different working conditions and parameters such as tool characteristic dimension, burnishing force, feed rate, and number of passes (Figure 3) on the resultant quality of the product, which may be expressed in terms of grain size, hardness, residual stresses, roughness, thickness of the affected layer etc.

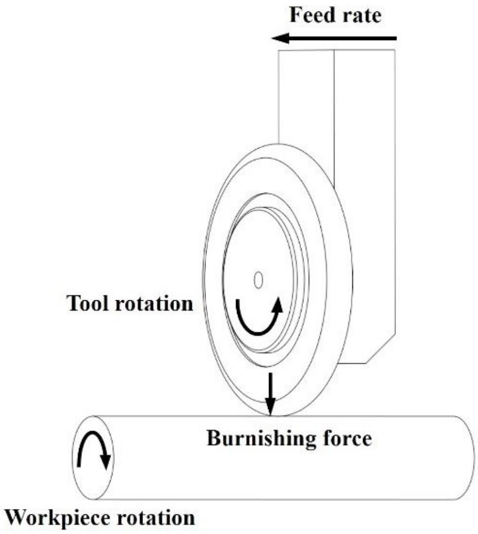

Fig. 3. Scheme of roller burnishing process.

During the first phase of the simulation, a rigid roller was pressed into the plastic workpiece in a displacement-controlled motion. Subsequently, the workpiece was put into rotation, thus allowing motion transmission to the tool as a result of friction. In this second phase, the transmitted force reached a steady value making it possible to define a value of imposed displacement (depth of burnishing) equivalent to the experimentally applied burnishing force. Figure 4 shows the boundary and movement conditions used into the model, together with the mesh, which is more refined in the contact area.

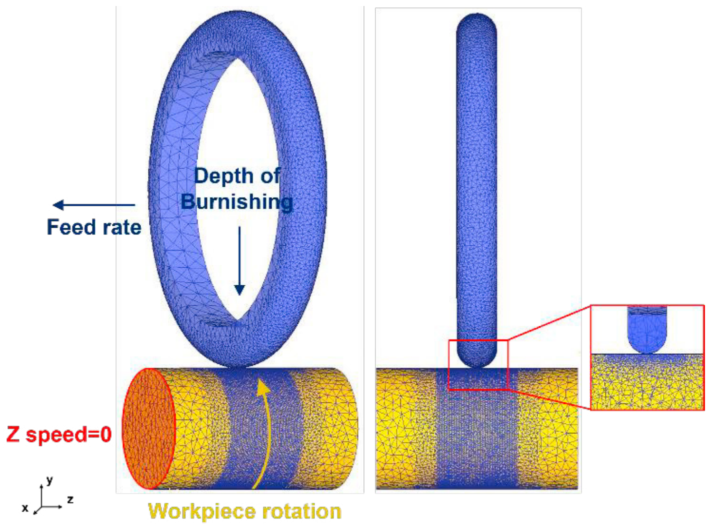

Fig. 4. Numerical model movement setup, boundary conditions and mesh.

Validating the sub-mentioned simulation model, it would be possible to optimize the burnishing process conditions without the need of further experimental tests, as explained in the flow chart reported in Figure 5. Thus, there is a lot of potential for proper process planning and reduction in terms of costs, materials and scraps while maintaining the same reliability obtained from experimental tests. Furthermore, the twinning between simulated and real process enables the manufacturer to satisfy customer special needs approaching as much as possible the concept of "complexity is free" embraced with additive manufacturing. In fact, after properly relating his requests to technical specifications and converting them into mechanical properties, optimized parameters can be directly obtained from numerical model.

In the end, it is important to draw attention to parameters reported in Figure 5, i.e. hardness (HIT), roughness (Ra) and residual stresses (RS), as they are determining factors for mechanical applications requiring high fatigue resistance.

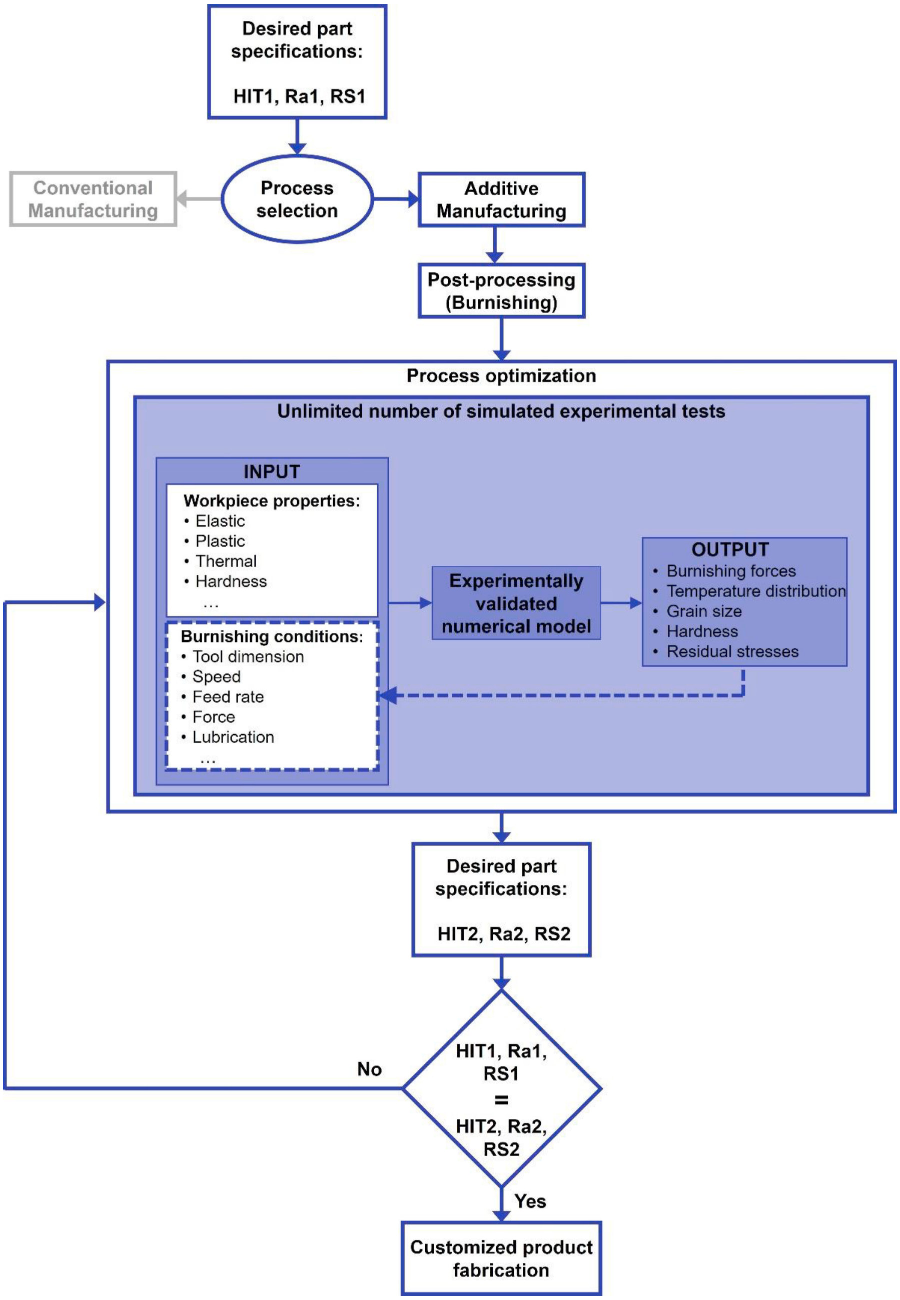

Fig. 5. Process selection and optimization workflow.

3. Results

The use of burnishing process helps to improve the surface and subsurface quality of the samples in terms of surface roughness, hardness, porosity and residual stresses. In fact, the surface roughness (Ra) of as printed specimens was about 11 µm, which, after turning, reached a value of 0.45 µm and, best case scenario, it dropped to 0.17 µm after burnishing. A consistent change in surface hardness was observed after burnishing process, as shown in Table 1.

Table 1. Surface hardness values for tests on as printed (AP), as turned (AT), as burnished best result (BR) and worst result (WR).

Specimen	AP	AT	BR	WR
HIT [GPa]	1.9	2.3	5.0	3.4

Residual stresses have been found to be compressive on and below the burnished surface, Figure 6 shows the results obtained for one of the tested samples.

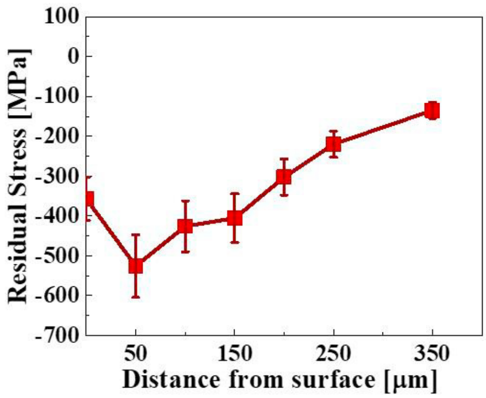

Fig. 6. Residual stresses profile for a burnished sample.

The simultaneous action of the above-mentioned effects led to an increase on high cycle fatigue life (Figure 7) up to 100% with respect to the as printed samples; compared to the 20% increment related to the sole turning.

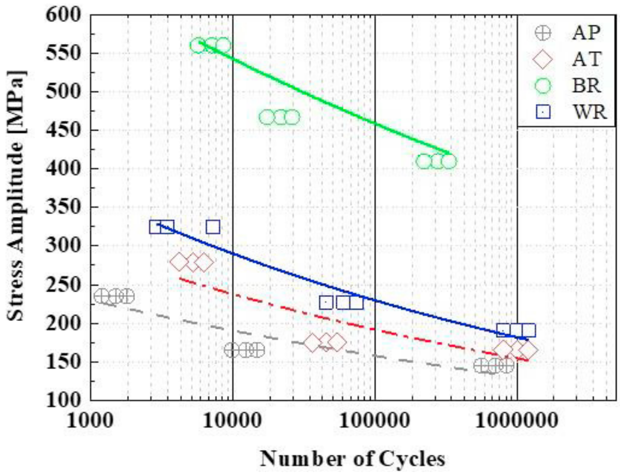

Fig. 7. High cycle fatigue life for as printed (AP), as turned (AT), as burnished best result (BR) and worst result (WR).

4. Conclusions

This paper demonstrates the validity of the designed process chain in producing customized high-performance products. In particular, the production line includes (i) manufacturing of the product near-net-shape by additive manufacturing, reducing costs, time and scraps generated, (ii) stress relieving, (iii) machining to remove the external layer generated by the AM process, resulting into a rough, unclean and heterogeneous surface. Afterwards, the burnishing process lets the product achieve a superior surface quality, together with a considerable enhancement of its performance under service.

The presence of a simulation model capable of reliably predicting final product quality in terms of the main factors affecting its performance contributes to drastically cut down the experimental results needed, leading to a tremendous reduction of production costs and time. The presented manufacturing line is flexible enough to accommodate the Industry 4.0 requirements without compromising the product needed quality. Besides, the sustainability implications of the configured chain have to be considered. In particular, the involved processes avoid the massive use of metalworking fluids, reducing the hazards for workers and the environment repercussions as the amount of generated waste is massively reduced. Also, the costs related to treating waste and safety issues due to machining process and conditions are reduced.

The overall results demonstrate how some of the Industry 4.0 pillars can be successfully implemented into an industrial context to provide product personalization and open new scenarios to companies, allowing the adoption of different technologies, thus extending the optimization area. Further research works could involve broadening the application of the above-mentioned methodology to other mechanical processes.

It should be pointed out that this process chain could be easily applied to new generation companies, which already employ consistent and interfaceable technologies with respect to the proposed ones; otherwise, considerable upgrade costs should be taken into account. Furthermore, the configuration under investigation would be mainly advantageous to companies having product customization as a primary purpose.

References

[1] Wang, Y., Ma, H. S., Yang, J. H., and Wang, K. S. (2017). Industry 4.0: a way from mass customization to mass personalization production. *Advances in Manufacturing*, **5(4)**: 311–320.

[2] Koren, Y., Shpitalni, M., Gu, P., and Hu, S. J. (2015). Product design for mass-individualization. *Procedia CIRP*, **36**: 64–71.

[3] Brettel, M., Klein, M., and Friederichsen, N. (2016). The Relevance of Manufacturing Flexibility in the Context of Industrie 4.0. *Procedia CIRP*, **41**: 105–110.

[4] Gu, X., and Koren, Y. (2018). Manufacturing system architecture for cost-effective mass-individualization. *Manufacturing Letters*, **16**: 44–48.

[5] Fera, M., Macchiaroli, R., Fruggiero, F., and Lambiase, A. (2018). A new perspective for production process analysis using additive manufacturing—complexity vs production volume. *International Journal of Advanced Manufacturing Technology*, **95(1–4)**: 673–685.

[6] Gibson, I., Rosen, D., and Stucker, B. (2015). Additive manufacturing technologies: 3D printing, rapid prototyping, and direct digital manufacturing, second edition. In *Additive Manufacturing Technologies: 3D Printing, Rapid Prototyping, and Direct Digital Manufacturing, Second Edition*.

[7] Abdulhameed, O., Al-Ahmari, A., Ameen, W., and Mian, S. H. (2019). Additive manufacturing: Challenges, trends, and applications. *Advances in Mechanical Engineering* **11(2)**: 1–27.

[8] Yang, Y., Gong, Y., Qu, S., Rong, Y., Sun, Y., and Cai, M. (2018). Densification, surface morphology, microstructure and mechanical properties of 316L fabricated by hybrid manufacturing. *International Journal of Advanced Manufacturing Technology* **97(5–8)**: 2687–2696.

[9] Schulze, V., Bleicher, F., Groche, P., Guo, Y. B., and Pyun, Y. S. (2016). Surface modification by machine hammer peening and burnishing. *CIRP Annals - Manufacturing Technology* **65(2)**: 809–832.

[10] Delgado, P., Cuesta, I. I., Alegre, J. M., and Díaz, A. (2016). State of the art of Deep Rolling. *Precision Engineering* **46**: 1–10.

[11] De Lacalle, L. N. L., Rodriguez, A., Lamikiz, A., Celaya, A., and Alberdi, R. (2011). Five-axis machining and burnishing of complex parts for the improvement of surface roughness. *Materials and Manufacturing Processes* **26(8)**: 997–1003.

[12] Rotella, G., Filice, L., and Micari, F. (2020). Improving surface integrity of additively manufactured GP1 stainless steel by roller burnishing. *CIRP Annals* **69**: 513–516.