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FULL RESEARCH ARTICLE

The ultrasonic burnishing of cobalt-chrome and stainless steel surface made by additive manufacturing

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Abstract The purpose of this paper is to investigate the post-processing of Co-Cr and 316L stainless steel components made by additive manufacturing (AM) using ultrasonic burnishing. AM is able to produce functional parts for medical and industrial applications; however, the parts require support removal and post-processing to achieve the technical requirements. To this end, ultrasonic burnishing is a formative method used to improve surface quality and increase surface hardness. The aim of this work is to characterize the effect of process variable (e.g. machine and workpiece relative displacements and spring compression) in the surface quality of AM burnished materials. Two separate design of experiments were performed to find optimal values for the process parameters. The analysis of the experimental result was performed using "Minitab 16" statistical software. To this end, an analysis of variance (ANOVA) was performed to study the effect and interactions of process parameter on the final surface quality. The results showed that surface roughness (Ra) was decreased to 0.18 µm for as-built Co-Cr and 0.55 µm for as-built 316L stainless steel. In addition, the relative increase in average hardness from as-built Co-Cr was 47.4% (i.e. 551.07 Hv) and 70.7% from as-built 316L stainless steel (i.e. 338.17 Hv). The optimal process parameters for post-processing Co-Cr material are around 0.05 mm/r for the feed and 1.5 mm for the spring compression, whereas post-processing of 316L requires 1000 mm/min for the feed speed, 0.025 mm for the side shift and 1 mm for spring compression, when taking also productivity into consideration. The results of this experiment show that the subtractive methods and labour-intensive post-processing of AM metal parts can be replaced by burnishing methods, thus reducing the cost barriers of additive technology and drive its adoption in industry.

Keywords 3D printing · Additive manufacturing · Post-processing · Direct metal laser sintering (DMLS) · Microhardness · Surface quality

1 Introduction

The post-processing of additively produced components has been identified as one of the bottlenecks for technology transferability [1, 2]. Previous research [3] and roadmaps in the field of additive manufacturing (AM), such as Horizon 2020 [4], identified that the geometrical stability and surface quality of AM metal components have to be improved to reach the high requirements of engineering applications. Therefore, automated mechanical post-processing techniques based on formative or subtractive methods are required to meet the engineering requirements and make the technology cost-effective for industries, such as the aerospace, automotive and medical industries. Research in the field now focuses on finding and testing new methods to automate and improve the post-processing of the surfaces of AM processes [5].

In this regard, the aim of this study is to characterize the performance of ultrasonic burnishing as an automated finishing strategy for AM produced metal components (i.e. cobalt-chrome and stainless steels). Research presented

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by Mahajan and Tajane [6] shows how burnishing can improve the surface quality of metal workpieces. The process itself consists of pressing feed motion hardened steel rolls or balls into the surface of the workpiece being post-processed. Ultrasonic burnishing works at high impact frequencies (over 20,000 impacts per second can be achieved [7]), and industry typically uses this technique to finish conventionally produced metal surfaces.

However, up-to-date results of ultrasonic burnishing in AM produced materials has not been presented. Hence, there is a need to explore this process as a post-processing strategy for AM produced metal components. This research presents new empirical data of AM burnish materials and the technique's comparison with traditional subtractive strategies, presenting the results in terms of surface hardness and surface quality. In relation to subtractive post-processing techniques, burnishing processes might also provide advantages. As presented by Hassan and Al-Bsharat [8], burnishing increases the surface hardness of the workpieces, which improves wear resistance. It also increases corrosion resistance and improves fatigue strength by inducing residual compressive stresses in the surface of the workpieces.

It not only treats material on the surface efficiently but also deforms it locally, producing compressive residual stresses in the treated workpieces [9]. A positive effect of ultrasonic burnishing is that the use of lubricants and cooling fluid are limited compared to subtractive processes [10]. The previous research results of conventionally produced materials show that for aluminium, 34-CrNiMo6 tempering steel and S355J2 structural steel, burnishing increased the hardness of the surface by up to 13.5% and decreased surface roughness by 88% when compared to the raw material [11]. Many other materials, such as deep cold rolled aluminium and steels, have been processed at higher pressure, obtaining higher hardness values but lower surface qualities [12].

Hocheng and Kuo [5] have reported that burnishing methods are suitable for processing plane-shaped geometries, and El-Khabeery and El-Axir [13] applied the same technology to process curved and double curved surfaces. In this regard, AM technologies are optimal for producing the organic geometries used in dental and medical applications [14] and additively produced Co-Cr implants have huge potential in the dental field, having the drawback of low surface quality directly after manufacturing [15].

In the case of industrial applications, mechanical post-processing techniques, such as shoot blasting or subtractive milling processes, are typically used to finish and improve the surface quality of AM-produced tools [16]. For instance, stainless-steel tool inserts for plastic injection moulds, as well as tool inserts for the hot spots of forming tools in automotive applications, are being produced using AM metal systems [17]. Typically, sequential Numerical Control (NC) milling is always required to achieve the geometrical requirements [18]. AM technology is also suitable for the reparation of aircraft engine parts, such as turbine blades, as well as suitable for the production of complex parts for end-use applications [19]. However, AM-produced or repaired components will still require post-processing, which is mostly performed by NC machining of the remanufactured part [20].

In both medical and industrial applications, the surface quality of AM parts is often a barrier and mechanical post-processing is often required [21], making the AM alternative even more costly. Nevertheless, by automating the post-processing of AM parts the use of this technology could become more cost effective and technically suitable for its final use. Therefore, the further study of ultrasonic burnishing for the post-processing of AM metals is interesting since the ultrasonic burnishing tool can be installed in conventional NC machines to improve surface quality and hardness.

2 Material and experimental methods

In literature, there is no previous data about burnishing parameters for any AM materials or traditional Co-Cr. To this end, the experiment started using round Co-Cr samples and lathe as holder for the tool. Since AM parts are very rare simple as tube and based on results from Co-Cr samples, machining centre was selected for more complex testing. The material tested was changed to 316L steel since there was more data and parameters about burnishing traditional steels and possible wider application field.

2.1 The additive manufacturing process

During the AM process, six test shafts were manufactured from EOS Cobalt Chrome SP2 (Co-Cr) powder using EOSINT M 270 equipment with default parameters and a layer thickness of 20 µm. The default parameters involved a scan speed of 1100 mm/s, laser spot size of 0.1 mm, hatch spacing 100 µm and a maximum power output of 195 W. During the AM process, the test shafts were oriented horizontally; hence, all tested surfaces are side surfaces since the top surface already has much better surface quality and only the bottom surface required support removal. Typically, in Co-Cr materials, the average surface hardness as-manufactured is approximately 360 ± 20 HV10 and surface roughness Ra 8 µm and Rz 30–50 µm [22].

In addition, four hexagonal prims were manufactured from EOS Stainless-steel 316L powder with 12 test surfaces on each. In this case, the machine was an EOSINT M 280 with default manufacturing parameters and a layer

thickness was 20 μm. These parameters involved a scan speed of 900 mm/s, laser spot size of 0.1 mm, hatch spacing 100 μm and a maximum power output of 195 W. No heat treatments or stress relieving were implemented. The 316L has high ductility and corrosion resistance and is used in applications such as jewellery making, tooling and manufacturing applications, as well as in the medical field and in aerospace. Typical hardness as-manufactured is 170 HV10 and surface roughness Ra 13 ± 5 μm and Rz 30–50 μm [22]. During the AM process, all 316L hexagonal prims we oriented horizontally, according to the same principle as that of the test shafts. In this regard, Fig. 1 shows the processed test pieces after the ultrasonic burnishing process.

These materials were selected due to their potential real applications, such as in medical manufacturing or tooling industry. As mentioned earlier, the additively produced and burnished high performance steel can be used for tooling applications and Co-Cr can be used in dental applications. Previous studies have characterized the ultrasonic burnishing of aluminium, tempered steel and its alloys, polymers, titanium, brass, nickel and copper [6]. However, additively produced materials have not been studied in depth and the chosen materials require characterization after the ultrasonic burnishing in order to study its suitability in the presented industrial contexts.

2.2 The experimental setup and the ultrasonic burnishing process

The ultrasonic burnishing equipment was installed first to a manual lathe to process the Co-Cr cylindrical parts (see Fig. 2a). On the other end, the same equipment was installed to process the 316L stainless steel prims using a NC machining centre (see Fig. 2b). The response variables for both experiment were surface roughness (Ra), and hardness values (Hv10) were measured for the most relevant results. The experiment had the objective to characterize surface roughness by means of ultrasonic burnishing of AM-produced metallic materials.

As an overview of the ultrasonic burnishing process, the finishing head is compressed against the test piece where the spring ensures constant contact. In addition, lubrication fluid is added between the finishing head and the work piece. The frequency can be controlled via the control unit. Both experimental setups (i.e. Co-Cr lathe processing and 316L milling processing) were connected to the same generator and control unit. Figure 3 shows a schematic of

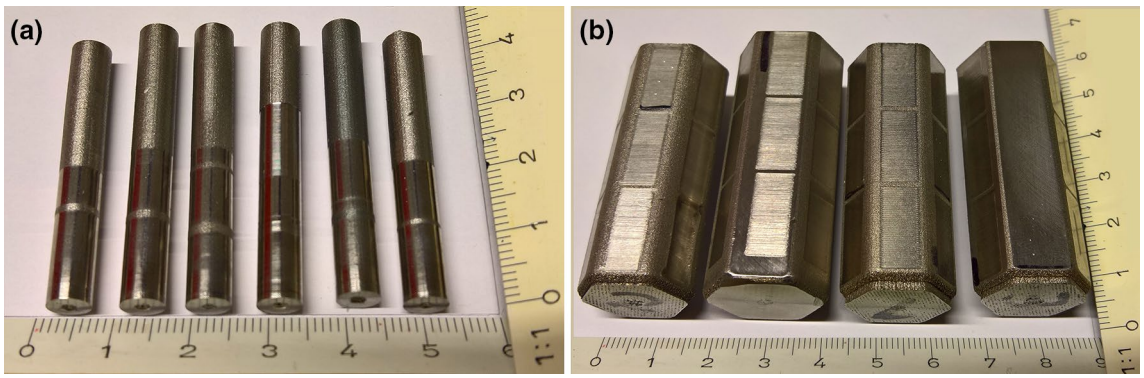

Fig. 1 **a** Co-Cr cylindrical test samples. **b** 316L Stainless steel prims. Images of the test pieces after ultrasonic burnishing

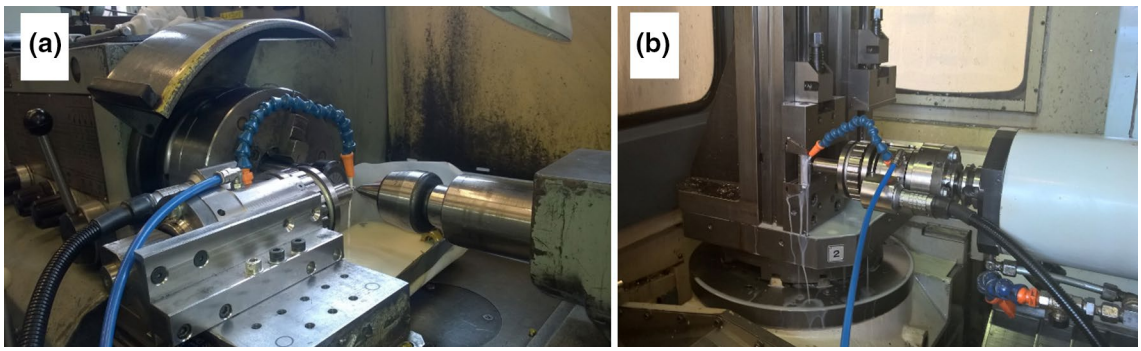

Fig. 2 **a** The ultrasonic burnishing equipment installed into a manual lathe. **b** The equipment installed in NC machining centre

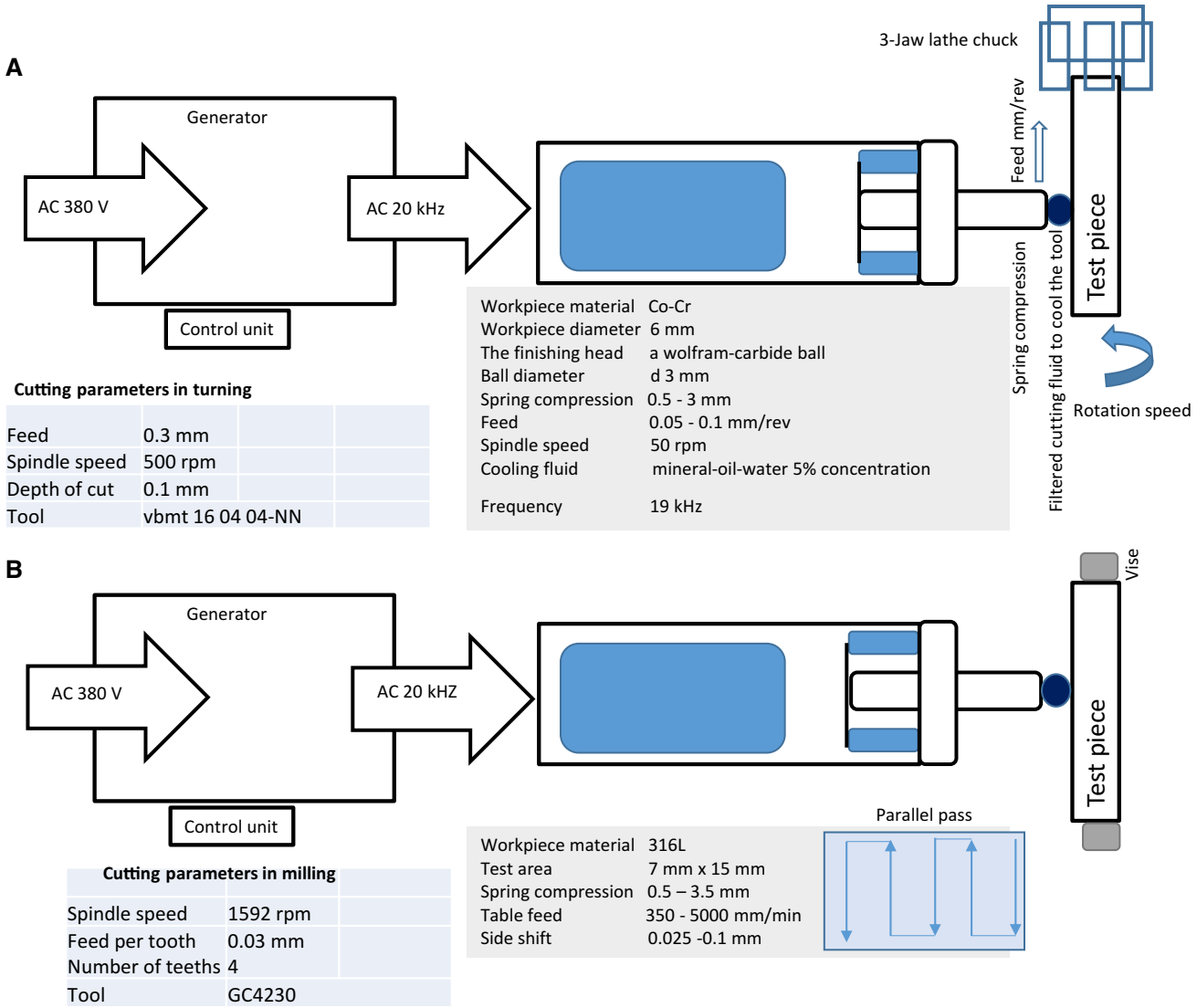

Fig. 3 The schematic of the ultrasonic burnishing system—the measurements and data acquisition process. **a** Co-Cr lathe processing and **b** 316L milling processing

the process as well as the detail of the process parameter involved in the experimental work.

To process the Co-Cr, we used a manual lathe with a spindle power of 11 kW. The burnishing was performed with the HIQUSA ultrasonic burnishing equipment, with a wolfram-carbide ball with a 3-mm diameter. Looking at the previous body of knowledge [6], the experiment required to fix some of the process parameters; these involved a spindle speed of 50 rev/min with an impact frequency of 19,000 Hz. This initial experiment plan involved a full factorial design of experiment (DOE) to obtain reference values. This was performed by studying two relevant factors: (1) feed (mm/rev) and (2) spring compression (mm). Feed had 2 levels (i.e. 0.05 mm/rev and 0.1 mm/rev) and spring compression was tested for 7 levels (i.e. ranging from 0.5 to 3 mm and intermediate values). The range of values for the controlled process variables were extracted from previous research [7, 9]. To this end, the full factorial DOE involved 18 experimental combinations. Replications was used to analyse measurement and experimental variance.

To process the 316L stainless steel, we used a Mazak milling centre with a power of 22 Kw. In order to limit the need for experimental work, the approach was to fit our experimental work to a fractional factorial DOE, in which only the more promising values for the process parameters were taken into consideration. To this end, the range of values for the controlled variables were extracted from previous experimental work with the lathe as well as

related research [9, 11] and we set the impact frequency to 19,000 Hz. During the milling process, we studied three relevant factors: (1) table feed (mm/min), side shift (mm) and (2) spring compression (mm). Table feed had 10 levels (i.e. ranging from 300 to 5000 mm/min with intermediate values), side shift had 5 levels (i.e. ranging from 0.025 to 0.2 mm with intermediate values) and spring compression was tested for 6 levels (i.e. ranging from 0.5 to 3.5 mm with intermediate values). To this end, the DOE involved 54 experimental combinations, from which the most promising experimental combinations were replicated several times.

The burnishing for both materials was performed with the same finishing head, a wolfram-carbide ball with a diameter of 3 mm. The cooling fluid used was a mineral oil–water mixture of 5% concentration for both experiments (i.e. Co-Cr lather processing and 316L milling processing). A lubrication fluid was utilized to avoid overheating the workpiece. The effect of noise factors, such as external noise (e.g. environmental conditions, temperature and humidity), deterioration noise (e.g. machine lifetime deterioration, machine maintenance and material quality) and variation noise (e.g. tool and machine stiffness and vibrations) was minimized by performing the experiment in a controlled environment.

The analysis of the experimental result was performed using "Minitab 16" statistical software. To this end, the data have been analysed by analysis of variance (ANOVA) and studying the effect and interactions of process parameter on the final surface quality. The results will show the corresponding main effect plots for surface quality, which has been used to model differences between level means at different levels. Finally, the interaction and the impact of the most relevant factors are studied using Pareto charts of the standardized effects. In this case, Pareto chart of the effects will be used to determine the magnitude and the importance of an effect and the effect of the interactions.

2.3 Measurement setup

The measurements were focussed on obtaining values for surface roughness (Ra) for each experimental combination and hardness for the most relevant results (Hv10). The surface roughness was measured with a Perthen perthometer M4P measuring device. The device uses a touch probe to measure the topology of a line on the surface. The measurements are in Ra values, which refer to the mean deviation of the surface profile in µm. There were three repetitions for each measured surface, three before process and three after process. Unusual values were rejected and measured again. A total number of 45 roughness measurements for Co-Cr and 162 for stainless steel 316L were done. The measurement direction of each sample was perpendicular to movement of the tool. In addition, the hardness was measured in three different points in both finished and unfinished surfaces by the Vickers method using a Brickers 220 hardness measuring device. In the hardness measurement of Co-Cr test pieces, the standard SFS EN ISO 6507 1 [23] was used to correct errors in the hardness values due to the cylindricity of the test pieces. This standard provides equations for compensating the cylinder effect.

As a reference and comparison, two surfaces of Co-Cr and three surfaces of 316L were machined before burnishing to compare how much surface roughness and hardness will differ from directly burnished samples. The milling parameters for 316L were 1592 rpm, 60-mm diameter face mill, 4 teeth, feed 1500 mm/min, feed per tooth 0.03 mm and 0.1 for depth of cut. Parameters for Co-Cr were 500 rpm, feed 0.3 mm/r and 0.4 mm as outer corner radius of the tool.

3 Results

3.1 AM and ultrasonic burnishing post-processing for Co-Cr

By analysing statistically the experimental data, we can indicate that optimal process parameters from the tested parameters for post-processing Co-Cr material are around 0.05 mm/r for the feed and 1.5 mm for the spring compression. The main effect for surface quality with different variables is shown in Fig. 4 and the Pareto chart in Fig. 5 is used to describe the most influential process parameter as well as possible interactions between feed and spring compression.

As a summary of the results regarding post-processing options for Co-Cr, Table 1 shows the measured surface quality and hardness, presenting minimum, maximum and average values of as-built Co-Cr, ultrasonic burnished Co-Cr, milled Co-Cr and milled and burnished Co-Cr.

The process time in ultrasonic burnishing depends heavily on spindle speed and feed rate. The fasted burnishing time in the tests for Co-Cr was 60 s and slowest one about 250 s compared milling time for the same area is 4 s. Table 2 shows the turning processing times with different parameters.

3.2 AM and ultrasonic burnishing post-processing for stainless steel 316L

By analysing the experimental data statistically, it can be indicated that the optimal process parameter values from tested ones, when taking consideration productivity, are around 1000 mm/min for the feed speed, 0.025 mm for the side shift and 1 mm for spring compression for

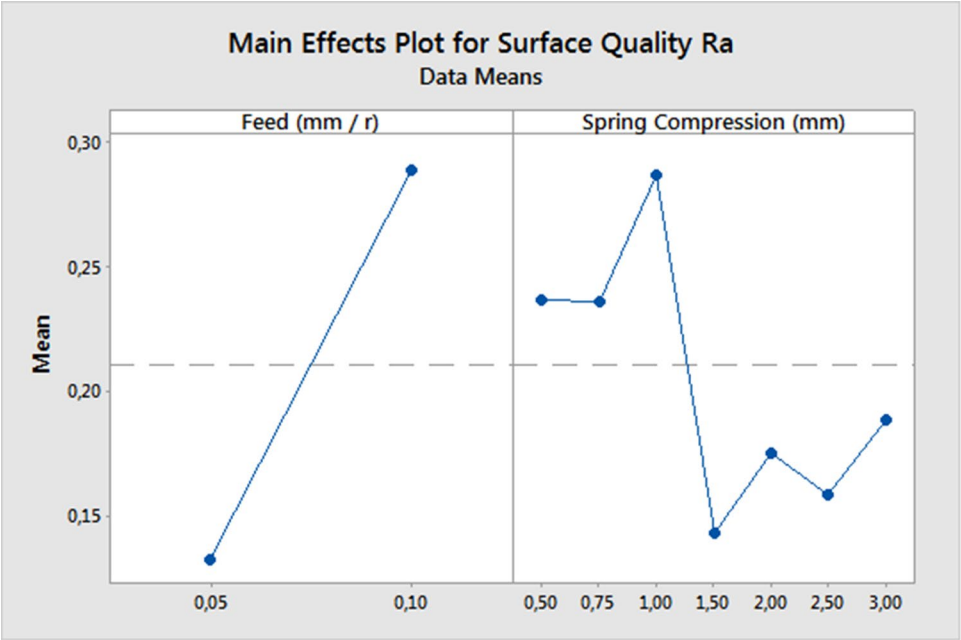

Fig. 4 Main effects plot for Co-Cr

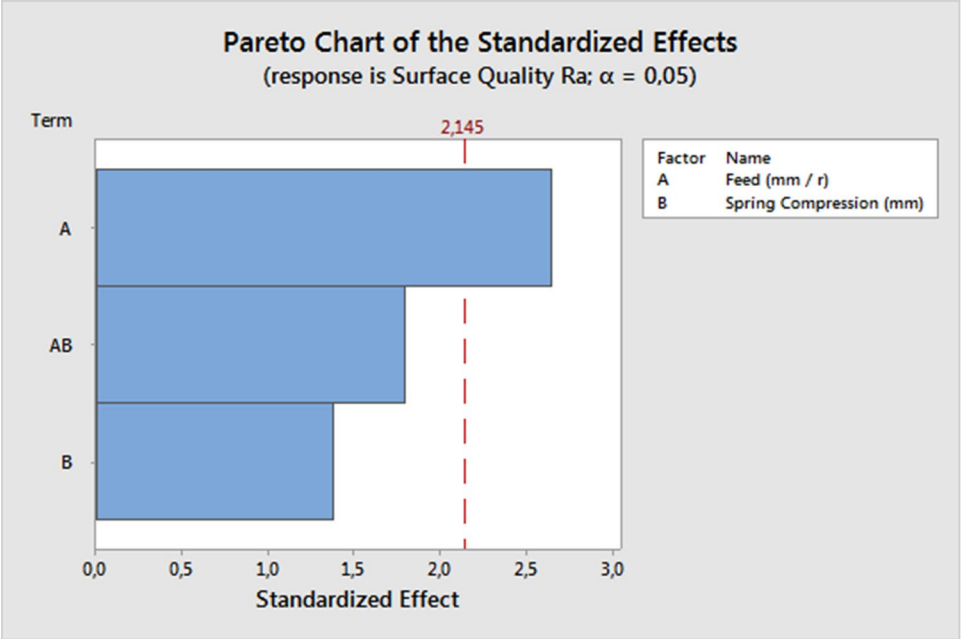

Fig. 5 Pareto Chart for Co-Cr

Table 1 A summary and comparison of the surface quality and hardness of Co-Cr

	Surface roughness Ra (μm)			Hardness (HV10)		
	Min	Max	Average	Min	Max	Average
As-built Co-Cr	4.30	7.81	5.66	367.04	380.63	373.84
Ultrasonic burnished Co-Cr	0.08	0.2	0.18	520.78	591.02	551.07
Turned Co-Cr	1.20	1.26	1.24	458.64	458.64	458.64
Turned and burnished Co-Cr	0.06	0.08	0.07	577.10	583.89	580.50

Table 2 Process times for Co-Cr

Ultrasonic burnishing				Turned			
The area of test piece (mm^2)	Spindle speed (rev/min)	Feed rate (mm/rev)	The burnishing time (s)	The area of test piece (mm^2)	Spindle speed (rev/min)	Feed rate (mm/rev)	The machining time (s)
13.7	50	0.05	240	13.7	500	0.3	4
		0.1	120				
		0.2	60				

post-processing 316L material. With feed 5000 mm/min, measured values were not reliable since the current construction of the tool started bend and the tip to drag behind. The main effect for surface quality with different variables is shown in Fig. 6 and the Pareto chart in Fig. 7 is used to describe the most influential process parameter as well as possible interactions between side shift, feed and spring compression.

As a summary of the results regarding post-processing options for 316L stainless steel, Table 3 shows the measured surface quality and hardness, presenting the minimum, maximum and average values of as-built 316L, ultrasonic burnished 316L, milled 316L, and milled and burnished 316L.

The process time in ultrasonic burnishing depends heavily on spindle speed and feed rate. The fasted burnishing time in the tests for 316L was 1 min and slowest one 17 min compared milling time for the same area is couple of seconds. The process times with different parameters are shown in Table 4.

4 Discussion

The lack of empirical research on ultrasonic burnishing applied to the post-processing of AM metallic materials motivated this research; therefore, the effects of process parameters, such as machine and tool relative displacement speeds (i.e. feed speeds and side shift), were initially

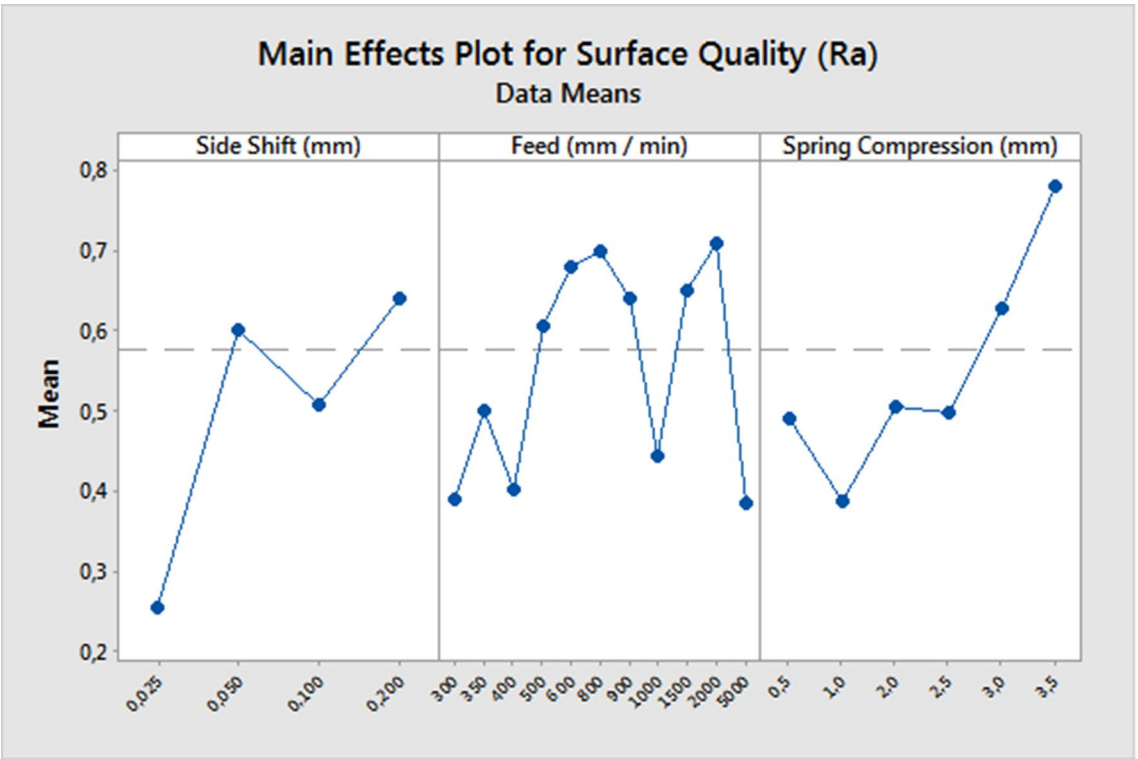

Fig. 6 Main effects plot for 316L

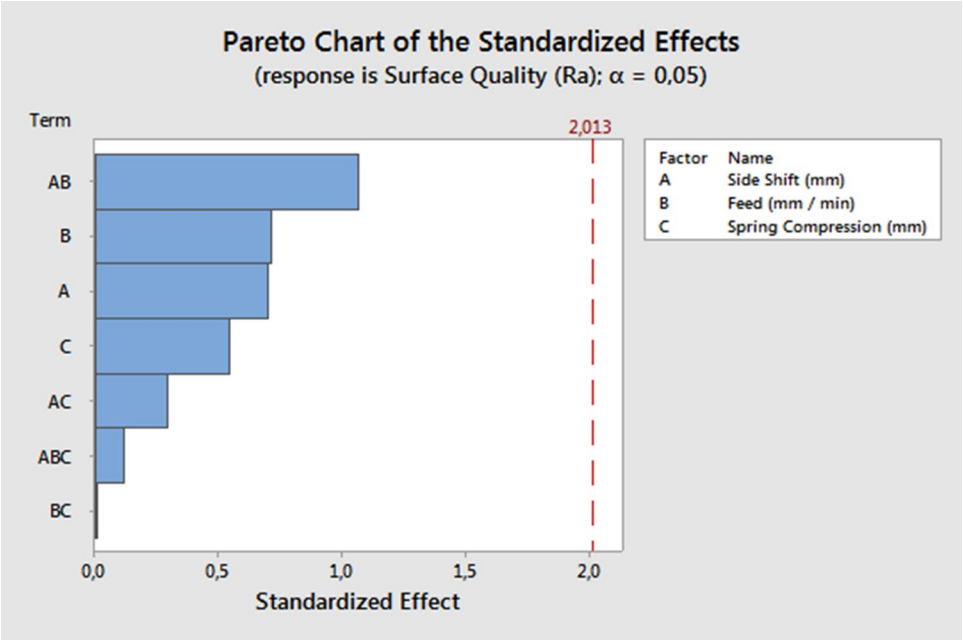

Fig. 7 Pareto chart for 316L

Table 3 A summary and comparison of surface quality and hardness for stainless steel 316L

	Surface roughness Ra µm			Hardness HV10		
	Min	Max	Average	Min	Max	Average
As-built 316L	5.73	9.27	7.39	194.50	205.00	198.06
Ultrasonic burnished 316L	0.22	1.23	0.55	298.67	374.00	338.17
Milled 316L	0.31	0.66	0.47	247.00	247.00	247.00
Milled and burnished 316L	0.94	1.10	1.00	366.00	383.00	375.17

Table 4 Process times for 316L

Ultrasonic burnishing				Milled			
The area of test piece (mm^2)	Side shift (mm)	Table feed (mm/min)	The burnishing time (min)	The area of test piece (mm^2)	Side shift (mm)	Table feed (mm/min)	The machining time (s)
105	0.025	1000	17.20	105	0.1	192	5
	0.05	1000	8.40				
	0.1	1000	4.20			1020	1
	0.1	5000	0.52				

studied. Furthermore, the effect of spring compression and ultrasonic burnishing frequency on surface quality and hardness was tested. The most relevant variables in the post-processing of AM produced metallic parts were initially mapped and tested in two different experimental manufacturing setups (i.e. Co-Cr lathe processing and 316L milling processing), the obtained data served as the ground for the presented analysis.

The results show that the post-processing of AM metallic material, implementing automated ultrasonic burnishing processes, can substantially improve the surface quality of as-built AM metals. Hardness values also improve substantially during the same process. However, optimization of the most relevant process parameters is required to obtain reliable machine setups. Currently ultrasonic burnishing is much slower compared to machining as it can be seen from the results, but in contrast, burnishing can become cost effective in comparison to hand polishing or other manual work. In addition, increased hardness might give better product performance to justify the process. Higher productivity values with a good surface quality and increased hardness can

be obtained with a better tool construction and minimizing vibrations.

4.1 The ultrasonic burnishing of Co-Cr and its medical applications

The experimental results presented in Fig. 4 show that surface roughness increases with the increase of feed speed and spring compression need to be not too low or not too high. Therefore, the optimization of these parameters is fundamental to achieve proper values in hardness and surface quality. The empirical evidence indicates that by fixing the feed speed to 0.05 mm/rev and having 1.5 mm of spring compression it is possible to obtain close to optimal results in terms of surface quality.

Looking at the summary of the results presented in Table 1, the post-processing of as-built Co-Cr by the ultrasonic burnishing method allowed a relative hardness increase of 47.4% (i.e. from 373.84 to 551.07 Hv), whereas (only) milled Co-Cr had a relative increase of 22.7%. When comparing ultrasonic burnished Co-Cr hardness versus milled and burnished Co-Cr (which had a relative increase in hardness of 55.8%), the difference is not substantial.

Regarding the surface quality improvement achieved in the post-processing of as-built Co-Cr by ultrasonic burnishing, Table 1 shows that the surface quality improved approximately 32 times from as-built Co-Cr (i.e. from Ra = 5.66 μm to Ra = 0.18 μm). Comparing only milled Co-Cr and ultrasonic burnished Co-Cr, the second process achieved better surface quality, with Ra values below 0.2 μm, which is a high level of finish and a perfectly smooth surface according to production standard ISO 1302:2002. When evaluating the difference of ultrasonic burnished Co-Cr (Ra = 0.18 μm) versus milled and burnished Co-Cr (Ra = 0.07 μm), the second process shows better surface quality, but nevertheless, the difference is not substantial as both processes fall under the same category in the ISO standard. In addition, the experimental results show that the most influential process parameter in the Co-Cr lathe processing experiment is the feed, the result of the Pareto analysis in Fig. 5 demonstrates that relative displacement of the burnishing ball and the test workpiece become fundamental to achieve optimal values. The interaction between spring compression and feed shows to be more important than the spring compression alone.

Based on this experiment, the post-processing of Co-Cr can be exclusively performed by ultrasonic burnishing in order to achieve surface and hardness quality. On the other hand, the milling operation can be limited to support removal. Hence, the ultrasonic burnishing approach could potentially be used for post-processing the Co-Cr dental crowns and bridges made by AM. Previous research has indicated that the finishing of Co-Cr dental applications made additively requires machining or the usage of manual dental laboratory equipment and techniques [24]. Typically, dental crowns and bridges made by laser-based AM requires manual finishing effort after NC milling [25]. Also removable partial denture alloy frameworks need manual polishing [26].

In the proposed solution, an automated process combining an ultrasonic burnishing tool head installed in a NC machine centre can be used to post-process Co-Cr in additively produced applications. This process will provide better hardness and good surface quality, improving resistance to abrasion and making it easier to sterilize. In addition, labour-intensive finishing processes can be replaced by setting up a more automated manufacturing system in order to provide a fully digitalized solution for dental applications, as well as other applications.

4.2 The ultrasonic burnishing of stainless steel 316L and its industrial applications

The experimental results presented in Fig. 6 show that surface roughness increases with the increase of spring compression as well as table feed speed. In addition, an increase in side shift values also has a negative impact on surface quality. Therefore, optimization of these parameters is fundamental in order to achieve proper values in hardness and surface quality. On the other hand, statistical analysis shows that combined effect from side shift and feed has the most effect to surface quality. Still even this combined effect will not statistically threshold as potentially important. This might be explained that in the process there might be variable that was not taken account enough, such as construction of the tool, vibrations etc. The empirical evidence indicates that by fixing the table feed speed to 1000 mm/min, the side shift to 0.025 mm and using a spring compression of 1.5 mm, it is possible to obtain close to optimal results in terms of surface quality and final hardness when also taking productivity in the considerations.

The effect of side shifts on the base roughness of material was relatively insignificant if the tool touches all the areas of the surface. In the experiments presented by López De Lacalle et al. [27], the best results after burnishing were achieved using 0.05 mm side shifts (Ra 0.18 μm). This value correlates with our experimental results. In addition, one should bear in mind that during ultrasonic burnishing the contact points of the post-processed workpieces should not be deformed too many times in order to ensure good burnishing results, as presented by Korzynski et al. [28].

The results presented in Table 3 show that the post-processing of 316L as-built stainless steel by ultrasonic burnishing method allowed a relative hardness increase of 70.7% (i.e. from 198.06 to 338.17 Hv), whereas (only) milled 316L stainless steel had a relative increase of

24.7%. When comparing ultrasonic burnished 316L hardness versus milled and burnished 316L, which had a relative increase in hardness of 89.4%, this second process has better results; however, the difference is only of an 18.7% gain in hardness.

The surface quality achieved in the post-processing of 316L as-built stainless steel by ultrasonic burnishing is presented in Table 3. The results show that surface roughness decreased by approximately 13 times after the ultrasonic burnishing of 316L as-built stainless steel (i.e. from Ra = 7.39 µm to Ra = 0.55 µm). Compared to (only) milled 316L and ultrasonic burnished 316L, the first process achieved better surface quality—Ra = 0.47 µm—whereas burnished 316L had an average surface roughness of Ra = 0.55 µm. Nevertheless, the difference is minimal and both finishing strategies would fall under the same category of *extra fine finish* for machine tools, according to production standard ISO 1302:2002 [25]. When evaluating the difference of ultrasonic burnished 316L (Ra = 0.55 µm) versus milled and burnished Co-Cr (Ra = 1 µm), the second process shows poorer surface quality. This counterintuitive effect can be explained due to the use of the same parameters for both post-process 316L and milled 316L. The experimental results show that the optimal process parameters need to be different post-process for milled 316L with ultrasonic burnishing. In addition, the experimental results show that the most influential process parameter in the 316L milling processing experiment is the interaction between feed speed and side shift, the result of the Pareto analysis in Fig. 7 demonstrates that the milling path becomes critical to achieve optimal values. Consistently, with existing body of research [23] as well as the previous experimental approach with Co-Cr, the most influential parameter in this experiment is the relative displacements of the burnishing tool and the workpiece followed by the spring compression.

The implementation of ultrasonic burnishing to post-process additively produced tool inserts could remarkably increase the surface hardness as well as the surface quality of the produced parts. Therefore, a tool insert located in the hot spots of forming tools will also increase wear resistance as well as fatigue life. Typically, milling post-processing can achieve specified high-quality roughness as long as the quality cutting tools and fluids are optimized. However, a high finish in milling requires that the end tool is changed periodically, whereas in the ultrasonic burnishing process the carbide ball has longer lifetime. AM-produced and ultrasonically burnished tool inserts have the potential to increase the performance of the forming process, as well as to reduce costs, when AM parts can be finished without machining, shortening working time.

5 Conclusions

Previous research has shown that the surface integrity of the material can be improved by ultrasonic burnishing processes [4]. The method has been used in a variety of materials to improve mechanical properties as well as to decrease surface roughness and increase surface hardness. However, the ultrasonic burnishing of additively produced metals and its possible applications have not been presented to date. This paper is the first attempt to research how ultrasonic burnishing post-processing methods impact on the surface roughness and hardness of AM metal components.

This work helps in understanding how the method affects the surface roughness and hardness of AM metallic materials. Judging by the experimental work presented in this article, ultrasonic burnishing improves the surface quality of metal AM parts: surfaces roughness improved remarkably and the surface hardness increases after burnishing. The experimental results confirmed the effectiveness of the ultrasonic burnishing method for enhancing the surface treatment with AM parts. The following conclusions can be drawn:

1. After ultrasonic burnishing, the average surface roughness (Ra) of Co-Cr was 0.18 and 0.55 µm for 316L stainless steel.
2. After ultrasonic burnishing, the relative increase in the average hardness of Co-Cr was 47.4% (i.e. 551.07 Hv) and 70.7% for 316L stainless steel (i.e. 338.17 Hv).
3. Optimal process parameters for post-processing Co-Cr material are around 0.05 mm/r for the feed and 1.5 mm for the spring compression.
4. Optimal process parameter for post-processing 316L material is around 1000 mm/min for the feed speed, 0.025 mm for the side shift and 1 mm for spring compression, when taking also productivity into consideration.

The results of this experiment point out that ultrasonic burnishing increases surface quality and surface hardness remarkably, also showing better results compared with the typical milling post-processing techniques used in the industry. This research was limited to study the side surfaces of the additively manufactured parts. Typically, the as-built top surface parts have better surface quality and the bottom surface requires support removal. Nevertheless, the effect of build orientation and the staircase effect in AM-produced parts can also be minimized by implementing an automated ultrasonic burnishing post-process. This could also reduce the labour-intensive processes of finishing metal parts made by AM processes and reduce cost barriers to the applications of additive technologies.

To conclude, future research need to focus on finding optimal burnishing process parameters considering the trade-offs between technical parameters (e.g. surface quality and surface hardness) and productivity issues (e.g. decrease manufacturing time) to drive this technologies to real industrial applications. To do so, more DOEs are planned to study the sensitivity of relevant process parameters (i.e. spring force, impact frequency, the effect of lubrication, feed speed, side shift, revolutions and the tool path of burnishing processes). In addition, the effect of noise factors (i.e. external noise, deterioration noise and variation noise, vibrations, construction of the tools) and trade-off over response variables (i.e. surface roughness and micro-hardness) had to be studied further. The industrial automation of ultrasonic burnishing post-processing for application in Co-Cr dental applications, as well as the post-processing of additively produced stainless steel for tool inserts, needs to be researched empirically in order to define technical parameters and drive the adoption of novel manufacturing methods based in additive processes in the industry.

Compliance with ethical standards

Conflict of interest On behalf of all authors, the corresponding author states that there is no conflict of interest.

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