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ScienceDirect

Procedia CIRP 49 (2016) 88 – 93

www.elsevier.com/locate/procedia

The Second CIRP Conference on Biomanufacturing

Laser micro-polishing of stainless steel for antibacterial surface applications

Chiara De Giorgi[a]*, Valentina Furlan[a], Ali Gökhan Demir[a], Elena Tallarita[b], Gabriele Candiani[b], Barbara Previtali[a]

[a]Department of Mechanical Engineering, Politecnico di Milano, Via La Masa 1, 20156 Milan, Italy
[b]Department of Chemistry, Materials, and Chemical Engineering "Giulio Natta", Politecnico di Milano, Via Mancinelli 7, 20131 Milan, Italy

* Corresponding author. Tel.: +39 02 2399 8530; fax: +39 02 2399 8530. *E-mail address:* chiara.degiorgi@mail.polimi.it

Abstract

In this work laser micro polishing (LMP) of cold rolled 0.3 mm thick 304 stainless steel with a pulsed fibre laser is studied, for applications where antibacterial properties are required. Due to its production method, the initial surface roughness of the tested material was considerably low (Sa=85.3±2.8 µm), rendering a demanding case for the laser polishing process. Accordingly, process feasibility under three different atmospheric conditions, namely ambient, Ar and N_2 atmosphere , was investigated. A large set of process parameter combinations was tested and initial analysis was carried out to identify the polishing feasibility by inspection under an optical microscope. Once the feasibility window was determined, a primary characterization was made on selected surfaces for roughness and waviness. Results show that in some process conditions belonging to the explored feasibility range, surface roughness could be decreased by 50%.

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Keywords: laser micro-polishing, stainless steel, antibacterial surface, surface roughness

1. Introduction

Austenitic stainless steel is widely used for different industrial purposes due to a combination of good mechanical properties and excellent corrosion resistance. Its anti-corrosive properties render it suitable for a variety of applications involving biological organisms. Grade 304 is one of the most versatile and most widely used stainless steel, available in a large range of products, forms and finishes. Typical uses are in architectural field, pharmaceutical and chemical industry processing equipment, heat exchangers, woven or welded screens for mining, quarrying and water filtration, food processing equipment [1,2]. Moreover this material is employed in applications where remarkable antibacterial properties are required, thanks also to its ability to withstand the corrosive action of various acids found in fruits, meats, milk, and vegetables. 304 stainless steel is used infact for domestic tools industry, such as sinks, troughs, table tops, stoves, refrigerators, other equipment and appliance; then it is also used in hospital environment for surgical and dental instruments.

Surface finish plays an important role regarding the interaction with the surrounding environment, hence with living organisms. Bacterial adhesion is an important concern in most of the related applications and are critically influenced by numerous variables [3], like surface morphology, physicochemical properties, environmental condition and type of pathogen. About surface morphology, it has been observed that the smoother surface implies the lower probability of bacterial attachment [4]. This occurs for three reasons: i) a higher surface area available for attachment, ii) protection from shear forces, iii) chemical changes that cause preferential physicochemical interactions [5]. On the other hand it seems that bacterial attachment is enhanced when the features of the surface have dimensions similar to bacterial size [4]. Hence, improved surface finish can prevent bacterial adhesion. For all of these considerations a polishing treatment could be appropriate to achieve antibacterial surface morphology properties. Several polishing technologies allow obtaining surface finishes in the nanometer range, for example abrasive polishing, lapping, mechanochemical,

Peer-review under responsibility of the scientific committee of The Second CIRP Conference on Biomanufacturing
doi:10.1016/j.procir.2015.07.055

electrochemical polishing, ultrasonic, and magnetoabrasive polishing [6].

Laser micro-polishing (LMP) is one of the presently available options capable to attain high surface finish levels. In comparison with other polishing techniques, laser polishing based on surface remelting shows several advantages. It is a fully automated and controlled process, with the capability to polish a well-defined area. It is a single step and quick process, without any types of contact avoiding mechanical forces at tool-workpiece interface and wear of tool, both typical problem of conventional polishing techniques. Laser micro-polishing, moreover, can be used to modify the surface chemistry, for example capturing in the molten pool molecules from an eventual gas flow [1,7,8]. However, the process of LMP has some disadvantages compared to other technologies. It is a thermal process, resulting in the formation of a heat affected zone that shows different mechanical properties compared to bulk material. Then it is strongly influenced by material initial roughness and by the possible presence of some surface defects like scratches; infact the surface finish could vary the absorption or reflection of the incident radiation [1,7,8].

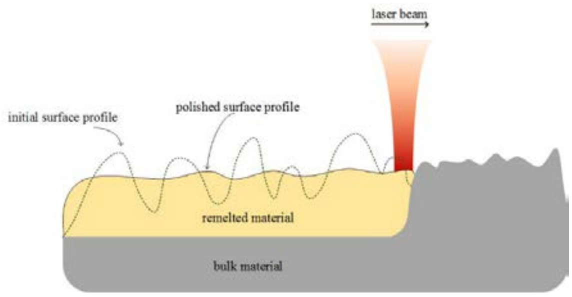

Fig. 1. Laser remelting process for polishing.

During laser micro-polishing (Fig.1), laser beam energy is delivered to workpiece surface; the molten pool of material formed tends to redistribute around the area adjacent to each initial surface asperity under the action of surface tension. This phenomenon results in the reduction of the majority of peak to valley heights and surface asperities, after the quick solidification of melted layer [7]. In this way, Yermachenko et al. demonstrated that the irradiation at appropriate parameters of the laser radiation in argon atmosphere leads to a decrease in the surface roughness of the titanium samples by a factor of five in comparison with the roughness of the original samples [9]. The same authors observed also an increase in the microhardness of the surface layer. Mai et al. presented the results of an investigation on laser polishing of 304 stainless steel surfaces, with roughness reduction of 62% [1]. Perry et al. introduced the concept of critical frequency to predict the effectiveness of polishing in the spatial frequency domain [10], showing the importance of different spatial components on the surface profile. As a matter of fact, primary profile of a surface is conventionally divided in two parts: i) roughness profile, that is simply a collection of all high-frequency components, and ii) waviness profile, that instead is a collection of small-frequency components. Roughness profile can be obtained by filtering the primary profile using a high-pass filter, while waviness profile using a low-pass one [11]. Therefore the parameter that determines what is roughness and what is waviness is the cut-off wavelength, i.e. the length at which the filters are applied and provided by ISO 4288:1996 [12].

Despite numerous works, one of the biggest challenge of the LMP process remains the achievement of low surface roughness when the initial surface morphology has already a good finishing quality, as occurred for cold rolled sheets.

In this work a fiber laser source in ns pulse regime was used to study the polishing feasibility of stainless steel surfaces, in order to obtain anti-adhesiveness properties against bacteria.

2. Experimental details

2.1. Material and systems

Stainless steel 304 alloy sheets were used throughout the study. The sheets were cold rolled to 0.5 mm thickness. The surface average roughness S_a was 85.3±2.8 nm, instead the surface average waviness S_a was 56.4±5.6 nm. The material nominal chemical composition is summarized in Table 1.

Table 1. Nominal chemical composition of employed 304 stainless steel.

Element	C	Cr	Ni	Mo	Si	Mn	P	S	N
wt.%	0.047	18.1	8.04	0.29	0.48	1.2	0.029	0.003	0.06

Before LMP, the specimens were cleaned in ultrasonic bath cleaning with deionized water (10 minutes), ethanol (10 minutes) and deionized water (10 minutes). Then the samples were dried in nitrogen.

A Q-switched fibre laser (YLP-1/100/50/50 from IPG Photonics, Oxford, MA, USA) in fundamental wavelength (λ=1064 nm) was used coupled to a scanner head (TSH 8310 by Sunny Technology, Beijing, China). The scanner head was equipped with an f-theta lens (SL-1064-70-100 from Wavelength Opto-Electronic, Ronar-Smith, Singapore), with focal length of 100 mm; so the calculated beam diameter in focal point was 39 µm. The workpiece was positioned in Z-axis with L490MZ/M motorized lab jack from Thorlabs, inside a gas chamber. The main specifications of the employed laser system are summarized in Table 2.

Table 2. Main specifications of the employed laser system.

Wavelength	**λ**	1064 nm
Maximum average power	P_{max}	50 W
Pulse duration	τ	250 ns
Pulse repetition rate	PRR	20-80 kHz
Quality factor	M^2	1.7
Collimated beam diameter	d_c	5.9 mm
Focal length	f	100 mm
Focused beam diameter	d_0	39 µm