STUDY OF POLISHING AISI 316L WITH STRUCTURED ABRASIVE

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Rezumat. *Procesul de finisare prin lustruire este de obicei folosit pentru a obține caracteristici ale suprafațelor de înaltă calitate, cum ar fi textura și rugozitatea. Aceste operații sunt în principal manuale, au nevoie de operatori foarte bine pregătiți, fiind limitate posibilitățile de repetabilitate și profitabilitate. Prin urmare, pentru a optimiza industrializarea procesului de lustruire este necesar să se modeleze procesul de bază, prin construirea unei baze de date cu parametrii de eficiență. Scopul acestui studiu este de a caracteriza lustruirea oțelului inoxidabil AISI 316L utilizând benzi abrazive structurate. Datele geometrice ale benzilor sunt date, iar apoi se propune un model pentru a determina rata de îndepărtare a materialului. Este configurat un banc de încercare experimentală pentru a testa acest model și pentru a caracteriza procesul de lustruire în termeni de forțe. Sunt obținute probe pentru diferite condiții de lustruire. Diferitele suprafețe lustruite sunt apoi analizate după rugozitate și capacitate de umectare. Folosind modelele experimentale, a fost validat modelul propus și s-au identificat parametrii care influențează operația de lustruire.*

Abstract. *Finishing process like polishing is usually used to obtain high quality mechanical surface characteristics such as texture and roughness. These operations are mainly handmade and need highly trained operators thus limiting their repeatability and profitability. To optimize the industrialization of the polishing process, it is therefore necessary to modelize the process to built efficient parameter database. The aim of this study is to characterise the polishing of 316L stainless steel with structured abrasive belts. The geometric data of the belts are given, and we then propose a model to determine material removal. An experimental test bench is set up to test this model and characterise the polishing process in terms of forces. It produces samples for different polishing conditions. The different polished surfaces are then analyzed thanks to the roughness and the wettability. Using experimental designs, we are able to validate the proposed model and identify the parameters that influence a polishing operation.*

Keywords: polishing, structured abrasive, roughness, material removal rate, wettability

Introduction

Polishing is the last stage in the manufacturing of industrial parts to give surfaces well-defined characteristics. These may be related to roughness for aesthetic or functional reasons, to surface stresses to ensure better fatigue behaviour or to corrosion and wettability when a protective coating is to be applied.

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This process differs from other material removal processes as the thrust force exerted by the abrasive grains on the polished surface has to be controlled. Other factors can intervene, such as the morphology of the surface to be polished and the aggressiveness of the abrasive grains, which can change in the course of the polishing cycle. These operations must therefore be carried out by experienced operators in order to meet the most stringent level of requirements for the polished parts.

To derive the maximum from abrasive tools in terms of quality, productivity and repeatability, it is necessary first to identify and control the parameters that govern the polishing process and the operating range of each one.

Here we describe a study carried out to provide this information for structured abrasive belts polishing a 316L stainless steel. We give the geometric characteristics of the abrasive belts used in the experiment and propose a model to characterise the material removal rate. Next, we describe the equipment set up to test this model and provide data to characterise the polishing process in terms of stress, roughness and wettability of the polished surface.

State of the art for the study of abrasive polishing

Studies to date can be divided into three categories according to their scale. At microscopic level, E. Felder and F. Klocke have studied the action of an indenter on the material [1], [2]. They demonstrate the different metal cutting/pickup mechanisms. The macroscopic approach, the second level of study, considers the overall effect of an abrasive tool on a portion of material. Finally, some authors consider the polishing operation as a whole. X. Pessoles defined the trajectory to be applied to the abrasive tool in order to obtain similar results to those produced by skilled workers [3]. F. Nagata studied mould polishing using a polyarticulated robot [4]. They show that it is vital to use a trajectory-stress combination to finish skew surfaces successfully.

To date, the models that best characterise polishing at macroscopic level are empirical models. The model by F.W. Preston is the one most often used to deal with the issue of material removal [5]. C. Wang [6], J. Luo [7] and A. Guiot [8] have attempted to complete this model for certain polishing processes and these models provide useful data for designing a polishing process. V. Lacharnay defined the operating procedure to achieve a mirror finish quality using rotating discs [9].

Here, we intend to validate Preston's model for polishing 316L stainless steel parts with structured abrasive belts and to characterise this process in terms of roughness and wettability of the polished surfaces.

Characterisation of the abrasive belts

The abrasive belts used in our study (reference TRIZACT 307EA, 3M) are structured abrasives. The aluminium oxide abrasive grains are arranged in the form of pyramids, with a synthetic resin ensuring cohesion between grains and the bond with the flexible cloth belt (see Figure 1).

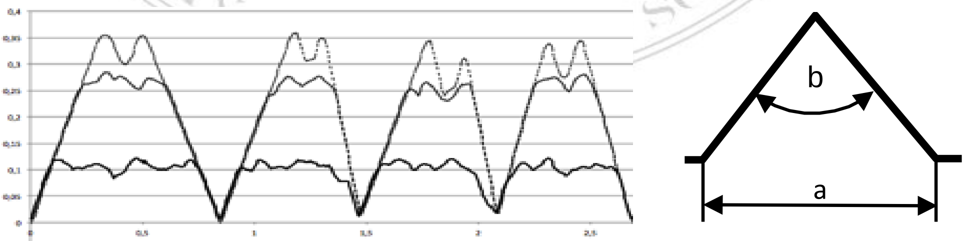
Fig. 1. Portion of new TRIZACT 307EA belt.

The grain sizes selected for our study cover the range offered by the manufacturer. They are given in Table 1.

Table 1. Average size of abrasive grains

3M Reference	FEPA Classification	Average grain size according to FEPA
A100	P180	82 μm
A30	P800	21.8 μm
A6	P2500	8.4 μm

The geometric characterisation of the belts is obtained by digitising the surface of the pyramids using a 3D ALTISURF 500 roughness meter with a conical 60° point. In order to take into account any variation in the dimension of the pyramids, each reading relates to an alignment of 10 pyramids. From each reading the profile of the pyramids is extracted in the plane normal to the belt and over their apex. Figure 2.a shows the profile of an alignment of grade A100 pyramids as new and then at two stages of wear of the abrasive belt.



a. Reading for alignment of pyramids **b.** Geometric parameters

Fig. 2. Geometric characteristics of abrasive pyramids

Figure 2.b shows the geometric parameters of a pyramid: the width of the base (*a*) and the angle at the apex (β). Table 2 gives the dimensions for the abrasive belts studied and their standard deviation, values for each belt reference derive from 100 pyramids: 10 alignments of 10 pyramids sampled from different belts.

Other parameters such as the concentration of grains, mechanical resistance and the adhesive strength of the synthetic resins also come into play when defining the process. However, these data are not usually provided by manufacturers and are rather difficult to determine experimentally.

Table 2. Width and angle at the apex of the pyramids and standard deviation.

Parameters	unit	A100	A30	A6
Width of base (a)	mm	0.638	0.483	0.499
Standard deviation of (a)	mm	0.077	0.070	0.054
Angle at apex (β)	degree	75.68	78.82	75.90
Standard deviation of (β)	degree	6.96	11.49	5.53

Study model

Using the model most often referred to in publications on abrasive machining, we put in the equations that govern material removal. From these we obtain valuable theoretical information for the designers of polishing processes based on the technology of structured abrasives.

Our study is based on Preston's model (equation 1). This defines the speed of indentation by the abrasive tool in the polished material (d*z*/d*t*). This speed is the product of a constant (*Cp*) specific to the polished material, the nature and size of the grains and the characteristics of the binder, and the pressure (*p*) exerted by the abrasive grains on the polished surface and the feed speed of the grains (*V*).

$$\frac{dz}{dt} = C_p \,.p\,.V \qquad (1)\ (2)$$

Taking into account the relative movement of the abrasive grains as they sweep a surface ($S_{projected}$), if pressure (p) is exerted at any point on the apex of the pyramid ($S_{contact}$) by the abrasive grains of which it is composed (see Fig. 3a), then the larger the abrasive-material contact area, the more material will be removed. To take account of changes in the geometry of the abrasives used according to the wear, an evolution of the Preston's model is given in equation (2).

$$\frac{dz}{dt} = \frac{S_{contact}}{S_{projected}} \cdot C_p \cdot p \cdot V \qquad (3)\ (2)$$

Considering the geometry of the pyramids when in use, as shown in Fig. 3b, the surface ratio is expressed in equation (3).

$$\frac{S_{contact}}{S_{projected}} = \left(\frac{x}{a}\right)^2 = \left(\frac{h-z}{h}\right)^2 = (1-k)^2$$ (4) (3)

where k represents the rate of wear of the pyramids. The pyramids are new when k=1, and fully worn when k=0. Equation (2) then becomes:

$$\frac{dz}{dt} = (1-k)^2 \cdot C_p \cdot p \cdot V$$ (5) (4)

From this, the material removal rate can be expressed:

$$\frac{dv}{dt} = S_{projected} \cdot \frac{dz}{dt} = S_{projected} \cdot (1-k)^2 \cdot C_p \cdot p \cdot V$$ (6) (5)

Pressure (p) derives from the thrust force (*Fz*) applied to a pad with a constant cross-section pressing the abrasive grains downwards onto the material to be polished. Here too the ratio of the area of the pad to the area of the pyramid apices in contact with the part to be polished must be taken into account.

$$p = \frac{F_z}{S_{contact}} = \frac{F_z}{S_{projected} \cdot (1-k)^2}$$ (7) (6)

When the thrust force is constant, the pressure exerted at the apex of the pyramids decreases as the contact surface of the abrasives increases due to the effect of wear. The material removal rate can then be expressed as

$$\frac{dv}{dt} = C_p \cdot F_z \cdot V$$ 8) (7)

and the indentation speed of the abrasive belt in the material can also be written:

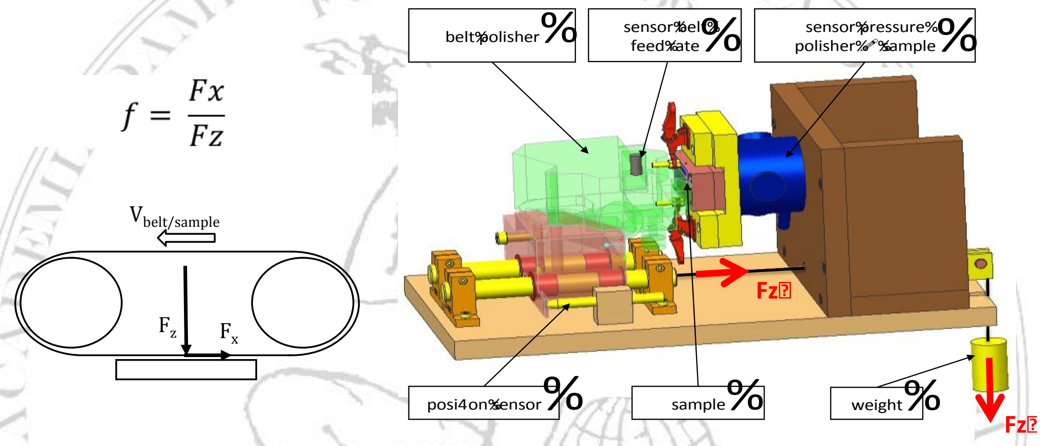
$$\frac{dz}{dt} = C_p \cdot \frac{F_z \cdot V}{S_{projected}}$$ 9) (8)

In the context of our study, designing a polishing process consists mainly of defining: the thrust force to be exerted by a polisher with a pad that has a constant cross-section and a feed speed for the belt. When these are determined, material removal is constant in theory, whatever the degree of wear on the structured abrasive belts.

Based on Preston's model, for pyramid-shaped structured abrasive belts we put in place models defining the forward speed of the polisher across the material and the material removal rate. We show that the material removal rate does not vary throughout the life cycle of the belts we studied, when the parameters of the process remain fixed. We shall see later to what extent this model is verified.

Experimental system

An experimental approach is used to characterise the polishing process of the pyramid abrasive belts. The aim is to characterise: the material removal rate, the tangential cutting coefficient, the ratio of the polishing force borne by the polished surface (*Fx*) to the thrust force (*Fz*) applied perpendicular to the polished surface (see Figure 4.a), the roughness and the wettability of the polished surface. We devised a test bench to measure the thrust force (*Fz*), the tangential stress (*Fx*), the feed speed of the abrasive grains (*V*) in the course of a polishing operation and the position of the polisher which remained normal to the material.



a. Polishing force → sample **b.** Layout of the polishing bench

Fig. 4. Principal features of the polishing bench.

Figure 4.b shows the layout of the polishing bench. It consists of a pneumatic abrasive belt polisher (reference DINABRADE 14200 – speed without load = 30 m/s – belt width = 25.4 mm – belt length = 457 mm).

To ensure that the polisher covers the sample correctly (maximum dimensions: 40 × 70 × 2 mm), it is guided in translation by sleeve bearings mounted on two rigid columns. The thrust force is obtained by a cable attached to a weight suspended in mid-air. The forces applied to the sample by the polisher are measured with a six-component dynamometric sensor. The feed rate of the belt is controlled by a flow regulator with a cone-point set screw. It is measured using an inductive sensor combined with a metal pad placed on the roller ahead of the polisher.

Lastly, the position of the polisher in relation to the sample is measured with an LVDT sensor. On the Figure 5, the normal polishing force (*Fz*), the tangential polishing force (*Fx*), the tangential polishing coefficient (*f*) and the linear speed of the abrasive (*V*) are presented.

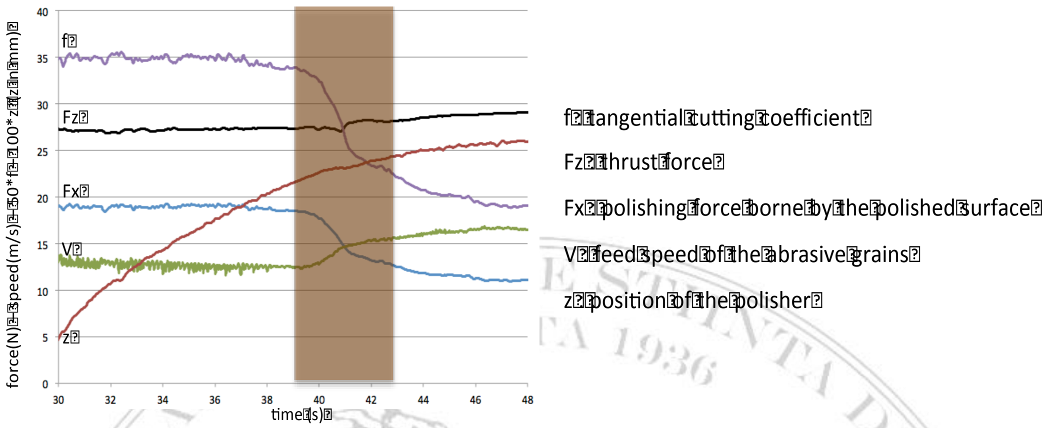


Fig. 5. Evolution of the process parameters.

Characterisation of the performance of the abrasive belts

6.1. Design of experiments

An factorial design of experiments (DOE) is proposed to determine material removal (dz/dt), the tangential cutting coefficient (f) and roughness (Ra) for polishing operations with grade A100, A30 and A6 belts.

The input parameters and their boundaries are given in Table 3. These boundaries of DOE are defined from preliminary tests and test bench limits.

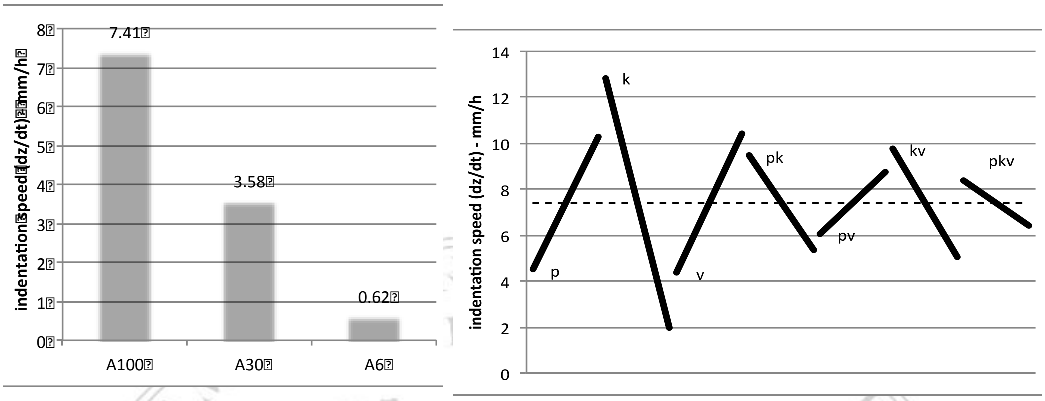
Table 3. Input parameters of the experimental design

Parameters	Symbol	Unit	Min. boundary	Max. boundary
Abrasion pressure	p	N/cm^2	10	20
Speed	V	m/s	10	25
Wear rate	k		0.2	0.7

6.2. Polisher indentation speed

These tests will help to identify influent parameters on material consumption (dz/d*t*) and will be compared to the modified Preston's model results. Figure 6.a shows the average indentation speed (dz/d*t*) for the three types of belt considered. The productivity of a polishing operation is closely linked with the size of the grains, with a ratio of 1 to 10 for the two extreme grades studied (A100 and A6).

Figure 6.b shows the coefficients for the input variables for the A100 belt. It can be seen that the weight of the p, k and V coefficients is significant, as are all the interactions. The different tests carried out on the A30 and A6 belts show identical changes to those shown in Figure 6.b.



a. Average values **b.** Coefficients of input parameters – A100 belt

Fig. 6. Results for indentation speed (d*z*/d*t*).

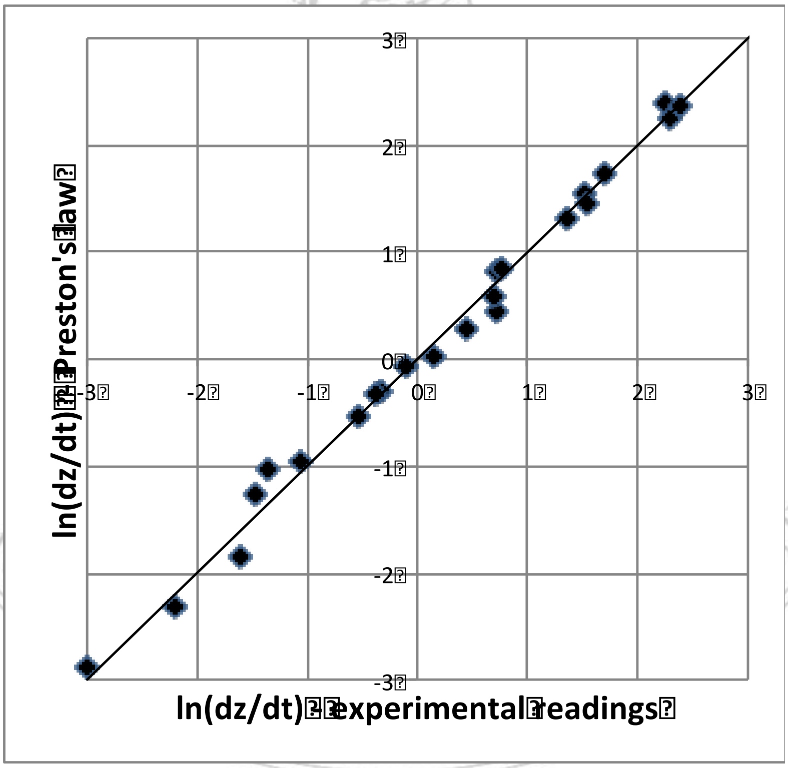


Fig. 7. Deviations between experimental readings and Preston's law.

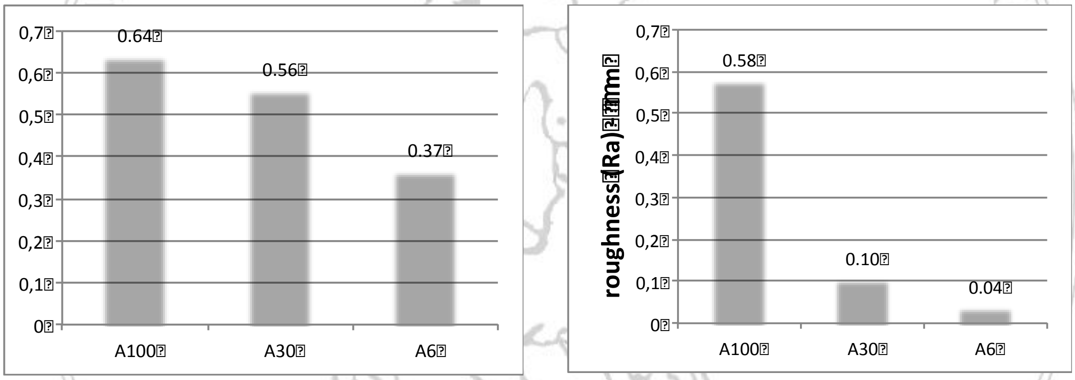
The tests established for this experimental design enable us to determine the Preston constant (Cp) using a least squares regression. We are therefore able to calculate the theoretical values for indentation (dz/dt) for each test in the experimental design.

In Figure 7, we show the comparison between these calculations and the values from the tests. An Ln-Ln scale is used for a better distribution of the points on the graph, revealing a good correlation between the model and the experimental values. The differences between the measurement and the values of the model are lower than 15 %.

6.3. Tangential cutting coefficient

From the experimental design dealing with the tangential cutting coefficient the average of this parameter can be established for each type of belt (see Figure 8,a). It is greater the larger the size of the grains.

The coefficients of input parameter effect and interaction are less than 1/10 of the average standardised value. The pressure, speed and abrasive wear parameters therefore have only a very weak influence on the tangential cutting coefficient.



a. Tangential cutting coefficient **b.** Arithmetic average deviation (Ra)

Fig. 8. Average values from experimental design.

6.4. Roughness of the polished surface

Standard NF EN ISO 4287 [10] suggests different parameters to characterise the roughness of a metal surface. For our work, we decided to use the arithmetic average deviation criterion of the profile (Ra). Readings were taken using a 3D ALTISURF 500 roughness meter equipped with a confocal white light sensor.

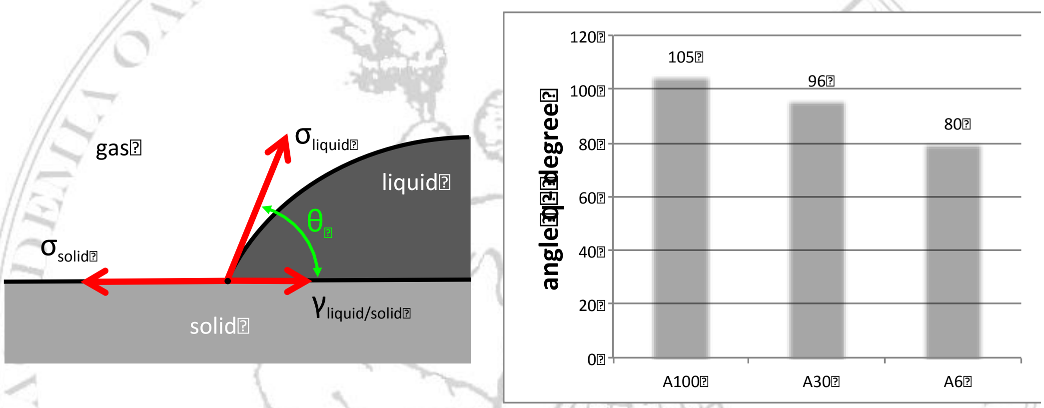
Figure 8.b shows the average values of (Ra) for the three types of belt studied. In this instance too, average values are lower the smaller the grain size. For the interaction coefficients specific to each input parameter, values have little influence on output, with most being less than 10% and with a maximum at 20%. And here too the parameters of the process, with the exception of grain size, have no influence on the arithmetic average deviation of the profile of the polished surface.

6.5. Wettability

Wettability is the ability of a liquid to spread over a surface. It is defined by the angle (θ) between the tangent at the base of a drop of distilled water and the surface on which the drop is placed.

Based on Young's equation, the link can be established between surface tensions σ_{solid} , σ_{liquid} , interfacial tension $\gamma_{liquid/solid}$ and contact angle θ using the following equation:

$$\sigma_{solid} = \gamma_{liquid/solid} + \sigma_{liquid} * \cos(\theta)$$ 10) (9)



a. Angle determining wettability. **b.** Angle (θ) for 316L stainless steel.

Fig. 9. Characterisation of wettability.

This ability runs counter to the process whereby paint or adhesive sticks to a backing. The greater the angle (θ) the more difficult it will be to make a coating adhere to the surface.

The results obtained here show the influence of particle size on the wettability of the surface obtained for 316L stainless steel.

Conclusion

The aim of this study was to characterise the polishing process for 316L stainless steel using structured abrasive belts. After describing their main geometric characteristics, we proposed a model based on Preston's law to determine material removal. We set up an experimental test bench in order to produce an experimental design and were thus able to validate the model suggested for different grain sizes.

We were also able to specify the tangential cutting coefficient, roughness and wettability of the polished surface for three types of belt and show that only grain size has a bearing on these production goals.

Acknowledgements

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R E F E R E N C E S

[1] E. Felder, "*Usinage par abrasion - principes généraux*", Techniques de l'Ingénieur. http://www.techniques-ingenieur.fr, 2009.

[2] F. Klocke, O. Dambon, and R. Zunke, "*Modeling of contact behavior between polishing pad and workpiece surface*", Prod. *Eng.*, vol. 2, no. 1, pp. 9–14, Apr. 2008.

[3] X. Pessoles and C. Tournier, "*Automatic polishing process of plastic injection molds on a 5-axis milling center*", J. Mater. Process. Technol., vol. 209, no. 7, pp. 3665–3673, Apr. 2009.

[4] F. Nagata, T. Hase, Z. Haga, M. Omoto, and K. Watanabe, "*CAD/CAM-based position/force controller for a mold polishing robot*", Mechatronics, vol. 17, no. 4–5, pp. 207–216, May 2007.

[5] F. W. Preston, "*The theory and design of plate glass polishing machines*", J. Soc Glass Technol., pp. 214–256, 1927.

[6] C.-C. Wang, S.-C. Lin, and H. Hochen, "*A material removal model for polishing glass–ceramic and aluminum magnesium storage disks*", Int. J. Mach. Tools Manuf., vol. 42, no. 8, pp. 979–984, Jun. 2002.

[7] J. Luo and D. A. Dornfeld, "Material removal mechanism in chemical mechanical polishing: theory and modeling," *IEEE Trans. Semicond. Manuf.*, vol. 14, no. 2, pp. 112–133, May 2001.

[8] A. Guiot, C. Tournier, and Y. Quinsat, "*Modélisation de l'usure des abrasifs pour garantir la qualité des surfaces polies*", presented at the 13ème Colloque National AIP PRIMECA, 2012.

[9] V. Lacharnay, C. Tournier, and G. Poulachon, "*Design of experiments to optimise automatic polishing on five–axis machine tool*", Int. J. Mach. Mach. Mater., vol. 12, no. 1, pp. 76-87, 2012.

[10] NF EN ISO 4287 - *Geometrical Product Specifications (GPS) - Surface texture : profile method - Terms, definitions and surface texture parameters.* International Organisation for Standardisation.