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# Towards the prediction of surface roughness induced by the belt finishing process: influence of the workmaterial on the roughness reduction rate

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## Abstract

The belt finishing process is of great interest for the automotive industry so as to obtain smooth surfaces, especially after hard turning operations. It enables to reduce and homogenize the surface roughness. It also prevents any shifting of surface quality from tool wear in hard turning. Belt finishing induces its own surface topography which will be rather independent of the previous one. Its surface signature is correlated to the abrasive belt topography. However models able to predict the final roughness of a part are missing. This article proposes to investigate the roughness reduction during the transitory state of the belt finishing process. The study is performed for different workmaterials. The main objective being to propose a first simple approach to predict the final roughness as a function of the initial roughness, work material and time.

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**Keywords:** belt finishing; surface roughness; prediction

## 1. Introduction

### 1.1. Belt finishing process

The belt finishing process is an interesting alternative to conventional grinding for the precision machining of mechanical components. Indeed this process can reduce manufacturing costs and time but also produces high quality parts [1]. Aeronautic [2], automotive [3, 4, 5] and railway [6] industries pay more and more attention to this process which develops rapidly. Even though a belt finishing machine can easily be instrumented on machine tools, the development of the process is rather new and requires more research studies.

The principle of the belt finishing process (see figure 1) is the following:

- A belt composed of abrasives (several tens of microns in size) is pressed against a rotating workpiece (tangential

speed  $V_t$  - order of magnitude: hundreds of m/min) with a radial pressure  $P$  (order of magnitude: bar).

- New abrasives are introduced continuously in the contact between the belt and the workmaterial thanks to a roller rotating with a rather low belt feed rate  $V_a$  (order of magnitude: tens of mm/min). As new abrasives are introduced, worn grains are eliminated. The worn belt never returns in the contact.
- The belt is oscillating at a frequency  $f$  (order of magnitude: tens of Hz) over a stroke distance  $d$  (order of magnitude: mm), in the axial direction of the bar. The goal of this oscillation is to get abrasives cutting perpendicular to the turning patterns.
- Additionally, the complete belt finishing device performs a linear movement (at a feed rate  $f_t$ : order of magnitude mm/rev) along the axial direction of the bar. As a consequence the belt finishing process can be applied back and forth on the workpiece to homogenize the bar surface topography.

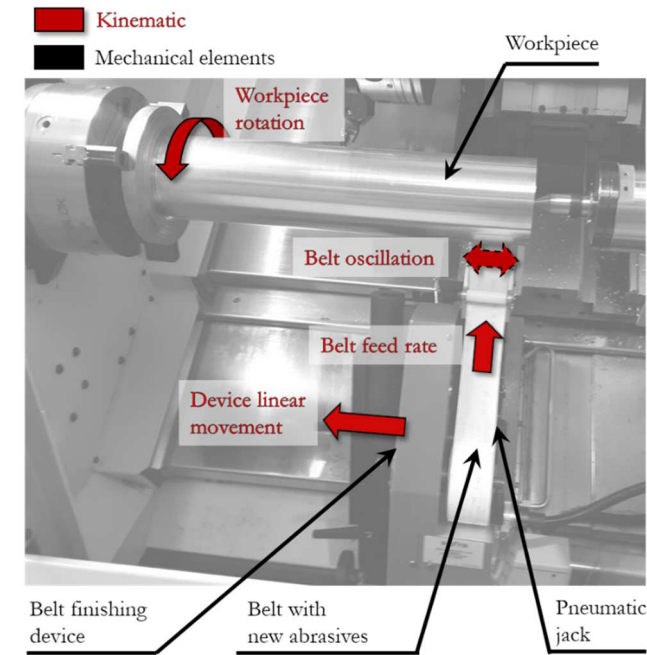
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- The process can be performed under dry, lubricated or MQL (Minimum Quantity Lubrication) conditions.

Figure 1: belt finishing process.

### 1.2. Belt finishing effect on Surface Integrity

Apart from economic considerations, the belt finishing process effect on surface integrity is very benefic. Indeed the following effects on the parts' surface integrity can be listed:

- Microstructure: the belt finishing process can remove the very thin external white layer which might be generated during previous machining processes [7].
- Residual stresses: compressive residual stresses can be generated thanks to this process [8, 9].
- Surface topography: the roughness can be improved [8] and homogenized (the average roughness  $R_a$  can decrease down to  $0.1 \mu\text{m}$ ). Further details will be given on this topic in the following section.

### 1.3. Focus on belt finishing parameters and their effect on surface topography

The particularity of the belt finishing process compared to other finishing processes is that new abrasive grains are introduced continuously in the contact between the belt and the workmaterial. Over the process time, a rather constant abrasive grain signature is therefore in contact with the workpiece [10]. As a consequence the process leaves over the part a homogeneous surface topography signature which is correlated to the abrasive belt topography.

The main process parameters influencing the surface topography are presented by [11] and listed below:

- The grain size has a great influence on surface roughness [12,13].

- The lubrication mode also plays a significant role. [14] pointed out that MQL lubrication had some interesting potential to reduce roughness.
- A high pneumatic jack pressure combined with a soft roller induces a larger contact area of the belt on the workpiece. As a consequence the surface roughness can be reduced as well [15]. In this article they also pointed out the importance of the belt feed rate.
- Finally the belt oscillation frequency and stroke distance as well as the tangential workpiece speed have low influence on the final surface roughness [16, 11].

One can mention that models able to predict the final roughness of a part are missing. Moreover, apart from [16] and [11], the aforementioned studies are focusing on the steady state part of the process (final roughness). Indeed the process reduces the roughness and part dimensions at a certain rate (transitory state) before reaching a steady state final roughness [17].

### 1.4. Aim of the study

The transitory state is of great importance to determine the minimum belt finishing process time on a workpiece surface. It will therefore indirectly determine the device linear translation velocity needed. Finally it will influence the thickness of the layer removed.

Therefore, this article proposes to investigate the roughness reduction during the transitory state of the belt finishing process. The study is performed for different workmaterials. The main objective being to propose a first simple approach to predict the final roughness as a function of the initial roughness, work material and process time.

### Nomenclature

$V_t$	Tangential speed of the workpiece (m/min)
$P$	Pressure of the device (bar)
$V_a$	Belt feed rate (mm/min)
$f$	Oscillating frequency of the belt (Hz)
$d$	Oscillation stroke distance (mm)
$f_t$	Device feed rate (mm/rev)
$V_d$	Device translation speed (mm/s)
$R_a$	Average roughness ( $\mu\text{m}$ )
$K_{rr}$	Roughness reduction rate ( $\mu\text{m/rev}$ )
$N$	Number of revolutions (rev)
$\omega_{\text{workpiece}}$	Workpiece rotational speed (rev/min)
$T$	Time to travel under the belt device (s)
$W_{\text{roller}}$	Roller width (mm)

## 2. Material and Methods

In this section the complete experimental procedure is presented. The workpiece materials studied are presented in section 2.1. The turning and belt finishing conditions are specified respectively in sections 2.2 and 2.3. Finally the surface measurement procedure is explained in section 2.4.

## 2.1. Material

Five different materials interesting for the aeronautic and automotive industries are studied and listed below:

- Two stainless steels: 15-5PH (martensitic) and 304L (austenitic).
- Structural steel: C45.
- Nickel alloy: Inconel 718.
- Titanium alloy: TA6V.

Most of the study is focusing on the 15-5PH stainless steel (sections 3.1 and 3.2). The proposed procedure is then applied to the other materials in section 3.3.

## 2.2. Turning

The workpieces are cylindrical bars from the different materials mentioned above. The bars are regenerated by turning under dry conditions. The turning operation is performed on a CNC machine CMZ TC25 Y<sup>1</sup> and a wiper tool CNMG 120408 WF 1115<sup>2</sup> is used. The following turning parameters are used and correspond to optimal ones recommended by the tool manufacturer:

Table 1: turning conditions for each material.

	Units	304L	Inconel 718	15-5PH	TA6V	C45
Cutting speed $V_c$	(m/min)	145	20	110	50	180
Feed rate $f$	(mm/rev)	0.3	0.22	0.3	0.3	0.3
Depth of cut $a_p$	(mm)	1	1	1	1	1

## 2.3. Belt finishing

The study is performed with a belt finishing device Supfina Typ 210<sup>3</sup> mounted on the CNC machine. The process is also performed under dry conditions and the device linear movement is set to zero in order to focus on the transient regime. Most of the parameters are fixed according to table 2. The variables studied are:

- Workmaterial.
- Workpiece tangential speed.
- Process time.
- Initial roughness.

Figure 2 presents a visual of a bar after different belt finishing conditions (variation of the process time and workpiece tangential speed).

Table 2: belt finishing conditions.

Belt finishing parameters	Units	Values selected
Alumina abrasive grain size	( $\mu\text{m}$ )	50
Pressure $P$	(bar)	5
Fixed parameters		
Roller hardness	(Shore)	50
belt feed rate $V_a$	(mm/min)	100
oscillation frequency $f$	(Hz)	18
Stroke distance $d$	(mm)	0.5
Device feed rate $f_t$	(mm/rev)	0
Variables		
Workmaterial		15-5PH; 304L; C45; TA6V; Inconel 718
workpiece tangential speed $V_t$	(m/min)	80; 120

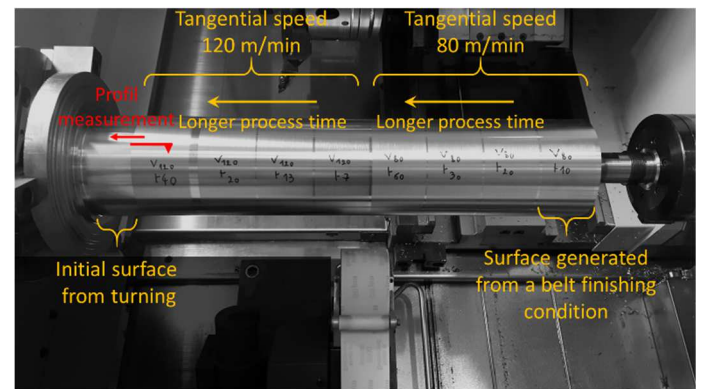


Figure 2: surfaces generated with different belt finishing conditions on an initial turned bar.

Variables	Process time	(s)	From 5 to 60 s
	Initial roughness $R_a$	( $\mu\text{m}$ )	1.4 and 1.7

## 2.4. Surface topography measurements

Surface topography measurements are performed:

- Before the belt finishing process (after turning operation).
- After the belt finishing process for different process times.

The instrument used is a portable profilometer MarSurf PS1<sup>4</sup> with a stylus tip radius of 2  $\mu\text{m}$ . Three measurements of profiles with a sampling distance of 5.6 mm ( $L_t$ ) are recorded for each condition: the location of the measurements is in the central part of the belt finished surface and it is repeated for 3 angular positions (120° spacing) on the bar. The form is removed by a second order polynomial. The roughness profile is obtained after filtering with a Gaussian filter ( $\lambda_c = 0.8 \text{ mm}$  and  $\lambda_s = 2.5 \mu\text{m}$ ). Figure 4 shows an example of roughness profile before and after belt finishing. Roughness

<sup>1</sup> CMZ, Spain. <https://www.cmz.com>

<sup>2</sup> Sandvik Coromant, Sweden. <https://www.sandvik.coromant.com>

<sup>3</sup> Supfina Grieshaber GmbH, Germany. <https://www.supfina.com>

<sup>4</sup> Mahr GmbH, Germany. <https://www.mahr.com/>

parameters can therefore be computed. This study will focus only on the average roughness parameter  $R_a$ .

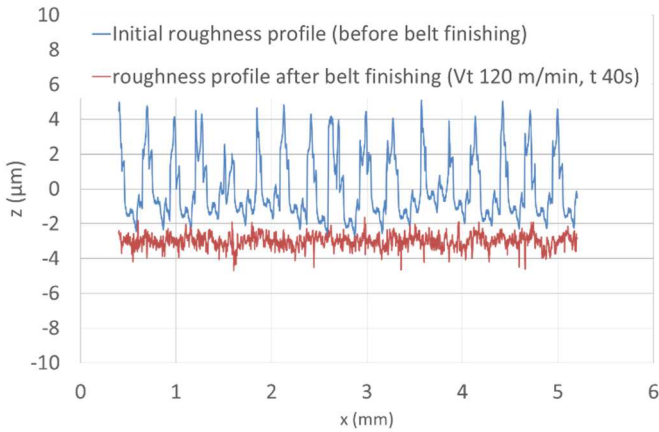


Figure 4: roughness profiles before and after belt finishing.

### 3. Results and Discussion

#### 3.1. Effect of process time and number of revolutions in contact

The two following sections are focusing on 15-5PH workmaterial. Turning is applied to the bar according to conditions mentioned in 2.2 and profile measurements are then performed. Afterwards the belt conditions presented in section 2.3 are applied and profile measurements are performed. The influence of the process time is then observed in terms of profiles (see figure 6) and average roughness

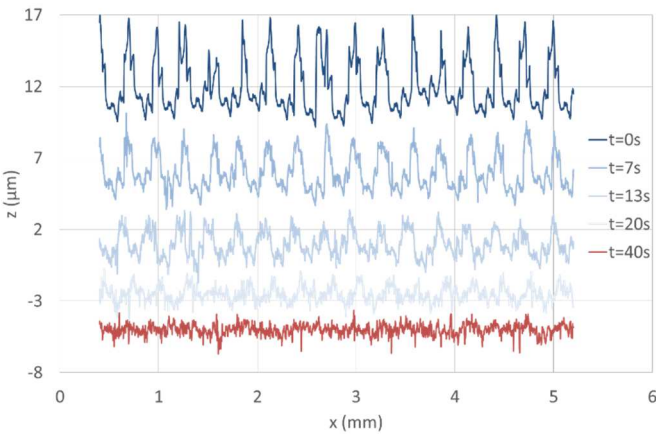


Figure 5: roughness profile evolution during belt finishing process at a workpiece tangential speed of 120 m/min.

$R_a$  (see figure 3).

In figure 6, one can observe that after 40 seconds of belt finishing the original turning grooves are completely removed. The permanent regime is therefore reached and the final surface is correlated to the belt signature. No more signature from the turning exists. In the transient regime, the turning signature persists.

In figure 3, one can observe that the steady state roughness is reached at different process times: a lower workpiece

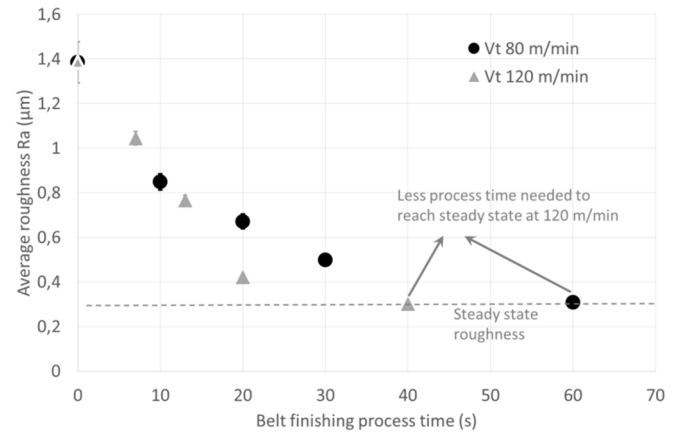


Figure 3: average roughness versus number of revolutions the workpiece undergoes.

tangential speed will induce more time to reach the steady state. As a consequence it is important to observe the roughness reduction as a function of a more relevant parameter. Indeed figure 5 now presents the same results than figure 3 as a function of the number of revolutions the workpiece surface undergoes inside the belt contact. For a device feed rate equal to zero, the mentioned number of revolutions  $N_{rev}$  is calculated as following:

$$N_{rev} = \frac{1000 \cdot V_t}{60 \cdot \pi \cdot D} \cdot t \quad (1)$$

with  $D$ , the workpiece outer diameter in mm.

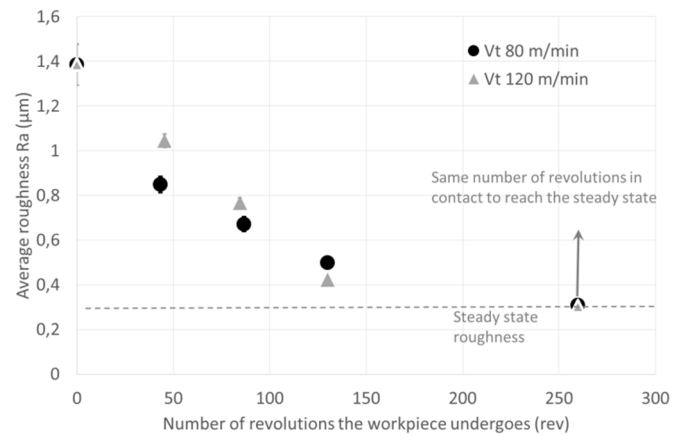


Figure 6: average roughness versus belt finishing process time for different workpiece tangential speeds.

As a consequence, according to figure 5, the steady state is reached (for both conditions) at the same number of revolutions the workpiece undergoes inside the belt contact. The rest of the study will therefore focus on this variable and not the process time.



### 3.2. Proposal of a “roughness reduction rate” parameter

Figure 8 presents results if the initial roughness is higher. In this case it is interesting to notice that the final steady state roughness is not yet reached after 250 revolutions. However the roughness reduction follow a similar rate in both conditions (low and high initial roughness). Based on this observation, a roughness reduction rate  $K_{rr}$  is proposed.

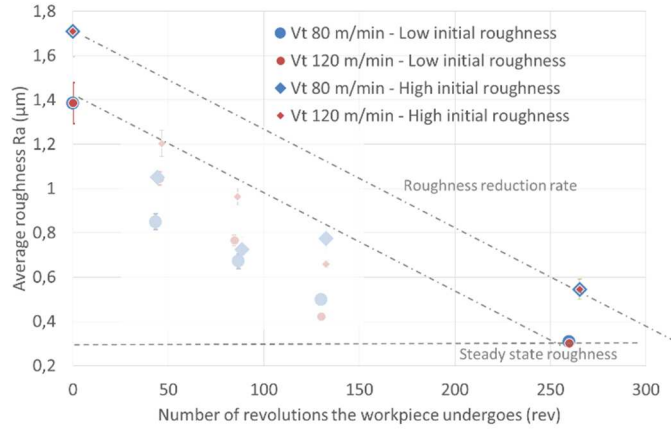


Figure 8: effect of a higher initial roughness and proposal of a roughness reduction rate.

This parameter corresponds to the slope of the curves presented in figure 8 and can be calculated experimentally by the following equation (2):

$$K_{rr} = \frac{Ra_{initial} - Ra_{steady\ state}}{N_{rev\ steady\ state}} \quad (2)$$

$K_{rr}$  is therefore expressed in  $\mu\text{m} \cdot \text{rev}^{-1}$ . Once this parameter is determined by preliminary experiments, it can be used in order to:

- Predict the roughness after a certain time in the transitory regime.
- Predict the number of revolutions (thus time) necessary to reach the steady state roughness.

### 3.3. Application to different materials

The experimental procedure presented in the previous sections is applied to the other workmaterials mentioned in 2.1. A roughness reduction rate can therefore be calculated for 304L, C45, Inconel 718 and TA6V materials. The roughness reduction rates for each material is presented in the following table 3 and in figure 7.

Table 3: roughness reduction rates for different materials.

Workmaterial	Roughness reduction rate $K_{rr}$
15-5PH	$5.9 \cdot 10^{-3} \mu\text{m} \cdot \text{rev}^{-1}$
304L	$3.2 \cdot 10^{-3} \mu\text{m} \cdot \text{rev}^{-1}$
C45	$3.3 \cdot 10^{-3} \mu\text{m} \cdot \text{rev}^{-1}$
Inconel 718	$0.5 \cdot 10^{-3} \mu\text{m} \cdot \text{rev}^{-1}$
TA6V	$0.9 \cdot 10^{-3} \mu\text{m} \cdot \text{rev}^{-1}$

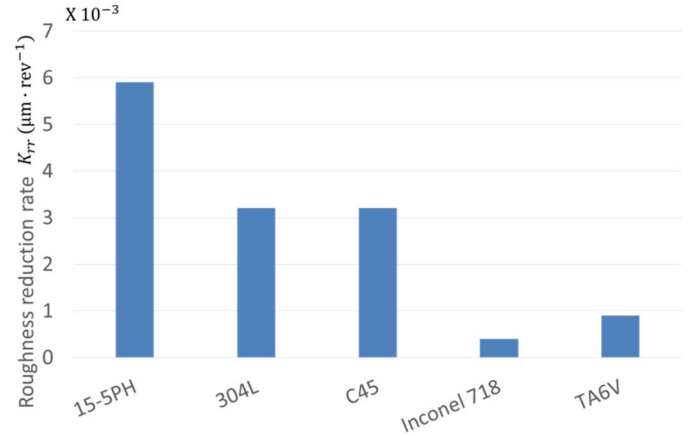


Figure 7: roughness reduction rates for different materials.

It is interesting to notice that two families of materials can be distinguished: hard to cut materials (Inconel 718 and TA6V) and easier to cut materials (15-5PH, 304L and C45). In the latter family, as expected the 15-5PH is the easiest material to belt finish since it has the highest hardness. The proposed values for  $K_{rr}$  are obviously valid for the experimental conditions tested: dry conditions, belt grain size of 50  $\mu\text{m}$ , pressure of 5 bar, roller hardness of 50 Shore, belt feed rate of 100 mm/min, oscillation frequency of 18 Hz and a stroke distance of 0.5 mm. One can expect that the rates would depend strongly on parameters such as the grain size and lubrication conditions for example. In future, the rate could be improved by modelling the contact between the belt and the work material. Indeed a contact width could then be extracted and a time of contact could therefore be computed. Nevertheless a parallel can be drawn between the roughness reduction rate and the wear coefficient proposed by Archard [18]: in both cases a wide range of variables can change the coefficients. Also experiments are still needed to determine the coefficients for a given condition.

### 3.4. Case of a belt finishing device in translation along the axial direction of the bar

In this section, the belt finishing device is now in translation along the axial direction of the bar. According to equation 2, the number of revolutions  $N_i$  needed to reach a certain roughness  $Ra_i$  is:

$$N_i = \frac{Ra_{initial} - Ra_i}{K_{rr}} \quad (3)$$

Therefore, the time  $T_i$  that a small cylindrical part of the bar will need to travel under the belt device is:

$$T_i = \frac{60 \cdot N_i}{\omega_{workpiece}} \quad (4)$$

With  $\omega_{workpiece}$  the rotational speed of the workpiece in  $\text{rev} \cdot \text{min}^{-1}$ .

The device translation speed (in  $\text{mm} \cdot \text{s}^{-1}$ ) needed is therefore:

$$V_d = \frac{2 \cdot W_{\text{roller}}}{T_i} \quad (5)$$

With  $W_{\text{roller}}$  the width of the roller. In that case it is considered that the belt finishing travels back and forth on the workpiece ( $2 \cdot W_{\text{roller}}$ ). The feed rate  $f_t$  will therefore be:

$$f_t = \frac{60 \cdot V_d}{\omega_{\text{workpiece}}} \quad (6)$$

Equations 3, 4 and 5 into equation 6 therefore gives the device translation feed rate needed:

$$f_t = K_{rr} \frac{2 \cdot W_{\text{roller}}}{Ra_{\text{initial}} - Ra_i} \quad (6)$$

#### 4. Conclusion

The aim of this study is to investigate the roughness reduction during the transitory state of the belt finishing process. The study is performed for different workmaterials. The main objective being to propose a first simple approach to predict the final roughness as a function of the initial roughness, work material and process time. The following conclusions are found:

- The main parameter influencing the final roughness is the number of revolutions the workpiece surface undergoes inside the belt contact.
- A simple link between initial roughness, final roughness can then be found by introducing a roughness reduction rate.
- An experimental protocol is proposed in order to determine experimentally this roughness reduction rate.
- The rate is then determined experimentally for different workmaterials. The results are in good agreement with the polishability and machinability of the materials.
- The proposed parameter can be used in order to determine the belt finishing device translation feed rate for a given material and turning conditions.

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