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Effect of abrasive grains size on surface integrity during belt finishing of a 27MnCr5 carburized steel

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Abstract

Belt finishing is a superfinishing process that enables to reach fine surface integrity properties, i.e. low surface roughness and compressive residual stresses in the external layer. Among the wide range of process parameters, belt grain size has a dominant influence on surface roughness. However the effect on residual stresses is rarely studied. This paper investigates the effect of a wide range of belt grain sizes on surface integrity (both surface roughness and residual stresses) generated during belt finishing. The study focuses on cylindrical shafts made of a carburized 27MnCr5 steel. The results show that the grain size has no clear effect on residual stresses. Furthermore, a too low grain size will induce a low material removal rate and the final surface signature will be difficult to reach under a reasonable process time (acceptable for mass production). Therefore, this experimental work highlights that an optimal grain size (around 20-30 µm) exists for a defined initial surface roughness and a process duration.

Keywords: Belt finishing, Abrasive grain size, Surface integrity

1. Introduction

Automotive industry is willing to improve the reliability of their components and to decrease their weight to save gas consumption. As far as gearboxes are concerned, and especially gear shafts, their functional properties require to generate smooth surfaces, as well as compressive residual stresses so as to ensure a high fatigue resistance. Therefore, superfinishing processes, such as grinding, honing, belt finishing… are commonly applied. Among these processes, belt finishing (Fig. 1) is well known for its ability to induce low surface roughness and compressive residual stresses [1-5]. Moreover, it is promoted by industry, as this process requires limited investments and is easy to handle.

An example of belt finishing operation is illustrated in Fig. 1. The set-up is composed by:

- A belt, composed by a single layer of abrasive grains having a calibrated shape, is installed on the set-up
- The belt is pressed against a rotating workpiece (N_p rotating speed – order of magnitude: hundreds of rev/min) with a normal force F_n (order of magnitude: hundreds of N) applied by a rubber roller. The belt scratches the original surface in the circumferential direction to decrease its roughness.
- In addition, the belt oscillates in the axial direction of the workpiece at a frequency f_{osc} (order of magnitude: tens of Hz) over a stroke distance a_{osc} (order of magnitude: mm). This axial oscillation is mandatory to scratch the initial surface texture within a non-parallel direction to the original surface texture. This is a key parameter that makes belt finishing efficient.

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- The belt is permanently regenerated with a feed rate V_{belt} (order of magnitude: mm/min). Worn grains are replaced by new grains in the contact zone.
- The process is performed under lubricated conditions (flood cooling with emulsion or MQL - Minimum Quantity Lubrication - with mineral or vegetal oil).

NB: Authors would like to underline the difference between belt grinding and belt finishing. The belt grinding process differs from belt finishing by scratching the surface in the circumferential direction only with a very high velocity (order of magnitude: m/s). No axial oscillation exists. Moreover, the abrasive belt rotates within a closed loop and is not regenerated. Belt grinding is a very energetic process, that is close to a grinding process. On the contrary, belt finishing is a gentle process leading to limited temperatures that makes it suitable to induce compressive residual stresses [2].

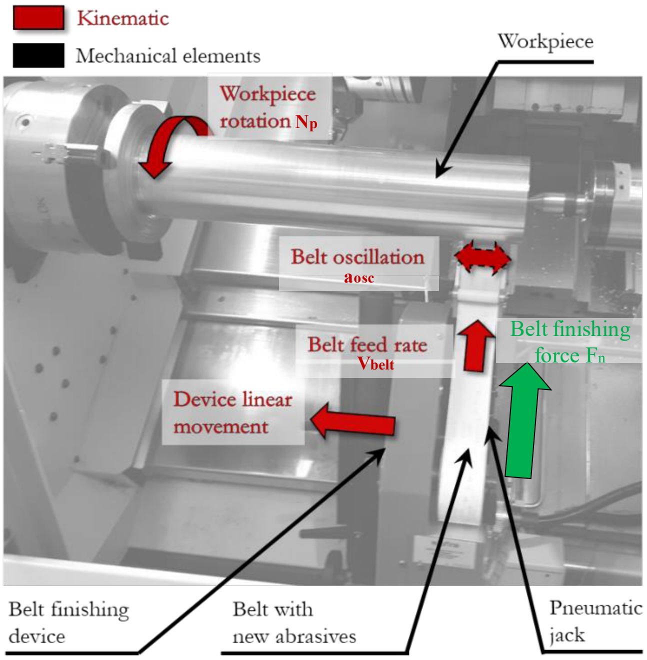

Fig. 1. Main features and parameters of a belt finishing operation (adapted from [6]).

Nomenclature

V_c	Cutting speed (m/min)
f	Feed rate (mm/rev)
a_p	Depth of cut (mm)
N_p	Workpiece rotation speed (rev/min)
a_{osc}	Oscillation amplitude (mm)
f_{osc}	Oscillation Frequency (Hz)
V_{belt}	Belt regeneration feed rate (mm/s)
P	Pneumatic Jack Pressure (bar)
F_n	Normal force applied on the workpiece (N)
R_a	Average roughness (µm)
R_k	Level difference on core surface (µm)
R_{pk}	Reduced peak height (µm)
R_{vk}	Reduced valley depth (µm)
R_{sm}	Mean width of profile elements (µm)

Belt finishing has been investigated by a limited number of authors, compared to other finishing processes such as grinding. Several experimental works were mainly concerned with sensitivity investigations to the grain size [8], to the normal force applied F_n [7, 9], to the application of a cutting fluid [4, 10-11], to the oscillation frequency, film feed rate and the workpiece rotation speed [6-7, 12-13]. These papers have shown the dominant influence of belt grain size. However, they have investigated a limited number of grain sizes (commonly two) and they were focused only on the final surface roughness (steady state). They have not analyzed the signature of the surface topography. Moreover, they have not considered the influence of belt grain size on the residual stress state.

This paper aims to investigate the influence of a large variety of belt grain size on surface roughness and residual stresses.

2. Description of the experimental work

2.1. Process parameters

This work deals with the superfinishing of cylindrical shafts made of 27MnCr5 carburized steel 750 HV (Fig. 2).

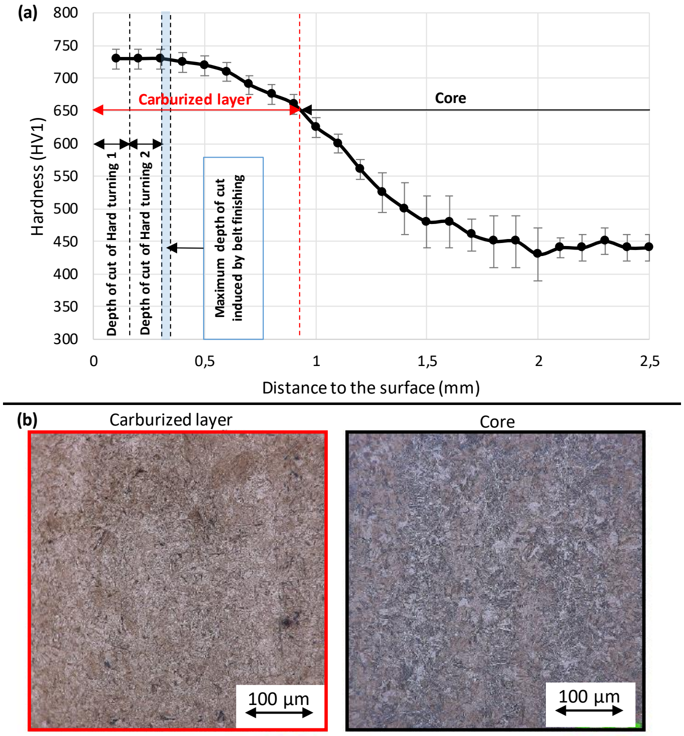

Fig. 2. Heat treated 27MnCr5 shaft: (a) Microhardness profile (HV1), (b) Microstructure (x600)

After heat treatment, shafts are preliminary hard turned with the following conditions:

- Insert CNMG 120408 WF 1115 from Sandvik[*]
- Cutting speed, V_c: 80 m/min.
- Feed rate, f: 0.1 mm/rev.
- Depth of cut, a_p: 0.15 mm.
- Cutting fluid: dry

Belt finishing tests have been performed thanks to a Supfina Type 210[†] device mounted on a turning machine. The process is performed under MQL conditions.

Six belts, having Al_2O_3 grain sizes from 9 to 100 µm, have been selected. Other process parameters have been kept constant and have been selected according to previous studies [6, 7, 11, 12]. The fixed parameters as well as the test variables are presented in Table 1.

Table 1. Belt finishing conditions

Belt finishing parameters		Units	Values
Fixed parameters	Finishing belt grains material		Al_2O_3
	Work material		27MnCr5
	Roller Hardness	(Shore)	80
	Oscillation frequency f_{osc}	(Hz)	24
	Oscillation amplitude a_{osc}	(mm)	0.5
	Workpiece rotation speed N_p	(rev/min)	900
	Applied force F_n	(N)	150
	Belt feed rate V_{belt}	(mm/s)	0.6
Variables	abrasive grain size	(µm)	From 9 µm to 100 µm
	Process time **t**	(s)	From 10 to 60s

2.2. Surface integrity analysis

During belt finishing tests, the roughness evolution has been monitored thanks to a profilometer MarSurf PS1[‡] (stylus tip radius of 2 µm). Three profiles (evaluation length l_n=4 mm) have been measured for each condition. Profiles were filtered with a Gaussian filter (λc=0.8mm and λs=2.5µm). In addition, the final areal surface topography has been recorded thanks to a RTEC[§] confocal microscope (measurement size of 2000 µm by 650 µm with a lateral resolution of 0.34 µm and a vertical resolution of 8 nm). Areal surfaces are treated and then visualized by removing the form with a polynomial filter of order 2. Profile and surface topography analysis are performed thanks to Mountains Map 8.2[**] software. This paper focuses on two roughness parameters:

- The average roughness R_a as a reference parameter
- The mean width of profile elements R_{sm} as a spacing parameter, indicator of the process signature

Residual stress measurements have been made by X-Ray diffraction method on a Proto[††] XRD. The parameters are listed below:

- Chrome X-ray tube operating at 20 kV and 4 mA
- Kα radiation has been observed
- Collimator diameter: 2mm
- Bragg angle: 156°, which corresponds to a {2 1 1} diffraction plane

A gradual material removal is applied using electro polishing in order to measure the stress distribution in depth. An electrolytic polisher was employed at 5V and 16 mA.

3. Results and discussion

3.1. Effect of abrasive grain size on surface roughness

Figure 3 plots the evolution of the average roughness R_a over the time during 60 seconds of belt finishing. This small process duration is consistent with the tack time on a production line in the automotive industry.

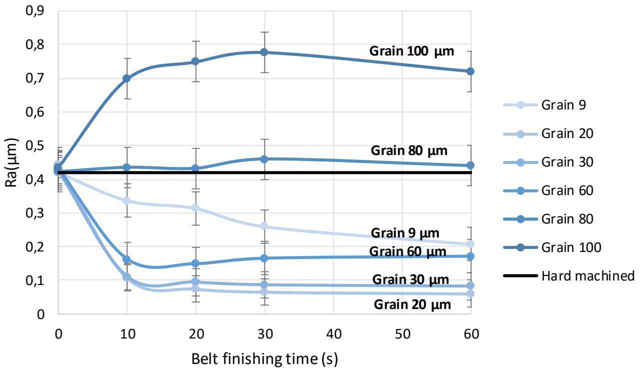

Fig. 3. Evolution of average roughness R_a during belt finishing time

The initial average roughness (hard machined roughness) is plotted in black (R_a~0.43µm). First, it can be observed that the largest grains (100 µm and 80 µm) deteriorate the original surface roughness (respectively R_a~0.72µm and ~0.45µm). For the smaller grain sizes (60, 30, 20 and 9 µm), surface roughness decreases over the time. The surface roughness signature of the process is reached after 10 to 20 seconds, except for the smallest grain size.

Figure 4 presents the 3D surface topography after 60 s of processing. On the left side, all the surface topographies are presented with the same color scale, whereas an optimized scale has been selected on the right side.

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[*] Sandvik Coromant, Sweden. https://www.sandvik.coromant.com

[†] Supfina Grieshaber GmbH, Germany. https://www.supfina.com

[‡] Mahr GmbH, Germany. https://www.mahr.com/

[§] Rtec-Instruments, USA. https://rtec-instruments.com/

[**] Digital Surf, France, https://www.digitalsurf.com/fr/

[††] Proto Mfg, USA. https://www.protoxrd.com/

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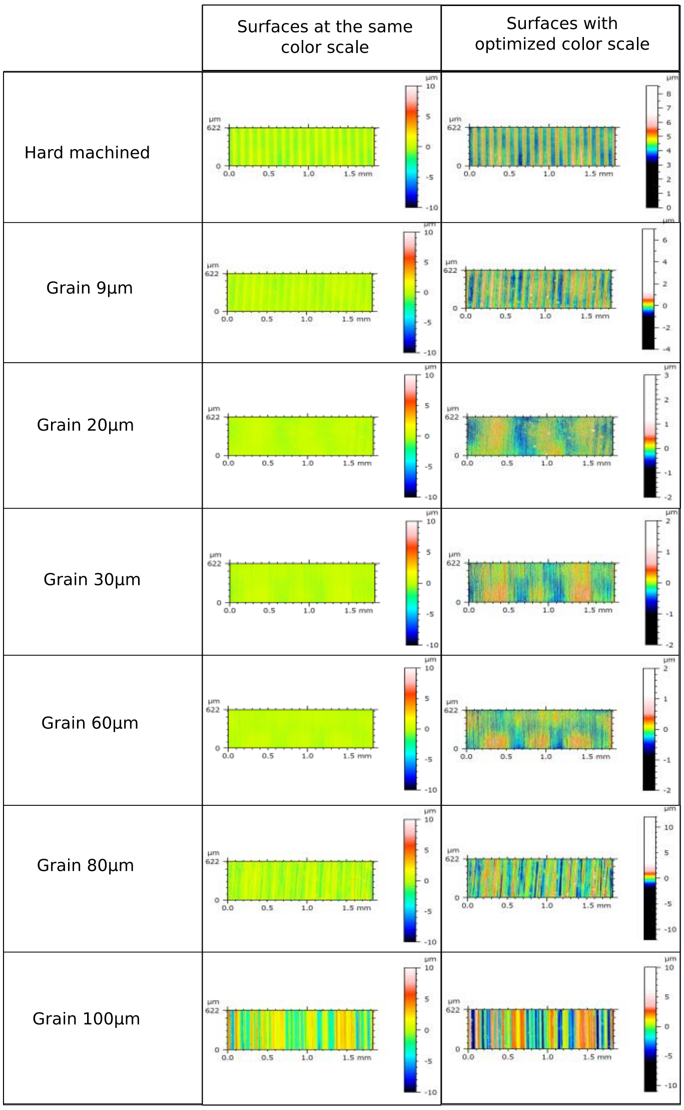

Fig. 4. Final surfaces for different grain sizes

Figure 5a plots the average surface roughness R_a over the belt grain size. As expected, the roughness is correlated to the grain size except for the smallest grain (9 µm). The same observation can be made for the mean width of profile elements R_{sm} (Fig. 5b).

Figure 6 provides an explanation for this statement. It plots an example of surface roughness profile after 60 seconds of belt finishing generated by the various belts, and the original profile. It appears that the largest grains (20 → 100 µm) induces their own profiles (i.e. signatures), whereas the smallest grain size (9 µm) is only able to remove the peaks of the original profile. So, the parameter R_{sm} remains unchanged for grain size 9 µm. This fine belt is not enough aggressive to remove such a rough original profile within 60 seconds. A longer process may be necessary. However, this is not acceptable for the mass production industry.

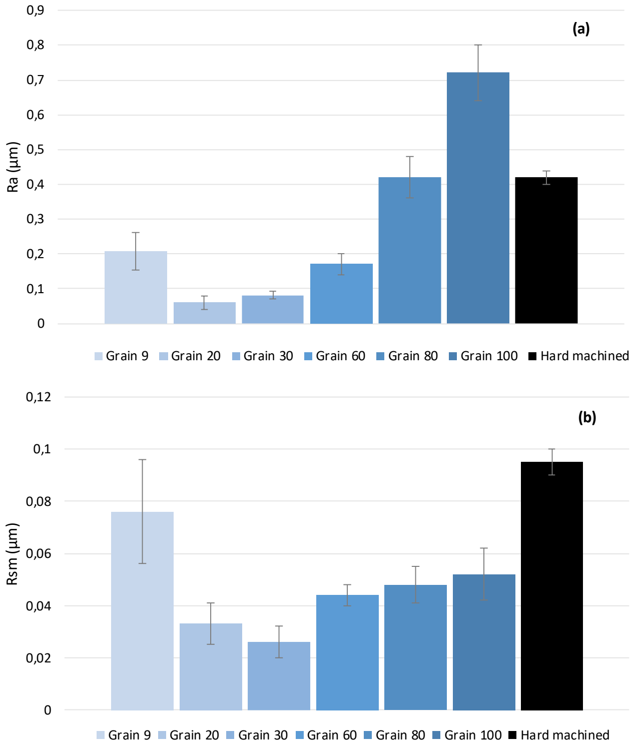

Fig. 5. Final roughness parameters for different grain sizes at 60s: (a). Average roughness R_a, (b). Mean width of profile elements R_{sm}

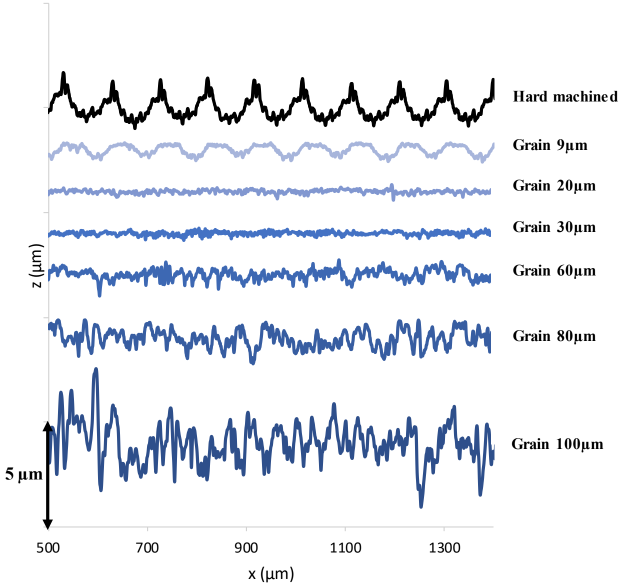

Fig. 6. Final profiles generated for various grain sizes at 60s

In addition, Figure 7 plots a superposition of the original profile and the profile induced by the 9 µm size belt (a), the 30 µm size belt and the profile by the 100 µm size belt (b). It appears clearly that 9 µm size belt is only able to remove the peaks of the original profile, whereas the valleys are not affected. On the contrary, the 30 µm and 100µm size belts removes the original profile and induces their own signatures.

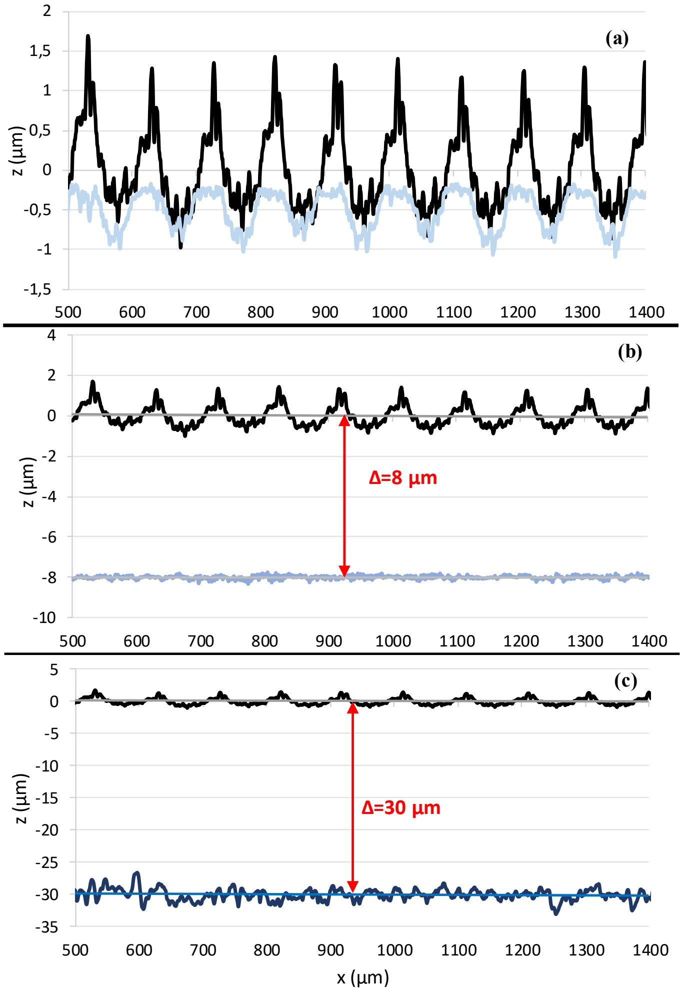

Fig. 7. Initial and final profile for (a) Grain size 9 µm (b) Grain size 30 µm (c) Grain size 100 µm

So, the lowest grain size is not appropriate to improve the surface roughness for the present original surface.

As the objective is to define the best belt grain size to get the smoothest surface roughness, Fig. 3 shows that the best surface roughness R_a is obtained by the 20 µm size belt. This grain size is a compromise between the ability to remove the original profile so as to generate its own signature, and the ability to induce small scratches that will lead to small roughness parameters R_a and R_{sm}.

3.2. Effect of abrasive grains size on residual stresses

This section compares the initial residual stresses induced by hard machining and the residual stresses induced by the various belts. Figure 8a and 8b present the residual stress profiles in the axial and circumferential directions respectively.

Residual stress profiles have been plotted by considering the effective amount of material removed by the process. So, the original residual stress profile starts on the horizontal axis with a depth of 0 µm. On the contrary, the surface induced by the 100 µm size belt is shifted of 30 µm, as this aggressive belt has removed a depth of cut of 30 µm. This shift was already observable in Fig. 7 (c).

As expected, it can be observed that the depth of cut is correlated to the grain size.

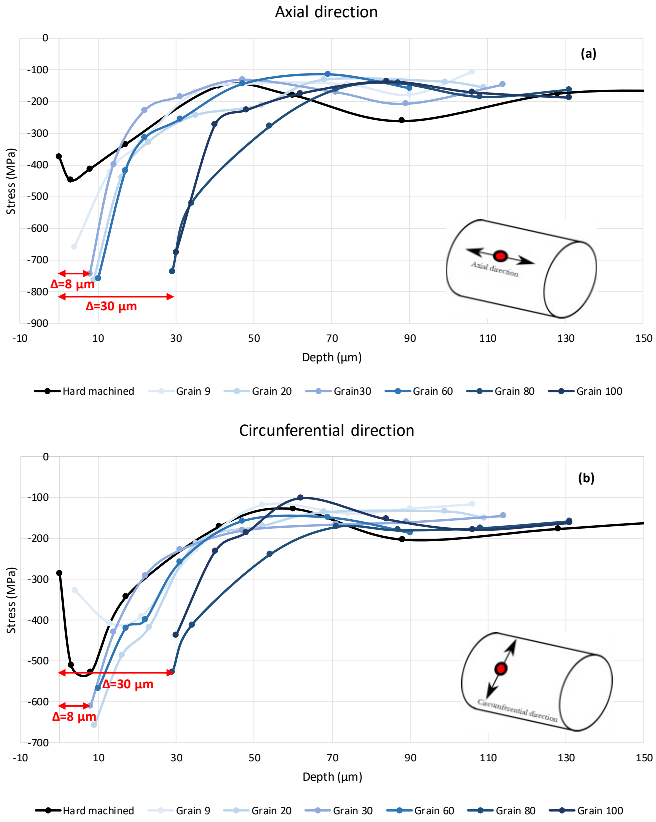

Fig. 8. Residual stress induced hard machining and belt finishing with various grain sizes in the: (a) axial direction and (b) the circumferential direction

By comparing hard turning and belt finishing residual stress profiles, it can be observed that the original hard turning profile has a hooked shape. This is a typical curve already reported in the literature [14]. The belt finishing process introduces additional compressive stresses in the near surface. This is observed in both directions: axial direction (≈720MPa-780MPa for the grain sizes 20µm, 30µm and 60µm) and circumferential direction (≈ 550 MPa-650 MPa for the grain sizes 20µm, 30µm and 60µm). The affected depth corresponds to approximately 20 to 30 µm. Beyond this depth, residual stresses return to the initial state (hard turning). The generation of compressive stresses within a thin layer was expected in accordance with previous works of [4,10]. They explained this trend by the mechanical scratching of the surface with a limited heat generation thanks to the low velocity and the presence of low friction coefficient (MQL) [2].

NB: the residual stress profile generated with the 9 µm size belt keeps its hooked shape in the circumferential direction. This reveals that the original stress profile induced by the hard turning operation remains. This is in agreement with previous analysis on the surface roughness profiles.

The dispersions obtained in residual stresses measurements do not permit further comparisons between the various grains. It is therefore assumed that the best surface integrity is obtained for the smoothest surface topography obtained with 20 µm size belt.

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4. Conclusion

The aim of this study was to investigate the effect of belt grain size on the surface integrity in the context of the automotive industry with a limited process duration. It has been shown that an optimal grain size exists around 20 to 30 µm. This belt size combines an efficient material removal rate to eliminate the original surface roughness profile, and, at the same time, generates its own signature through small scratches. The best surface finishing was not obtained using low grain sizes (for example 9µm) because they are not able to remove the original surface roughness profile induced by hard turning, and large grain sizes induces large scratches that limit the roughness improvement.

This work has also confirmed the ability of belt finishing to induce a compressive layer within a depth of 20 µm irrespective of the grain size.

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