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Surface Integrity induced by the Belt Finishing Process and Effects on the Fatigue Limit of a 27MnCr5 Carburized Steel

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Abstract

Among superfinishing processes, belt finishing is well known for its ability to induce compressive residual stresses and low surface roughness. Moreover, it is promoted by industry, as this process requires limited investments and is easy to handle. Combined with hard turning, precise dimensions and fine surface roughness of the parts can be ensured. Therefore, the combination of these processes could replace the grinding operation performed on automotive gear shafts for example. The article proposes to study the effects of the belt finishing operation on surface integrity of 27MnCr5 carburized steel shafts. Residual stresses and surface roughness are investigated for hard machined and belt finished samples. Afterwards, rotating bending fatigue tests are performed, and the fatigue limit of the belt-finished samples is compared with hard machined ones.

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Keywords: Belt finishing; hard turning; surface roughness; residual stresses; fatigue limit

1. Introduction

Automotive industry is willing to improve the reliability of their components and to decrease their production cost at the same time. Gears and gear shafts are among the most critical components to optimize. Indeed, more than 25% of the component failures in vehicles originates from the transmission [1]. To mitigate the risk of failures, fatigue resistance of the produced parts needs to be improved. The fatigue resistance is determined by the parts surface integrity (microstructure, residual stress state, surface topography) [2, 3]. Moreover, surface integrity is highly influenced by the final processes applied on the parts to produce.

The production line of gears and gear shafts include pre machining, then heat treatment followed by various finish cutting processes. Among the finishing processes, one can mention the interesting combination of hard turning followed by belt finishing. Indeed, precise dimensions, smooth surface topographies and compressive residual stresses of the parts can be ensured thanks to such combination [4].

The belt finishing process is promoted by industry since it requires limited investments and is easy to handle. This process is well described by Cherguy et. al. [4]. A short description is provided below (see figure 1): a belt finishing device can be mounted on CNC machines. The belt is composed by a single layer of abrasive grains. The belt is pressed against a rotating workpiece with a normal force applied by a rubber roller. The belt scratches the original surface in the circumferential

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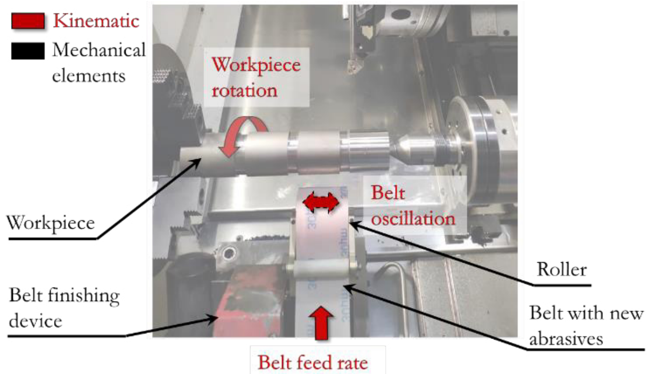
direction (thanks to the workpiece rotation and the belt feed rate) and in the axial direction (thanks to the belt oscillation).

Fig. 1: Main features of a belt finishing operation



Concerning hard turning, several papers have investigated the effect of the process on surface integrity of case hardened steels [5-7]. They identified cutting inserts geometries/materials [6] and conditions [5, 7] as the key parameters affecting the residual stresses.

Concerning belt finishing, the process has been investigated by a limited number of authors, compared to other finishing processes. The ability of the process to generate compressive residual stresses [8] and low surface roughness [4, 9] have been emphasized.

The combination of both processes (hard turning and belt finishing) and the respective effects on surface integrity have not been studied in detail. Likewise, the respective effect of both processes on the fatigue performance has not been studied. This paper proposes to investigate the influence of hard turning and belt finishing on residual stresses, surface roughness and fatigue performance. Consequently, this study attends to isolate the effect of the belt finishing process on the parts performance in terms of fatigue resistance.

Nomenclature

Hard turning
a_p Depth of cut (mm)
f Feed rate (mm/rev)
V_c Cutting speed (m/min)

Belt finishing
a_{osc} Oscillation amplitude (mm)
f_{osc} Oscillation Frequency (Hz)
F_n Normal force applied on the workpiece (N)
N_w Workpiece rotation speed (rev/min)
t Belt finishing processs time
V_{belt} Belt regeneration feed rate (mm/s)

Surface integrity and fatigue tests
R_a Average roughness (µm)
σ_{xx} Residual stress in the axial direction (MPa)
σ_{yy} Residual stress in the circumferential direction (MPa)
σ_d Fatigue strength at 2.10^6 cycles (MPa)
σ_0 Lowest stress level of the least frequent event (MPa)
d Increment of stress (MPa)
i Stress level
n_i Number of occurrence of the less frequent event at stress level i

2. Material and Methods

2.1. Samples preparation

A 27MnCr5 steel - commonly used by the automotive industry for gear shafts - is the material of interest for this study. The composition is given in Table 1.

Table 1. 27MnCr5 chemical composition

C	Mn	Cr	Cu	Ti	Al	Si	S	P
0.23	1.10	1.00	<0.40	<0.01	0.015	0.10	0.025	<0.03

Two types of samples are produced for this study: surface characterization samples and rotating bending fatigue samples (four point loading parallel specimens). Both types of samples are produced by following the very same production steps and treatment/process conditions that are described below:

- Pre machining and heat treatment: the 27MnCr5 annealed steel is pre machined and then case-hardened by a carburizing process performed at Bodycote: heating at 920 °C for 1h30 under vacuum and cooled a high nitrogen pressure (15 bars) very quickly. Followed by a tempering at 150 °C in air for 2h. The surface hardness reached is about 800 HV1 and the carburized layer thickness (layer with a hardness higher than 700 HV1) is about 0.6 mm.
- Hard turning: chamfered CBN inserts (Sandvik, DNGA 150408S01020) are employed to perform the dry hard turning on a CNC lathe. The final pass of finishing is performed with a depth of cut $a_p = 0.15\,mm$, a feed rate $f = 0.1\,mm/rev$ and a cutting speed $V_c = 80\,m/min$. The cutting edge is changed every 5 samples to avoid any flank wear effect on the residual stresses.
- Belt finishing: after hard turning, samples are belt finished. Table 2 summarizes the selected belt finishing conditions. The normal force applied by the roller on the workpiece is changed between characterization and fatigue samples. Indeed the normal load is modified to ensure similar belt/workpiece contact pressures. Moreover, a specific rubber roller is manufactured to conform to the fatigue sample geometry. An axial translation of the belt device (11 mm at 0.04 mm/rev) is needed to process the fatigue samples over their full length.

Table 2. Belt finishing conditions

Belt finishing parameters		Units	Values
Fixed parameters	Finishing belt grains material		Al_2O_3
	Belt grains size	µm	30
	Roller Hardness	(Shore)	80
	Oscillation frequency f_{osc}	(Hz)	24
	Oscillation amplitude a_{osc}	(mm)	1
	Workpiece rotation speed N_w	(rev/min)	900
	Belt feed rate V_{belt}	(mm/s)	0.6
	Lubrication		MQL
	Process time **t**	(s)	30s
Variables	Applied force for characterization samples F_n	(N)	75N
	Applied force for fatigue samples F_n	(N)	15N

Hard turned samples for characterization and fatigue tests are produced by following the two first presented steps. Belt finishing samples for characterization and fatigue tests are produced by following the three presented steps. The hard turning step previous to belt finishing is identical to the hard turned samples to observe the impact of the last process on fatigue behavior. Figure 2 summarizes the workflow of the produced samples.

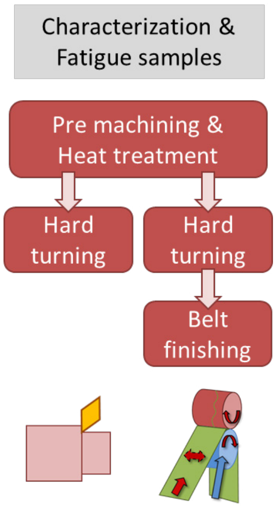


Fig. 2: Samples preparation workflow

In total, 12 belt finished and 12 hard turned samples are produced for fatigue tests. And, 1 belt finished and 1 turned samples are produced for surface integrity characterization.

2.2. Surface integrity characterization

Residual stress measurements are performed by X-Ray diffraction method on a Proto* XRD. The measuring conditions are presented 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 {2 1 1} diffraction plane

A gradual surface layer removal is applied thanks to electro polishing to observe the stress distribution in depth. Two directions of the residual stresses are observed: circumferential and axial directions (respectively σ_{xx} and σ_{yy}).

Concerning, surface topographies: roughness profiles are acquired thanks to a Taylor Hobson profilometer (stylus tip radius of 2 µm). Four profiles (evaluation length $l_n = 4\ mm$) are acquired for each sample. Roughness profiles are then analyzed thanks to MountainsMap 9.1 software. Form is removed by a polynomial filter of order two and roughness profiles are obtained by filtering with Gaussian filters ($\lambda_c = 0.8\ mm$ and $\lambda_s = 2.5\ \mu m$). This paper focuses on the arithmetic mean height Ra (in µm), a reference parameter for industry.

2.3. Fatigue tests

Before any fatigue test, a first approximation of the expected fatigue limit for a 27MnCr5 steel is needed. It is computed thanks to the Basquin model [10] with a slope set to a constant (m=8) according to literature [11].

The samples presented above are then submitted to fatigue tests: Locati tests followed by staircase campaigns. The Locati test enables rapidly evaluating the fatigue strength thanks to the cumulative damages hypothesis [12]. This first test facilitates calibrating the staircase campaign by providing a first estimation of the expected fatigue limit.

The different types of fatigue tests are performed with a four-point bending rotating machine Walter + bai AG UBM 200 (see figure 3). The desired stresses are applied on samples by means of dead weights that are generating a constant bending torque on the central part of the specimen. Unlike traction/compression fatigue tests, the maximum bending stresses are reached near the sample surface and are computed thanks to equation (1):

$$\sigma_{max} = \frac{32PL}{\pi {d_m}^3} \qquad (1)$$

Where P is the applied load, L the length of the lever (here 0.5 mm) and d_m the diameter in the middle of the fatigue specimen (here 10 mm). The machine is closed-loop and a sensor detects automatically failures.

The experimental conditions are:

- Rotation frequency: 50 Hz
- Fatigue stress ratio: R=σmin /σmax = -1
- Test at room temperature

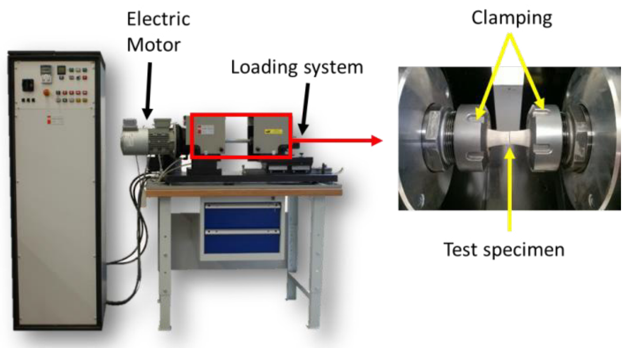


Fig. 3: Rotating bending fatigue test bench

Concerning Locati tests: the Basquin model provide an approximation of the fatigue limit. Fatigue tests are run with stresses below the calculated value. Only one sample is needed for each process condition (hard turning and belt finishing). Tests are run and stresses are increased progressively every 50 000 cycles with a step of 50 MPa until the sample fails. A better estimation of the fatigue limit is then found for each

* Proto Mfg, USA. https://www.protoxrd.com/

process by using the cumulative damages hypothesis [12]: 700 MPa for the hard turned sample and 750 MPa for the belt finished sample.

Stair case campaigns are performed to refine the estimation from Locati tests. 11 samples are used for each process (hard turning and belt finishing). The first sample is submitted to the stress levels found by the Locati tests. The fatigue test is run with a constant stress level until failure occurs or until 2.10^6 cycles are reached. If failure occurs before 2.10^6 cycles, the next test is performed with a stress level that is decreased of 25 MPa. Else, the test is performed with a stress level that is increased of 25 MPa. The procedure continues until the 11 samples are tested. The stress levels, the result of each test (failure marked by a cross or run-out marked by a circle) is then reported in a table. The fatigue limit can be computed according to:

- Equation (2) when the least frequent event is run-out.
- Equation (3) when the least frequent event is failure.

$$\sigma_d = \sigma_0 + d\left(\frac{A}{N} + \frac{1}{2}\right) \quad (2)$$

$$\sigma_d = \sigma_0 + d\left(\frac{A}{N} - \frac{1}{2}\right) \quad (3)$$

In equations (2) and (3), σ_0 is the lowest stress level (MPa) where the least frequent event occurred. σ_0 is computed thanks to equation (1), knowing the sample geometry and the loading conditions applied. Furthermore, in equations (2) and (3), d is the increment of stress chosen during the tests: in that case 25 MPa. Finally, A, N and B are computed thanks to equations (4), (5) and (6):

$$A = \sum n_i \quad (4)$$

$$N = \sum i \cdot n_i \quad (5)$$

$$B = \sum i^2 \cdot n_i \quad (6)$$

With i, the stress level which is starting at 0 for the level where the less frequent event is observed. n_i is the number of occurrence of the less frequent event per level.

3. Results and discussion

The surface profile average roughness, axial and circumferential residual stresses profiles are presented for both processes respectively in figures 4, 5 and 6.

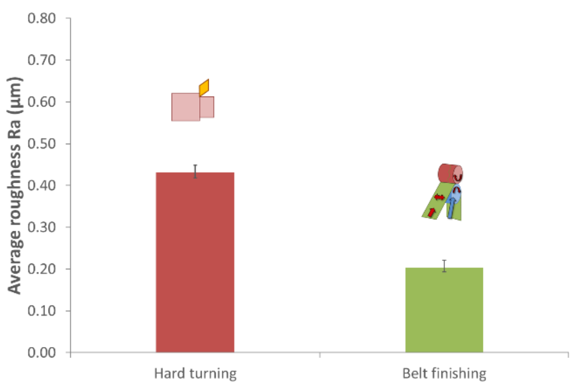


Fig. 4: Average roughness for hard turning and belt finishing processes

Error bars in figure 4 correspond to maximum and minimum measured values. Concerning belt finishing residual stresses, a fatigue sample has been used instead of the characterization sample.

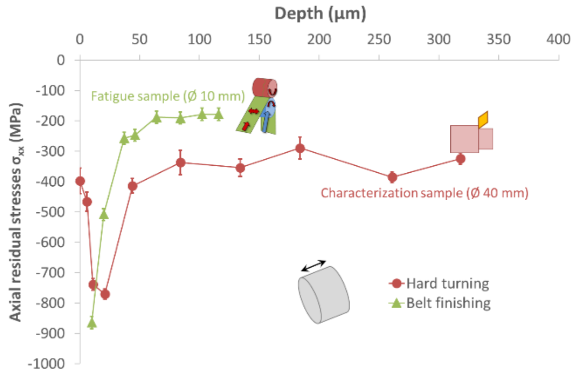


Fig. 5: Axial residual stresses for hard turning and belt finishing processes

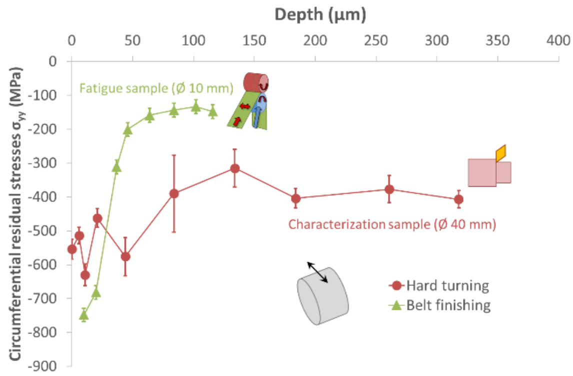


Fig. 6: Circumferential residual stresses for hard turning and belt finishing processes

As expected, the surface roughness is decreased by the belt finishing process (see figure 4).

When analyzing residual stresses (figures 5 and 6), it is important to divide the curves into two parts for a more comprehensive evaluation of the results:

- The first part relates to the near surface (depth of approximately 0 to 30 µm) and is primarily influenced by the applied manufacturing processes. In this layer, the original hard turning profile has a hooked shape which is a typical curve already reported in the literature [5]. The belt finishing process induces additional compressive stresses in the near surface in both the axial and circumferential directions. This trend can be explained by the mechanical scratching of the surface with a limited heat generation.
- The second part relates to the bulk (below 30 µm) and is primarily influenced by the thermal history of the samples, which depends on the material and sample geometry. Due to their different dimensions and geometries, the residual stresses obtained for the fatigue sample and the characterization sample are different. This part is of limited interest for the study. Indeed, the fatigue test conditions were selected to initiate cracks on the near surface, which experiences the maximum bending stresses. This allows for the study of the impact of the manufacturing processes.

Concerning fatigue results, figures 7 and 8 summarizes the staircase results obtained respectively for hard turning and belt finishing.

Hard turning — **Fatigue strength (MPa) 697**

Stress (MPa)	Samples number 1	2	3	4	5	6	7	8	9	10	11	Number of failure	Number of run-out	i	ni	i.ni	i².ni
730						x				x		2	0	1	2	2	2
700	x		x		o		x		o		o	3	3	0	3	0	0
670		o		o				o				0	3				
												5	**6**				

N	A	B	s
5	2	2	N/A

Fig. 7: Fatigue test results for hard turning samples following the staircase method for 2 million cycles

Belt finishing — **Fatigue strength (MPa) 743**

Stress (MPa)	Samples number 1	2	3	4	5	6	7	8	9	10	11	Number of failure	Number of run-out	i	ni	i.ni	i².ni
775		x								x		2	0				
750	o		x		x				o		x	3	2	2	2	4	8
725				o		x		o				1	2	1	2	2	2
700							o					0	1	0	1	0	0
												6	**5**				

N	A	B	s
5	6	10	24

Fig. 8: Fatigue test results for belt finishing samples following the staircase method for 2 million cycles

Figure 9 plots the fatigue strength results as a function of average roughness and external residual stress in the circumferential direction.

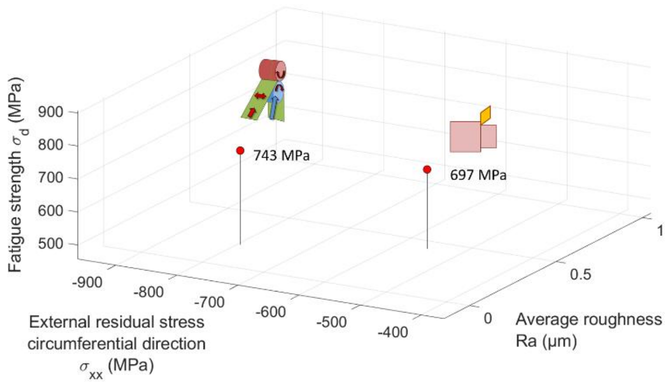


Fig. 9: Fatigue strength results versus average roughness and external residual stress in circumferential direction

The figure confirms that the belt finishing process promotes a higher fatigue strength compared to the hard turning process. The final step of superfinishing which decreases the surface roughness while inducing compressive residual stresses is therefore beneficial. However, it is not possible to discriminate the effect of the surface roughness and of the residual stresses on the fatigue strength.

4. Conclusion

The article proposed to study the effects of the belt finishing operation on surface integrity and fatigue strength of 27MnCr5 carburized steel shafts. For this purpose, hard turning samples (from second last process) are compared to belt finishing samples (from last process) in terms of surface roughness, residual stresses and fatigue strength.

It is shown that the belt finishing process has a significant positive effect on the samples fatigue strength (increase from 697 MPa to 743 MPa). By reducing the surface roughness and inducing more compressive residual stresses, this last process beneficial for the functionality of the components.

However, it is not possible to discriminate the effect of the surface roughness and of the residual stresses on the fatigue strength. In future, it would be interesting to generate different belt finishing samples and hard turning samples by variating the process conditions to extend the map plotted in figure 9. This could lead to a variety of surface roughness (by changing belt finishing conditions) and residual stresses states (by changing hard turning conditions). Therefore, this could help to discriminate the surface roughness and residual stresses effects on the fatigue strength.

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References

[1] Heyes, A. M. Automotive component failures. Engineering Failure Analysis, 1998, vol. 5, no 2, p. 129-141.
[2] Matsumoto, Y., Hashimoto, F., et Lahoti, G. Surface integrity generated by precision hard turning. CIRP Annals, 1999, vol. 48, no 1, p. 59-62.
[3] Davim, J.P., Rech, J., Hamdi, H., et al. Workpiece surface integrity. Machining: fundamentals and recent advances, 2008, p. 59-96.
[4] Cherguy, O., Elicegui, U., Cabanettes, F., et al. Effect of abrasive grains size on surface integrity during belt finishing of a 27MnCr5 carburized steel. Procedia CIRP, 2022, vol. 108, p. 305-310.
[5] Rech, J. et Moisan, A. Surface integrity in finish hard turning of case-hardened steels. International Journal of Machine Tools and Manufacture, 2003, vol. 43, no 5, p. 543-550.
[6] Rech, J. et Claudin, C. Influence of cutting tool constitutive parameters on residual stresses induced by hard turning. International Journal of Machining and Machinability of Materials, 2008, vol. 4, no 1, p. 39-50.
[7] Gunnberg, F., Escursell, M., et Jacobson, M. The influence of cutting parameters on residual stresses and surface topography during hard turning of 18MnCr5 case carburised steel. Journal of Materials Processing Technology, 2006, vol. 174, no 1-3, p. 82-90.
[8] Rech, J., Kermouche, G., Claudin, C., et al. Modelling of the residual stresses induced by belt finishing on a AISI52100 hardened steel. International Journal of Material Forming, 2008, vol. 1, no 1, p. 567-570.
[9] Wang W, Salvatore F, Rech J, Et Jianyong Li. Effects of belt's adhesive wear on surface integrity in dry belt finishing. Procedia CIRP, 2018, vol. 71, p. 31-34.
[10] OH, Basquin. The exponential law of endurance tests. In : Proc Am Soc Test Mater. 1910. p. 625-630.
[11] Beaumont P, Optimisation des plans d'essais accélérés Application à la tenue en fatigue de pièces métalliques de liaison au sol, PhD Thesis, Université d'Angers, 2013.
[12] Miner, M.A. Cumulative damage in fatigue. 1945.