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Effect of innovative finishing operations on the tribological performance of steel 27MnCr5

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Abstract

Transmission shafts used in the automotive sector must have a good tribological performance, and therefore an enhanced surface integrity. This paper aims to study the effect of eco-friendly innovative finishing operations (belt finishing, cryogenic grinding and dry grinding) on the surface integrity and tribological performance of steel grade 27MnCr5, and compare to the behavior of components produced by conventional wet grinding process. For that purpose, a total of seven finishing conditions were analysed: wet grinding as reference, two dry grinding conditions, two cryogenic grinding conditions and two hard turning+belt finishing conditions. The surface integrity (roughness, residual stresses, hardness and microstructural defects) of samples was assessed. Finally, the step-loading test method was used to determine the scuffing resistance of the samples. Tested innovative finishing operations led to higher scuffing resistance than conventional wet grinding. Results demonstrate that higher surface hardness and roughness leads to higher scuffing resistance, while the effect of surface residual stresses is not significant.

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Keywords: belt finishing, grinding, cryogenic, surface integrity, tribology

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1. Introduction

The European Union is committed to reducing the number of traffic accident victims. To attain this goal, the first step is to reduce the probability of accidents and, given that component failures is one of the main causes for vehicle accidents [1], the likelihood of piece failures must be minimised. More than 25% of the component failures in vehicles are related to transmission parts [2], such as, shafts and gears of the gearboxes. The main way to reduce the risk of failure is improving the component properties, mainly the fatigue and tribological performance. Shafts and gears work in sliding contact with their counter part transmission components, and therefore they must possess good tribological performance in terms of wear and friction. Undoubtedly, to reach or improve the tribological requirements, manufacturing of components with enhanced surface integrity (SI) is a key factor.

Focusing on transmission shafts, the finished surface of the contact region of transmission is usually produced by grinding with conventional coolants. Unfortunately, conventional cooling systems are associated with environmental, health, and cost issues in grinding operations [3]. Beyond this context, several eco-friendly approaches alternative to the finishing operations have been explored for the last years, to produce the target surface integrity without lubricant or with a minimum quantity (MQL).

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The application of cryogenic grinding is one of the most promising alternatives. In their early study, Chattopadhyay et al. extensively analysed [4-6] the use of LN2 in grinding process of a variety of steels, and they found that it reduces cutting forces and tensile residual stresses compared to conventional grinding. Sanchez et al. [7] reported that the application of CO2 and MQL reduces wheel wear compared to wet grinding, without negatively affecting the surface roughness and microstructure of the workpiece. Abedrabbo et al. [3] compared the surface integrity generated in 27MnCr5 steel (commonly used for automotive applications) when grinding with a CBN wheel and using conventional cooling, LN2 and LN2 +MQL. Interestingly, they demonstrated that LN2 can produce similar surface integrity characteristics (low roughness, compressive residual stresses and absence of microstructural defects) to those obtains when using conventional pollutant coolants.

Combination of hard machining and belt finishing is another interesting approach to produce shafts with improved surface integrity [8,9]. The main benefits provided by the inclusion of belt finishing after the hard machining are: i) roughness improvement (*R*a ~ 0,1 µm), ii) generation of high compressive residual stresses in the surface layer, iii) removal of surface layer defects produced in preceding process, and thus leading to a very stable surface quality of the final product. Importantly, recent developments have shown that the belt finishing process does not require the use of a high amount of lubrication, reducing the environmental impact. An oil mist with a vegetal oil is sufficient to induce a strong compressive layer as well as to drastically reduce the surface roughness [10,11].

The capacity of these eco-friendly approaches to produce similar or even better SI properties than conventional processes is demonstrated. Particularly, the combination of hard turning and belt finishing reduces significantly the roughness and increases compressive residual stresses. However, there is a lack of research on the impact of surface integrity on tribological properties of the final product [12] and further research is necessary to clarify: i) which SI parameters are directly link to the tribological behavior and ii) if the innovative processes also improve the tribological behavior. Beyond this context, this study is aimed at evaluating the surface integrity and tribological behavior of 27MnCr5 steel samples produced by conventional grinding, dry grinding, cryogenic grinding (using LN2 coolant) and hard turning + dry belt finishing.

2. Material and specimen manufacturing

The 27MnCr5 steel widely used in the automotive industry was selected for this study. The cylindrical specimens were carburised prior to grinding and hard turning + belt finishing tests. This heat treatment led to a martensitic structure with a surface hardness of 59-64 HRC and a carburised layer of 0.7-0.9 mm in the outer diameter. The geometry of the specimens is shown in Fig. 1. Then, a total of 35 specimens were produced, five by each finishing condition: wet grinding (WG), two dry grinding conditions (DGA, DGB), two cryogenic grinding conditions (CGA, CGB) and two hard turning+belt finishing conditions (BF30, BF60).

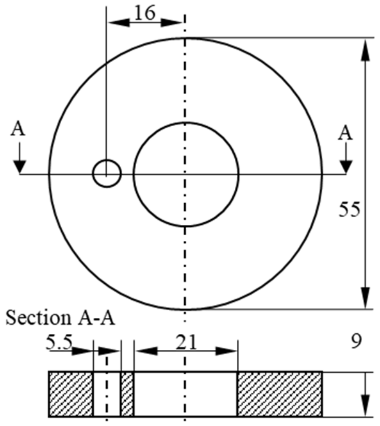

Fig. 1. Geometry of the specimens.

Wet and dry grinding tests were carried out in a Lizzini grinding machine using CBN wheels (ref. B107 900804 for wet and ref. B91 102025 for dry conditions). The wheel was dressed before each of the finishing tests. Five specimens were produced using emulsion (WG) at feed of 1 µm/rev, grinding wheel speed V_s = 70 m/s, workpiece speed V_o = 222 rpm. Two batches of five specimens were produced at dry conditions (cooled compressed air) using the same V_s = 70 m/s, pre-finishing feed of 2 µm/rev and finishing feed of 1 µm/rev but changing the sample speed; i) DGA: V_o = 222 rpm and ii) DGB: V_o = 259 rpm. Test conditions are summarised in Table 1.

Table 1. Finishing conditions of wet and dry grinding tests

Test	V_s (m/s)	V_0 (rpm)	Feed (µm/rev)	Coolant
WG	70	222	1	Emulsion
DGA	70	222	1	Cooled air
DGB	70	259	1	Cooled air

Cryogenic grinding tests were done in a Danobat cylindrical grinding machine using a CBN wheel (ref. 3D1V-400-15-5-25-27-B107-SA-100-V69M). A jet of liquid nitrogen (LN2) was directly applied to the grinding wheel into a near zone between the contact of the wheel and workpiece (2 cm approx.), using a circular nozzle with a diameter of 5 mm, and inclined approximately 45° with respect to the workpiece surface. The liquid LN2 was storage in a tank with a pressure of 2 bar. A conduit allowed the nitrogen to fluid from the tank to a phase separator, and then to flow to the nozzle. The phase sepataror ensured that nitrogen impacted the wheel in liquid stage. The wheel was dressed before each of the finishing tests. Two batches of five specimens were produced using two different finishing conditions at fixed infeed rate of 0.3 mm/min: i) CGA: grinding wheel speed V_s = 40 m/s, workpiece speed V_o = 300 rpm and ii) CGB: V_s = 52.6 m/s and V_o = 100 rpm. Test conditions are summarised in Table 2.

Table 2. Finishing conditions of cryogenic grinding tests

Test	V_s (m/s)	V_0 (rpm)	Feed (mm/min)	Coolant
CGA	40	300	0.3	LN2
CGB	52.6	100	0.3	LN2

Before the belt finishing operation, the specimens were hard turned in a CMZ CNC lathe under dry conditions. In all tests, a CNMG 120408 WF 1115 insert from Sandvik was used, a cutting speed V_c= 80 m/min, feed rate f=0.1 mm/rev and depth of cut a_p=0.15 mm. Then two batches of five specimens were obtained by dry belt finishing using a SUPFINA machine installed on a CMZ CNC lathe, using two different alumina grain sizes: 30 µm and 60 µm, for conditions identified as BF30 and BF60 respectively. Other process parameters were defined based on previous studies and were kept constant: oscillation frequency of 12 Hz, amplitude of 0.5 mm, applied force of 150 N during 60 s, workpiece rotation speed of 900 rpm, and feed of 0.6 mm/rev. These values correspond to optimum values based on previous studies [10-13]. Table 3 summarises the fixed and variable parameters of the belt finishing tests.

Table 3. Belt finishing conditions

	Parameters	Units	Values
Fixed	Finishing belt grains material		Al_2O_3
	Roller Hardness	(Shore)	80
	Roller Young modulus	(MPa)	50
	Roller Poisson's ratio		0.5
	Roller radius	(mm)	35
	Roller width	(mm)	50
	Oscillation frequency	(Hz)	12
	Oscillation amplitude	(mm)	0.5
	Workpiece rotation speed	(rev/min)	900
	Applied force	(N)	150
	Process time	(s)	60s
	Belt feed rate	(mm/s)	0.6
BF30	Abrasive grain size	(µm)	30
BF60	Abrasive grain size	(µm)	60

3. Surface integrity characterisation

Residual stresses were measured in the axial and hoop directions of the specimens by X-Ray diffraction method using a Proto XRD diffractometer. Kα radiation was observed using a Chrome X-ray tube operating at 20 kV and 4 mA and a collimator with a diameter of 2 mm. To quantify residual stresses Bragg angle 156° was used, which corresponds to {2 1 1} diffraction plane. To measure the in-depth residual stresses, surface layers were removed by electropolishing in successive steps.

The surface roughness was measured in the axial direction of the machined surface employing a Mitutoyo roughness tester SJ-210 and following the ISO 4287:1997 standard. A cut-off length of 0.8 mm and a sampling number of 5 was used in the measurements, characterising a total length of 4 mm. The roughness measurements were taken at three equidistant points separated by 120º in the outer diameter of the specimen. Finally, the mean value of the three tested surfaces was averaged for each finishing condition.

The microhardness profile of the machined surfaces was characterised using a hardness tester ZWICK. For that purpose, a load of 50 g and a loading time of 10 s was applied in the indentations. These profiles were generated from the surface to the bulk of the material in four steps of 25 µm near the surface, followed by four steps of 50 µm, seven steps of 100 µm, and a final increment of 500 µm, characterising a total depth of 2 mm. Three repetitions per finishing conditions were done.

The microstructure of the machining affected layer was observed by optical microscopy. Samples were cut out by wire electro discharge machining from one specimen of each machining condition. These samples were polished and etched with Nital (5%) solution. Finally, the subsurface microstructure was observed on an optical microscope equipped with a digital camera Leica DMC 2900. The micrographs were obtained using a magnification of ×500 and analysed using Leica LAS V4.9. software.

4. Tribology tests

The most critical aspects for the shafts performance from a tribological point of view are the sliding contact areas with supports and the scuffing risk. All scuffing tribological test protocols involve a progressive increase in the severity of contact and interaction between the test surfaces until scuffing occurs. In present work the step-loading test method was used: the contact load is increased in pre-determined discrete steps and duration until scuffing occurs, whereas all other test variables are held constant. Scuffing resistance is then determined by the values of applied load at which scuffing failure occurs and an abrupt increase of friction coefficient is recorded (Fig. 2).

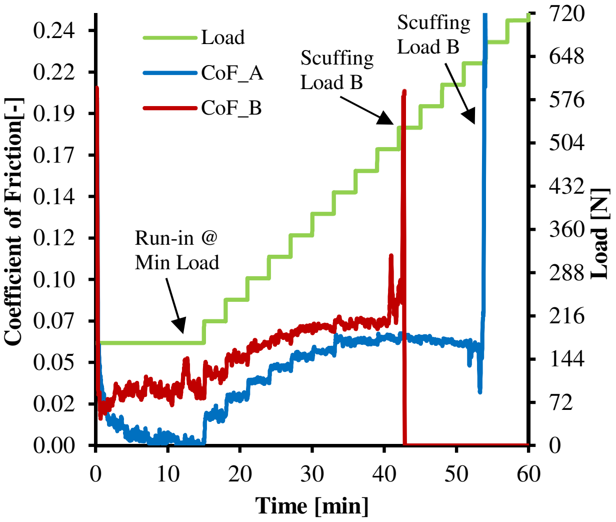

Fig. 2. Example of step-loading test.

The shaft-support pure sliding contact condition was reproduced by a block-on-ring test configuration (Fig. 3). The 27MnCr5 finished disc was driven in rotation by the tribometer horizontal shaft at 850 rpm and a counterpart 100Cr6 polished coupon was then pressed against its peripheral surface by a pneumatic actuator. The load, as described above, was then increased until seizure starting from a min value of 172 N up to a theoretical max value of 892 N by 36 N increasing steps. An oil dropping set at 1 mil/min operated by a peristaltic pump ensured the boundary lubrication condition in the contact area between the two specimens. A transmission low viscosity oil (4,3CSt @100°C, 15CSt @14°C) was used for lubrication purposes. Three test repetitions were carried out for each ring finishing condition.

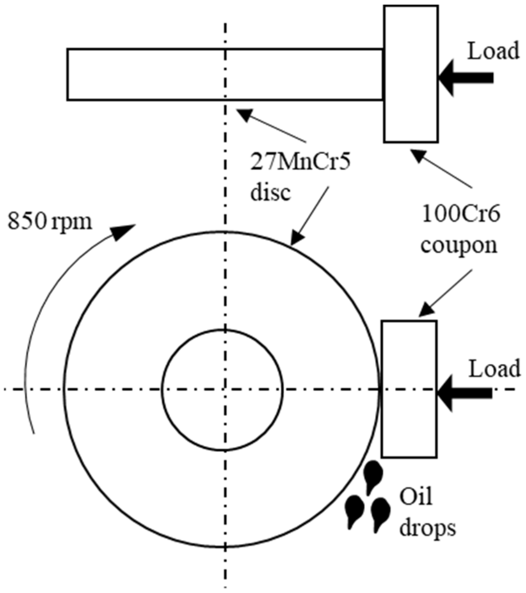

Fig. 3. Scheme of the tribological tests.

5. Results and Discussion

5.1. Residual Stresses

Fig. 4 presents the residual stress results for the different processes and parameters. Each process studied induced additional compressive residual stresses near the surfaces (first 20 µm), being more compressive in the axial direction than in the circumferential direction.

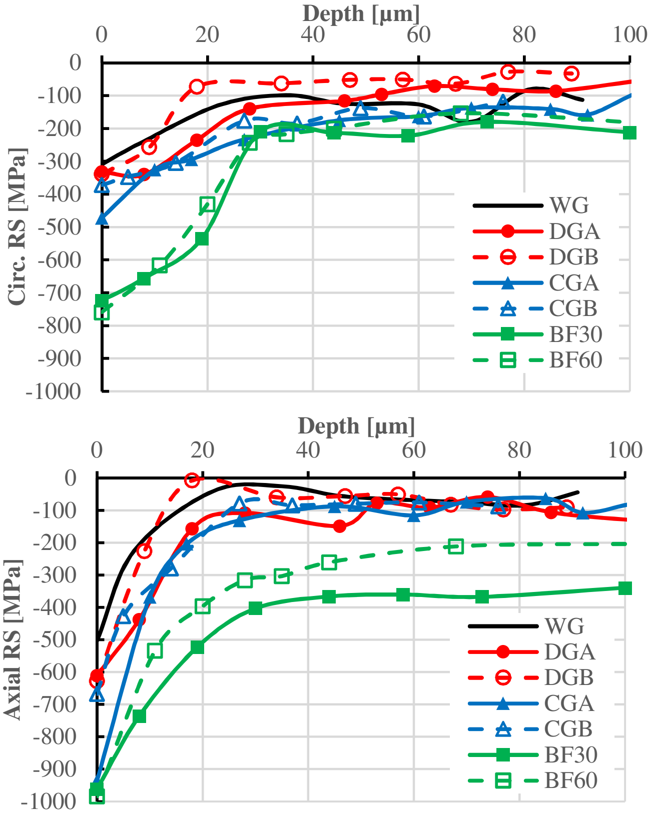

Fig. 4. Circumferential and axial residual stresses for the different processes.

Both cryogenic (CGA, CGB) induced slightly more compressive residual stresses than dry grinding (DGA, DGB) and conventional wet grinding (CWG) process. Interestingly, the belt finishing, independent of the grit size used in the tests, induced the best compressive residual stresses, ≈950 MPa in the axial direction and ≈750 MPa in the hoop direction. Moreover, the magnitude of these compressive residual stresses was higher beneath the surface than those produced by other processes, particularly in the axial direction. These higher compressive residual stresses are probably due to ploughing effect of the abrasive grains which is acting mainly in the axial direction. Although results are not included, it should be noted that the hard turning process applied before the belt finishing step, induced maximum compressive stresses of 400 MPa and 500MPa respectively for axial and circumferential directions.

5.2. Roughness

Fig. 5 summarises the results obtained in the roughness measurements. In all tested surfaces average roughness Ra was below 0.3 µm. Both dry grinding conditions produced slightly rougher surfaces (DGA, Ra ≈ 0.28 µm; DGB Ra ≈0.25 µm) than the reference conventional wet grinding process (Ra ≈ 0.19 µm). Both cryogenic grinding and belt finishing conditions led to lower roughness Ra than the wet grinding, but also slightly higher peak to valley Rt values. It must be highlighted that when belt finishing with the grit grain sizes of 30 µm, really smooth surfaces were reached, Ra < 0.073 µm.

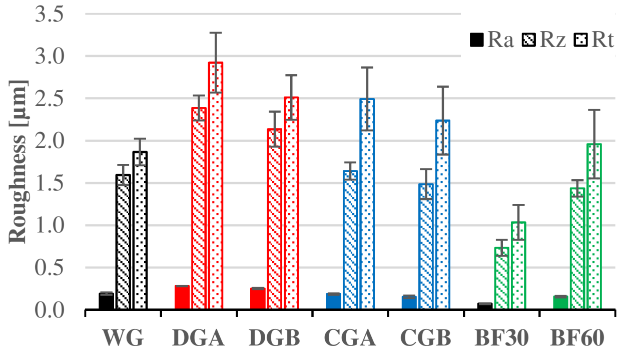

Fig. 5. Roughness generated by tested finishing conditions.

5.3. Microhardness

Microhardness profiles measured in the surface layer of the seven tested conditions are shown in Fig. 6. The five grinded surfaces showed $HV_{0.05}$ hardness values above 700 within the first 0.5 mm. This implies that the properties of the carburised layer were not severely affected by the selected process conditions. However, it seems that there is a very slight reduction of the hardness near the surface, which could be due to the thermal effect (softening) or uncertainty of the measurement (indentation close to the border). Nevertheless, the hardness of the belt finished surfaces was lower than the grinded surfaces, and it also seems that the carburised layer is thinner. Therefore, this reduction in hardness could be because initially the specimens had a lower hardness, or more probably due to the higher amount of material removed during hard turning.

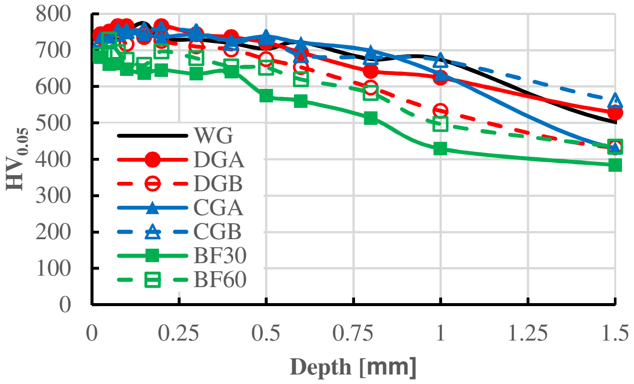

Fig. 6. Microhardness profiles obtained by tested conditions.

5.4. Microstructure

Fig. 7 shows the main microstructural defects observed in the surface layer of the specimens manufactured by the different processes and parameters.

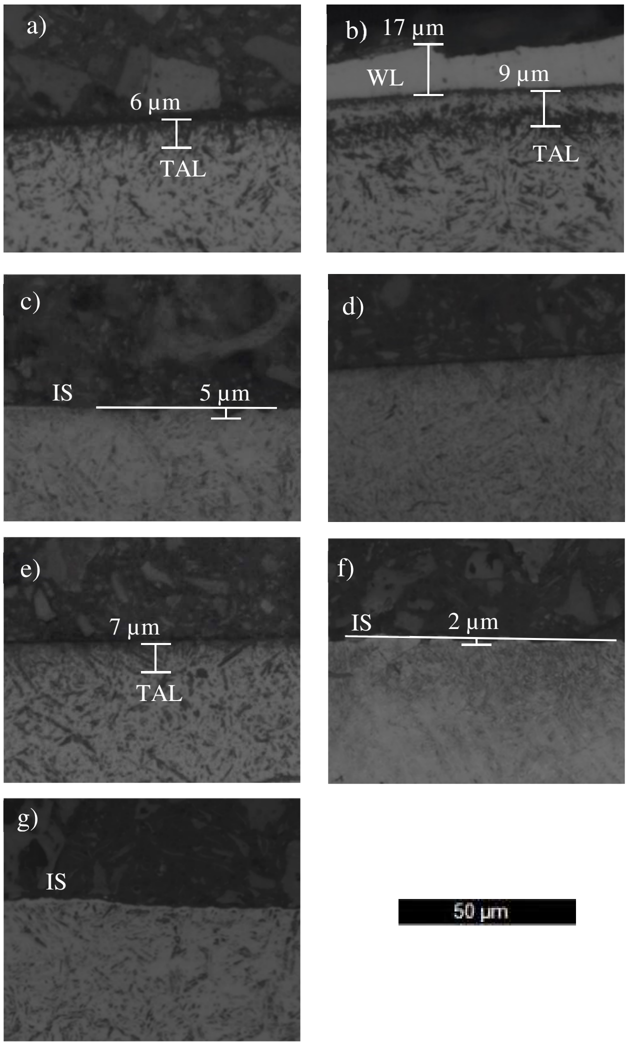

Fig. 7. Microstructure of the surface layer produced by a) WG, b) DGA, c) DGB, d) CGA, e) CGB, f) BF30 and g) BF60

The conventional wet grinding did not generate significant microstructural alterations, and only a thermally affected layer (TAL) thinner than 6 µm was found in some regions (see Fig. 7a). Cryogenic grinding also produced a very thin TAL when using the highest cutting speed (CGB, see Fig. 7e) and no defects were observed when decreasing the cutting speed (CGA, Fig. 7d). Similarly, both belt finishing conditions did not generate microstructural alterations, and only a very shallow irregular surface (IS) was found in both conditions (see Fig. 7f and Fig. 7g).

However, dry grinding conditions produced more significant microstructural alterations. Particularly, DGA generated a white layer with maximum thickness of 17 µm as consequence of the aggressiveness of the process (high amount of heat generated) as can be seen in Fig. 7b. Additionally, an irregular surface (≈5 µm) was generated when grinding under dry conditions. This finding is also aligned with the rougher surfaces measured in these two surfaces, as already discussed in section 5.2.

5.5. Tribological behaviour

Bar chart in Fig. 8 shows the average value of Scuffing Load (SL) for the innovative finishing conditions: all the innovative finishing technologies show an improved scuffing resistance if compared to WG, set as the reference technology.

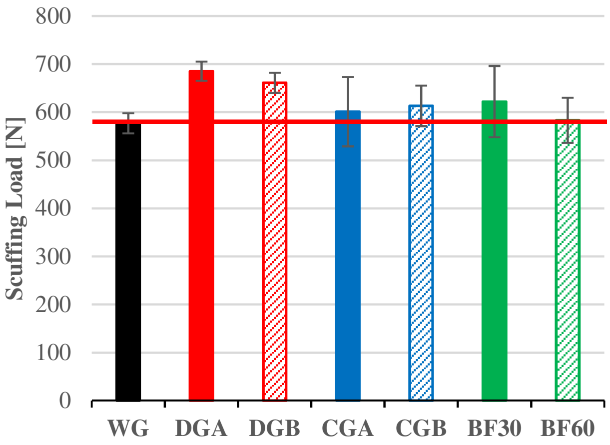

Fig. 8. Average value of Scuffing Load for tested conditions.

To find the correlation between the Scuffing resistance and the SI characteristics in Figs. 9-11, three graphs are reported in which each of the relevant surface parameters (hardness, roughness and surface circumferential residual stress) is showed with SL. In general, SL increases with increasing surface hardness, confirming previous findings on this topic, and decreases with decreasing roughness probably due to a lower surface wettability, whereas it does not show any correlation with surface residual stress status.

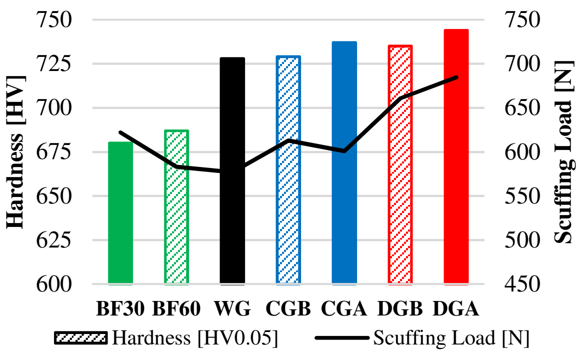

Fig. 9. Scuffing Load vs Hardness.

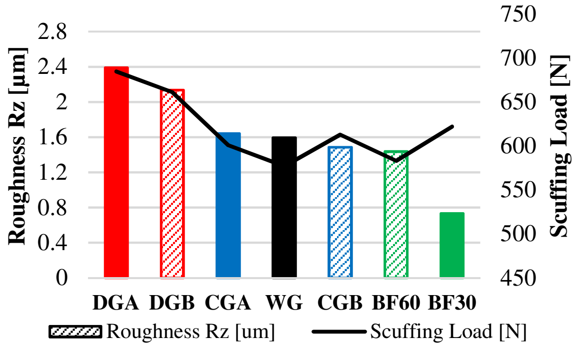

Fig. 10. Scuffing Load vs Roughness *Rz*.

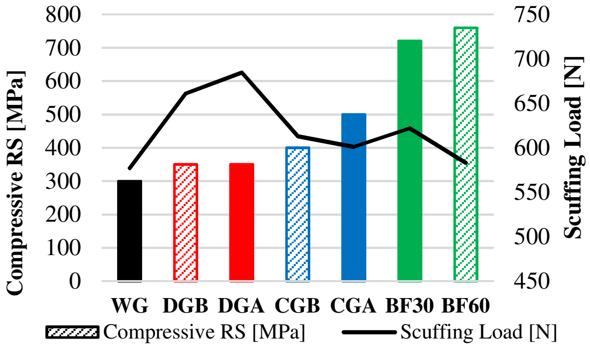

Fig. 11. Scuffing Load vs Residual Stresses.

6. Conclusions

This research analysed the effect of eco-friendly processes on the surface integrity and tribological performance of steel grade 27MnCr5. The main conclusions are:

- All tested innovative finishing operations generated compressive residual stresses near the surface. The most compressive residual stresses were generated by belt finishing reaching values ≈ -700 MPa in the circumferential direction and ≈ -900 MPa in the axial direction.
- Surface roughness *Ra* was below 0.3 µm in all tested conditions, and the smoothest surfaces were obtained by belt finishing.
- Microhardness measurements showed that the carburised layer was not significantly affected by the innovative finishing operations. No significant microstructural defects were observed in samples manufactured by cryogenic grinding and belt finishing. However, very thin white layers were detected in the samples produced by dry grinding.
- The scuffing resistance of the samples produced by innovative finishing conditions was higher than the samples generated by wet grinding. The scuffing resistance increased when increasing the hardness and surface roughness, whilst the effect of surface residual stress was unclear.

Acknowledgements

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