



Isotropic finishing of austempered iron casting cylindrical parts by roller burnishing

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Abstract

Roller burnishing technique to achieve isotropic surface topography on cylindrical components made of austempered ductile iron (ADI) casting is presented in this paper. In the last years, ADI casting components are used in many mechanical applications, due to their enhanced mechanical properties. ADI castings are difficult-to-cut materials; therefore, advanced techniques to improve manufacturing productivity are necessary and under research. On the other hand, spiral roughness pattern produced by turning operation is a common source of unconformities in several applications. Turning produces a defined kinematic pattern, similar to a thread. This work presents a theoretical and experimental validation using different burnishing conditions. Roughness and surface topography and surface integrity were checked. Results show that the technique greatly improves surface roughness, and eliminates the kinematic-driven roughness pattern of turning, leading to a more isotropic finishing. A comparison between roller burnishing and ball burnishing is also presented in this paper.

Keywords Roller burnishing, · Austempered ductile iron, · ADI isotropic finishing, · Surface integrity, · Topography

1 Introduction

The combination of novel materials and advanced manufacturing processes is key in many manufacturing sectors such as aeronautics, automotive, gear industry, heavy duty equipment, etc. In this work, the use of a novel cross-hatch type technique using conventional roller burnishing tools applied on austempered ductile iron (ADI) casting components is presented. Some relevant research results were presented by authors previously in [1] about burnishing of rotary components. Moreover, the elimination of surface profile generated after turning brake disks was also analyzed by authors

applying abrasive brushes [2]. Turning operation always induces a kinematically defined pattern, with spirals on part surfaces or thread-like profiles. Spiral/thread patterns can bring up many problems, such as leakage of oil in sealed zones in gearboxes, vibrations in brakes, and many others. In some applications, manufacturing requirements forbid turning due to this drawback.

In the field of cast iron materials, gray cast iron, in which graphite is in form of layers, was replaced years ago in some applications by ductile cast iron, also known as nodular cast iron or spheroidal graphite cast iron. This one, developed and patented around 1948, is formed by graphite spheroids in a metal matrix, giving superior mechanical characteristics [3]. This material was quickly introduced in equipment designs to make lightweight components [4]. Afterward, ADI (austempered ductile iron) castings represented a new step in the evolution. In ADI, graphite still appears spheroidal, but the rest of the microstructure forms the so-called austoferrite. Thus, ADI casting 5-stage heat treatment (heating, austenitizing, quenching, austempering, and final cooling) causes that acicular ferrite retains the carbon-stabilized austenite, named ausferrite microstructure. Austempering temperature determines the structure quality and final mechanical properties. Austempered Ductile Iron (ADI) began to be used in the 1980s, spread in the automotive sector for components

Highlights

- A novel procedure to get surface topography with cross-hatch patterns is presented using the roller burnishing technique.
- A proposed finishing operation is developed for ADI materials.
- Burnishing parameters and their influence are analyzed for cylindrical components.
- Isotropic and no-directional pattern is obtained after turning

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of high-end vehicles; since then, the increase was spectacular. This is because parts made of this material show an excellent strength-to-weight ratio, improving significantly ratio values offered by aluminum alloys, steel, and other castings [5, 6]. ADI mechanical properties are superior to pearlite ductile castings and forged steels, which has a maximum strength of around 700 MPa. In ADI, ultimate strength ranges from 800 to 1400 MPa, being those between 800 and 1100 the most used because they keep good ductility. For instance, ADI 1000 is a logical step from ductile iron grade around 700 MPa. Standards for ADI are ISO 17804-2005, EN1564, and ASTM A897M [7]; see table and Fig. 1. Hence, ADI 900 is achieved at temperatures of 390°, while the hardest and most strength ones at lower temperatures.

Regarding machining [8, 9], the first choice for ADI removal is the use of carbide inserts type K, as is recommended for the rest of castings. However, ADI castings have lower machinability than other castings, resulting in increased tool wear due to abrasion and adhesion phenomena.

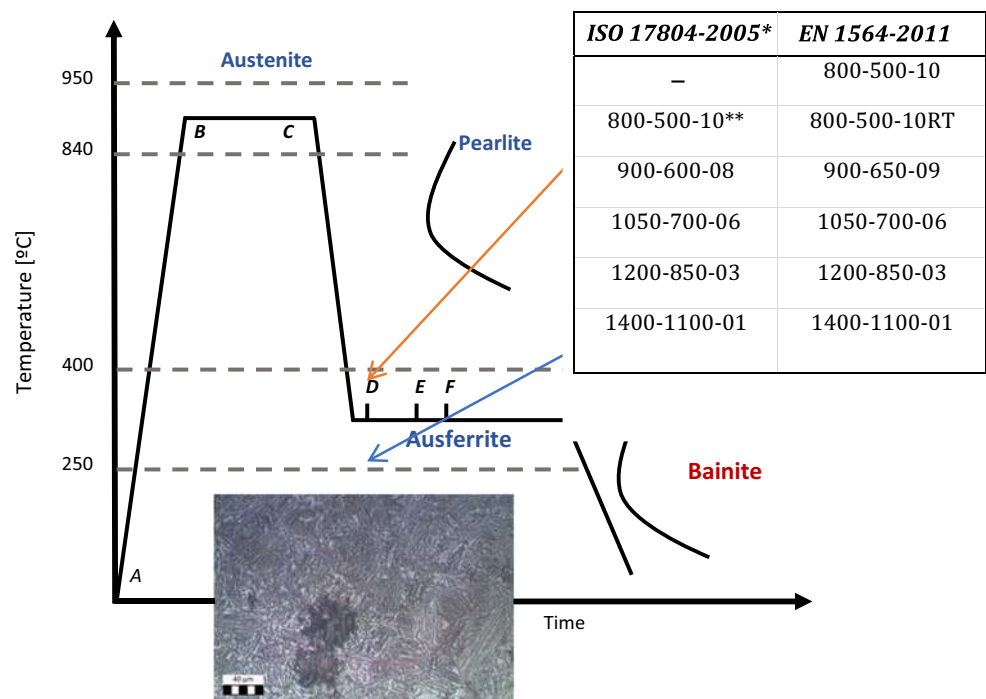
In order to reduce machining time, burnishing techniques could eliminate finishing turning operations. The idea is to maintain roughing operation conditions, applying burnishing just afterward. The sequence allows to achieve the final surface roughness, reducing both time and costs. Moreover, combining turning and burnishing in opposite directions (i.e., turning is clockwise, and the other is counterclockwise), it would be possible to eliminate the directional roughness pattern, typical of turning parts. Another fact to take into account is that residual stresses are also critical [10] in many applications; burnishing process introduces compressive residual stresses

and strain hardening on workpiece surfaces, which are excellent for improving fatigue life.

Burnishing is a simple operation, inexpensive and which generates high-quality final surfaces [11–13]. The type roller burnishing technology (known as rolling) is applied in lathes, and it allows finished surfaces within the quality of grinding (i.e., less than 1- μm Ra). Thus, roller burnishing can replace finishing processes and mechanical treatments such as grinding, shot peening, or hand polishing. In addition, burnishing is applied on the same machines' tools than the previous turning, using inexpensive additional burnishing tools. Burnishing is based on making small plastic deformations generating a material displacement that modifies surface topography micro-irregularities. This mechanism is performed by a rolling element that moves onto the just machined surface, applying a regular compression force at the same time.

Burnishing systems can be (a) roller-type, in this case the process is known as “rolling” or “roller burnishing” and (b) ball-type [14, 15] whereby the term “ball burnishing” is used. Otherwise, deep ball burnishing commonly refers to a hydrostatic burnishing tool capable of supplying pressures of 20–30 MPa, introducing compressive residual stresses over 1 mm in depth. A variation of this technique is the so-called low-plasticity burnishing (LPB) by Golden and Shepard [16]. LPB is a mechanical surface enhancement technology developed and patented at Lambda Technologies®. This technique uses a minimal amount of plastic deformation needed to create the desired level of compressive stress. LPB is mainly applied to improve the fatigue properties of gas turbine engine components [17]. Burnishing was also used combined with other

Fig. 1 Heat treatment for austempering, ADI grades, and austoferrite structure. High strength ADI grades are achieved at lower austempering temperatures. The picture is of ADI 1000, showing austoferrite



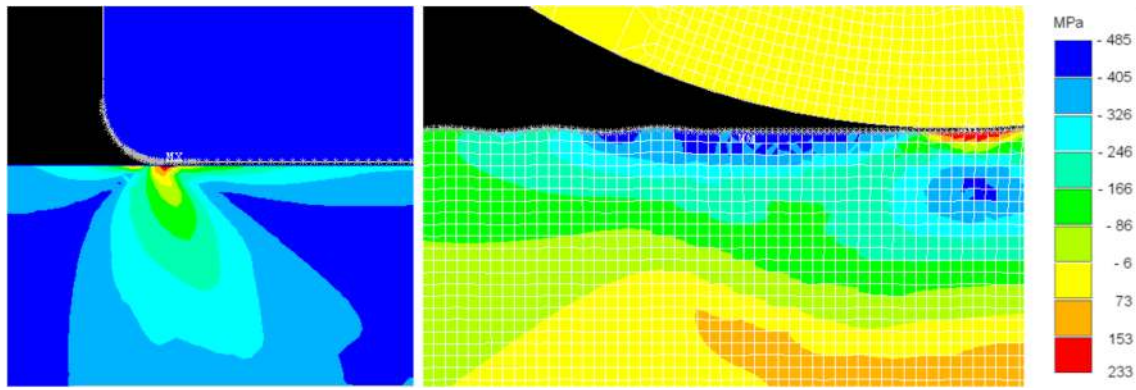


Fig. 2 Geometry of the multi-pass 2D model for roller burnishing process. Stress field obtained during contact and after simulation

industrial manufacturing processes, such as friction stir welding [18, 19] or incremental sheet forming [20]. Burnishing improves the surface quality [12]; increases the surface hardness of the workpiece [21]; produces high compressive residual stresses in the workpiece surface [22]; and, as a result, increases corrosion resistance, wear resistance, and fatigue life, as presented by authors in [23, 24]. Thus, burnishing can replace other finishing processes, such as grinding, shot peening [25], or hand polishing.

During the last decades, several predictive models were developed for the burnishing process and, consequently, to analyze the influence of process parameters in the workpiece surface properties. Models of burnishing are classified in three categories, (a) statistical, (b) analytical, and (c) FEM models. Thus, some authors [26] developed statistical models based on the response surface method (RSM) to relate surface roughness to burnishing parameters, but these do not represent physical phenomena occurring during the process. Other works [27, 28] presented analytical models to determine roughness of burnished surfaces. The equations presented depend on rolling or

burnishing feed, on the normal displacement of the ball, and on the initial surface roughness from previous turning and/or grinding. Finally, some authors developed FEM models, capable of predicting surface integrity [29, 30]; in this work, a novel FEM model is also presented in order to understand the rolling process through a theoretical approach. Tajane and Pawar [31] considered burnishing as an alternative to heat treatment and grinding operations, which results into minimization of cycle time. On the other hand, Travieso et al. [32] applied burnishing to workpieces with a convex or concave surface.

Grinding operation is also concerned by surface state [33–35]. Burnishing and rolling can compete with grinding regarding the final surface finishing; besides, grinding does not introduce a defined pattern on roughness, whereas machining processes introduced it [2]. That is why some brake disks are ground after turning. Grinding implies near-to-isotropic roughness, but machine-tool and process are more expensive.

The present work proposed an easy way to achieve isotropic finishing in pieces by means of rolling or burnishing.

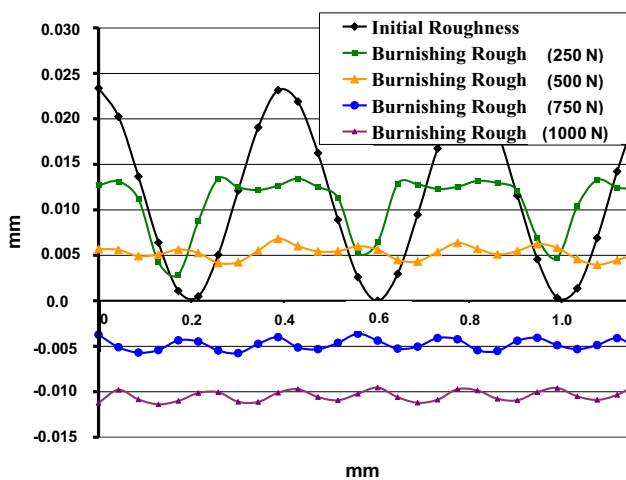


Fig. 3 Effect of burnishing force on surface profile, rolling feed $f_b = 0.2$ mm/rev

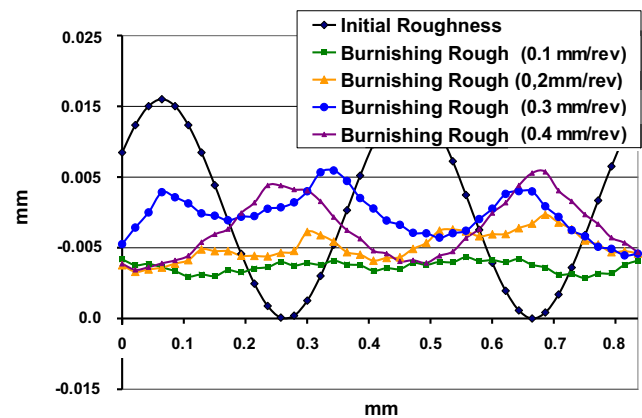


Fig. 4 Roughness profiles obtained with different burnishing feed, force = 500 N

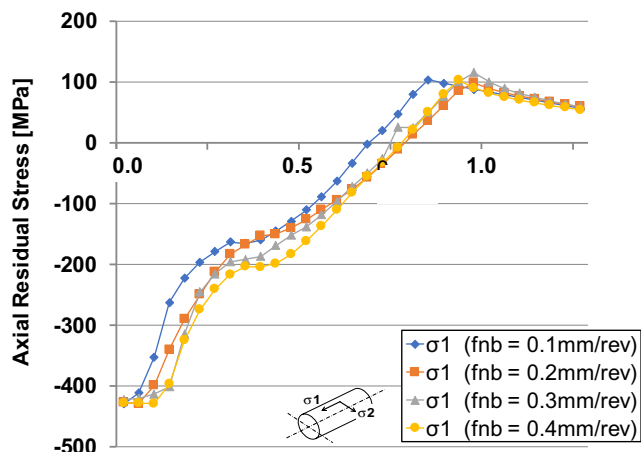


Fig. 5 Prediction of the residual stresses (in the axial direction) for different burnishing feed rates, along depth

2 Isotropic and surface integrity: A numerical approach

Burnishing is a cold-working process performed on a previously machined surface; in many cases, burnishing is applied immediately after turning or milling. So the process is based on making small plastic deformations on part surfaces, which causes material displacement from the “peaks or ridges” to the “valleys or depressions” of surface micro-irregularities. This mechanism is performed by a rolling element (the tool, it can be a ball or a roller) that moves on the surface, applying a regular compression force.

The “crushing” causes four effects on the surface:

1. Reduction of surface roughness in more than an order of magnitude. The final quality is similar to grinding, even reaching a mirror-like aspect.
2. Generation of high compression residual stresses on workpiece surfaces, which is beneficial for the component fatigue behavior. Moreover, the absence of heat produced by this mechanical surface treatment prevents from metallurgical changes on surfaces.
3. Surface hardness increment, between 30 and 60% (HBN) in mild steel and cast iron cases.

Table 1 Parameter definitions for ADI 1000 testing experiments

		Test 1	Test 2	Test 3
Turning	V_c [m/min]	80	80	80
	f_n [mm/rev]	0.4	0.4	0.4
Burnishing	F_b [N]	1000	1000	1000
	f_{nb} [mm/rev]	0.4	0.2	0.1
	V_b [m/min]	80	100	120

4. Dimensions are within tight tolerances (< 0.01 mm). In fact, using special tools for hole calibration is a typical application of spring-type burnishing devices, mandrel type.

The state of the art of numerical models for mechanical surface treatments is still on a fundamental level. Finite element method (FEM) models are available in academics and research projects, due to their potential, for an early prediction of the effects induced for these processes, and the possibility to reduce physical testing. This section aims to present a FEM model for burnishing, which allows the study of the influence of parameters such as burnishing feed and pressure on workpiece surface roughness and residual stresses.

Burnishing is a three-dimensional process; however, the use of a 3D FEM model supposes significant computational times, and it does not give better results than simplified 2D models. A 2D model is easier to propose and permits to study the process parameters’ influence on surface finish level and residual stresses. In this study, workpiece material was steel of ultimate strength 1000 MPa, because data for ADI 1000 are not in literature. The 2D FEM model process parameters were (i) initial turning roughness, (ii) burnishing pressure, and (iii) feed of the burnishing tool (similar in concept to the turning feed, so it is measured (fb) in mm/rev).

A multiple-pass indentation process was considered, as shown in Fig. 2. The full formulation, which includes large strain elastoplastic and contact models, is defined in a previous authors’ work [1]. Hence, plane strain conditions were assumed with displacement constraints located very far from the burnishing zone to avoid edge effects. The domain was discretized with four-noded isoparametric finite elements with standard Gauss integration quadrature and a B-bar technique to circumvent the plastic volumetric locking. The meshing in the region where the indenter acts needs to be fine enough in order to improve the accuracy of the results in this region, a zone in which large gradients in the solution variables are expected. A mesh refinement sensitive analysis was previously carried out in order to ensure mesh-independent results. Thus, the resulting element size in the indentation region was $5 \times 5 \mu m$. The rolling tool was considered as a perfectly rigid body (rolling tools are made in ceramic or carbides, very stiff).

2.1 Surface characteristics

One of the more relevant outputs is surface roughness. It is really interesting to know how the profile will be just using numerical modeling. Some simulations were carried out and surface profile was obtained for each one. To calculate the profile, several nodes of the previous turned profile were selected and Y axis displacements were calculated. In this way, each simulated profile was obtained through the difference

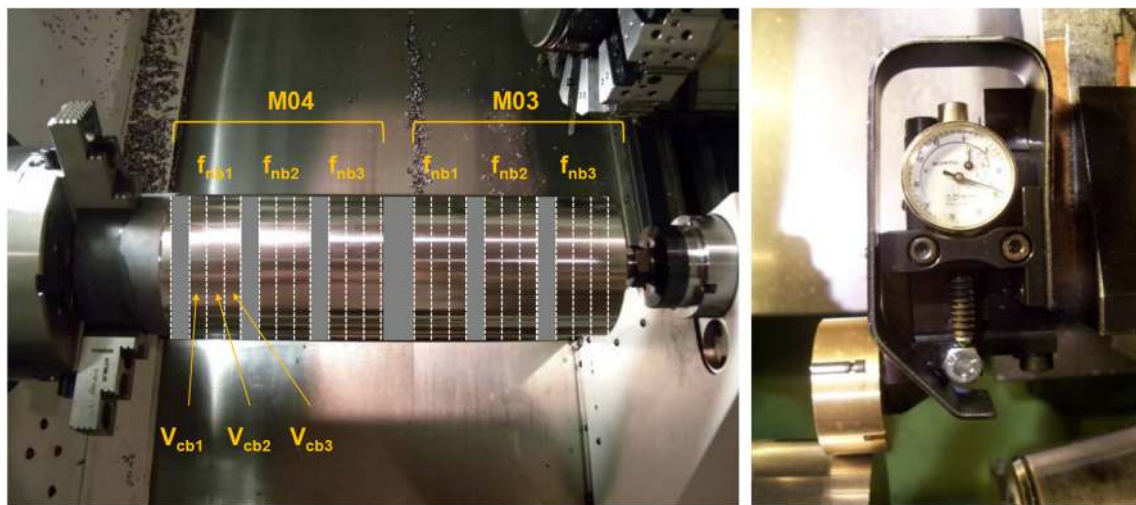


Fig. 6 Experimental set-up. (Left) testing part and burnishing parameters, values are those of burnishing tests. (Right) roller burnishing tool

between the values of the Y axis just before and after burnishing.

Figure 3 shows the effect of burnishing pressure on workpiece surface profile. Thus, the roughness profiles obtained with the finite element model show that by applying a force of 250 N, the burnishing tool flattens the surface roughness peaks by half. In the figure, roughness peaks appear 0.4 mm separated, which corresponds to the previous turning feed rate.

By increasing force to 500 N, the midline of the profile decreases, and although some peaks are appreciated at 0.4 mm, burnishing feed marks begins to be noted, generating peaks of roughness at 0.2 mm (i.e., the burnishing feed). Surface profiles obtained at 750 N and 1000 N show that final roughness was generated by the rolling tool, being the peaks at a distance of 0.2 mm. In addition, the roughness midline is very small compared with the initial one, but with these forces, the tolerances of the workpiece are not ensured. It can be concluded that the optimum burnishing force in would be

around 500 N, since higher pressures do not guarantee work-piece tolerance and also leads to a waste of energy.

Figure 4 shows the effect of burnishing feed on workpiece surface profile. Roughness profiles obtained by FEM simulations show that final roughness improves at the smallest burnishing feed values. Also, it can be appreciated that the roughness peaks occur at the same distance as the value of burnishing feed in all the simulated cases. The best surface roughness is achieved by applying a burnishing feed of 0.1 mm/rev; roughness peaks are negligible in comparison with other feed values.

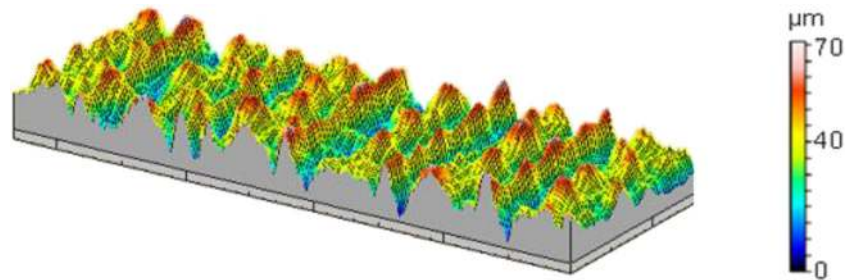
2.2 Residual stress distributions

Residual stress distribution based on burnishing feed per revolution is studied here. From an industrial point of view, it is interesting to reduce surface treatment process time by increasing the radial burnishing feed. To investigate residual

Table 2 R_a and R_z roughness results obtained experimentally (average value of three tests)

	F_b [N]	V_c or V_{cb} [m/min]	f or f_{nb} [mm/rev]	M03		M04	
				R_a	R_z	R_a	R_z
Turning	–	80	0.4	2.12	11.5	2.12	11.5
Burnishing	1000	80	0.4	1.16	7.19	0.92	7.34
		100	0.4	1.21	9.97	1.02	7.44
		120	0.4	1.02	6.09	1.17	9.47
		80	0.2	0.94	6.74	0.94	7.7
		100	0.2	1.21	9.67	1.02	7.84
		120	0.2	1.07	10.5	0.79	6.15
		80	0.1	0.90	7.01	0.74	5.87
		100	0.1	0.82	4.99	0.79	6.58
		120	0.1	0.83	5.02	0.79	6.42

Fig. 7 3D topography after turning operation



stresses in two directions, (a) along the material surface and (b) the in-depth direction when using different radial feeds and burnishing pressures, a 2D numerical simulation is performed.

Figure 5 shows the effect of burnishing feed on simulated residual stress distribution. Thus, the higher the burnishing feed is, the higher the compressive stresses are generated. In fact, burnishing speed variation hardly affects workpiece surface finish and hardness. Thus, it is possible to burnish using the maximum rotational speed supported by the lathe, reducing processing time in this way. Otherwise, burnishing feed per revolution is important for increasing productivity. Total process time analysis includes optimum turning feed (initial roughness) and burnishing feed.

3 Experimental set-up

Some tests must be performed to check the feasibility of these numerical approaches. Thus, some cutting experiments were conducted in a CMZ TC25BTY turning center with a FANUC® 31iT HVi numeric control, 25-Kw maximum speed 3000 rpm. The workpiece, a cylinder of ADI 1000, was rigidly clamped and machined using typical cutting conditions for roughing operations. The turning tool was a carbide one type CNMG12, without chipbreaker; new inserts were used in each test. ADI correct grade was tested by cutting-off several coupons. After machining, burnishing tests were carried out. An Ecorrol® EG5–1 burnishing tool was used; values used in tests are shown in Table 1. This tool is based on a spring preloaded provided with a dial to control the rolling force, with a relation of K 4.1 E6 N/m. Tool rollers are made out of sintered carbide.

Testpiece surface was prepared by turning, using common values in roughness operations for this material; cutting speed was 80 m/min. After turning, rolling was performed using different parameters. The force applied was the maximum acceptable for this roller tool, 1000 N. The idea was to generate a great deformation on the surface, eliminating the previous turning pattern. Burnishing feed was checked in three levels, and burnishing direction was applied both in the turning direction and helix-crossed direction (Fig. 6).

4 Results and discussion

Table 2 shows roughness obtained in burnishing tests, burnishing along the same rotation direction than in the previous turning (M03, turning and rolling are parallel spirals), and also when the rotation direction was just the opposite (M04, so in this case the pattern was helix-crossed; turning and rolling spirals are in opposite directions). The purpose was to check whether using the latter, the helix crossing approach, the elimination of directionality patterns generated by the previous turning is possible. Values in the table are average values of three tests, with divergence of 5% maximum.

Results show that roughness parameters are better using helix-crossed burnishing. In all the cases, the final roughness is better with small values of feed per revolution. Regarding the cutting speed variation, results do not make clear the influence of this parameter on the surface quality obtained.

Figure 7 shows a 3D surface topography of the turned surface after roughing conditions. Typical turning peaks and valleys (and grooves) are shown in this picture. On the other hand, in Fig. 8 (left), the topography after burnishing in M03 is shown (turning was also in M03). A decrease in surface

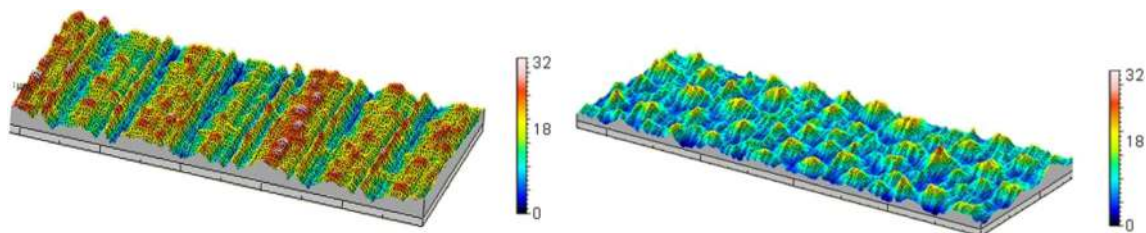


Fig. 8 (Left) 3D topography after conventional burnishing M03, same turning rotational direction. (Right) 3D topography after burnishing M04 (helix-crossed), directional pattern elimination is appreciated

Table 3 Obtained results from roller and ball burnishing processes

	Parameters	Roller burnishing			Ball burnishing		
		<i>Ra</i> [μ- m]	<i>Rz</i> [μ- m]	Hardness [HBN]	<i>Ra</i> [μ- m]	<i>Rz</i> [μ- m]	Hardness [HBN]
Turning	$V_c = 200$ m/min $f_n = 0.4$ mm/rev	3.66	15.3	153	3.56	14.2	151
Burnishing	$V_b = 150$ m/min $F_b \approx 550$ N $f_{nb} = 0.2$ mm/rev	0.105	1.08	238	0.31	1.72	242

roughness is observed, but the turning characteristic roughness pattern is still there, parallel grooves-like.

However, Fig. 8 (right) is with turning in M03 and burnishing in M04, it shows that the well-known turning pattern was disappeared, obtaining an isotropic surface finishing after helix-crossed burnishing application. Finishing is near to be isotropic.

5 Roller burnishing vs ball burnishing

After results using roller tools in the previous section, a comparison using mechanical roller-burnishing technique and hydrostatic ball-burnishing technique is presented. To make the comparison, ball-burnishing and roller-burnishing tests were performed using the same process parameters and on the same material. The burnishing force used in the tests was 550 N (0.15 mm dial), similar to the force measured when using the hydrostatic equipment at 20-MPa pressure. Turning and burnishing parameters and obtained roughness results are shown in Table 3.

Values are the average of three tests.

The results show that the final surface roughness was better when using a single roller mechanical burnisher than using a ball burnisher. For the same feed per revolution and radius of the roller or ball, a diagram of the expected theoretical profile

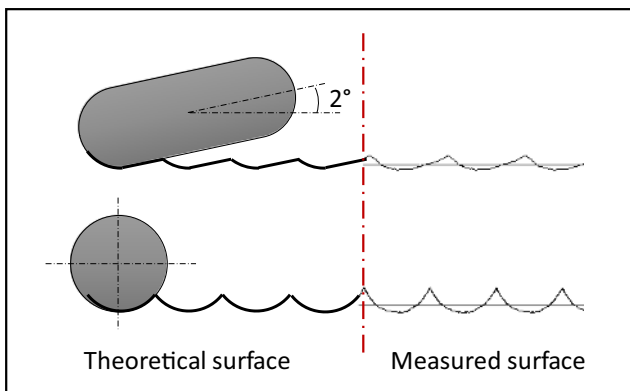


Fig. 9 Finishing geometry sketch using roller and ball burnishing process (left) and the comparison with real measured values (right)

and the actual surface obtained using both tools are shown in Fig. 9.

Roughness values using roller burnishing is always lower than using a ball one. Rollers normally work at a position angle of approximately 2°; therefore, the lateral roller straight area crushes the roughness peaks as it passes by, thus achieving a better finish. So, final finishing depends on the roller rounded edge geometry and the nominal angle of inclination at which it works. This fact, on the other hand, means that roller tools can only be used in simple geometries. For complex geometries and freeform surfaces, the most suitable tool is the ball burnishing tool, as presented in [12, 13] by authors.

With regard to residual stresses, X-ray diffraction measurements for both techniques are shown in Fig. 10. Results showed small quantitative differences, especially on the part surface where the compressive stresses generated by the roller are lower than those generated by the ball (≈ 150 MPa lower). However, the stress field is very similar along depth, marking practically equal values under 0.1 mm of treated surfaces.

6 Conclusions

The influence of roller burnishing on ADI 1000 turned parts was investigated. A numerical approach analyzed the influence of the primary process parameters. In addition, surface

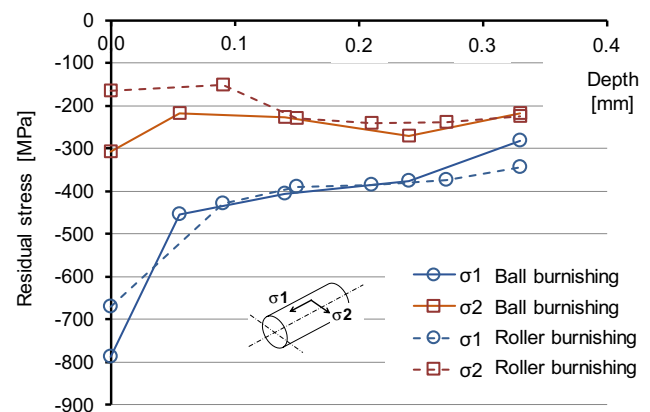


Fig. 10 Residual stresses comparison generated after ball burnishing and after roller burnishing application

characteristics achieved were analyzed. And finally, a comparison between two different tool geometries, roller and ball, is also presented. Based on the experimental results, the following conclusions can be pointed out:

- Roller burnishing process improves significantly the surface roughness of ADI 1000 parts.
- Combining the helix-crossed rolling approach and low values of feed per revolution, surface roughness improvement could be achieved.
- Directional roughness patterns generated in turning operations could be eliminated if rolling is applied in an opposite rotational direction (M03 and M04). The idea has direct application in hard turning, in which the kinematically defined pattern is always a drawback in comparison with grinding.

Roller burnishing improves both physical and mechanical properties of ADI 1000 turned parts. Particularly, this technique improves surface quality (even reaching $0.7 \mu\text{m Ra}$) and introduces compressive residual stresses, which are favorable for increasing the piece fatigue life and for improving the wear resistance.

Burnishing can be performed using the maximum spindle speed and feed rate of lathes. This fact, along with the advantage of applying burnishing on the same machine tool that produced the finishing operation, makes burnishing a fast and simply finishing technique, significantly reducing production time compared with grinding or hand polishing.

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