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A Review on Surface Integrity of Ball Burnishing Process

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ABSTRACT:

Surface quality of product plays a vital role to take competitive advantages in present market condition. Surface finish is an important service characteristic of a product, such as corrosion resistance, wears resistance and fatigue life. Burnishing is one of the cost-effective surface finishing processes which is utilized in the aerospace, biomedical and automotive industries to increase the component's reliability and performance. Burnishing produces a very smooth surface finish by pressing a ball or roller against the machined workpiece. In addition, due to the surface plastic deformation caused by the movement of the hardened ball or roller, the mechanical and physical properties such as residual stresses, surface finish, hardness, roundness, diameter reduction, wearing, etc. could also be improved. These positive improvements are dependent on burnishing process parameters such as speed, feed rate, burnishing force, ball diameter, strategy and a number of revolutions, etc. Diverse studies have been focused on the theoretical, numerical and experimental stages of this process in order to analyze and predict the influence of process parameters.

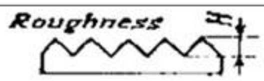
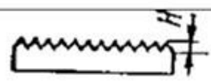
The most important purpose of this work is to present the reviewed state of the art of various studies of the burnishing process, providing a general overview of the developing research of the process. The studied materials and the main parameters are discussed, stating the value ranges preferred by different researchers. In addition, other important parameters are discussed such as: kind of tool, geometry of the working piece, design of experiments, kind of lubricant and effect of the process on the surface integrity of the workpiece.

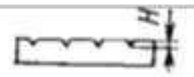
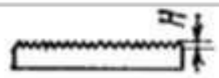
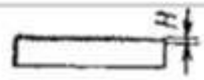
Keywords: burnishing, surface roughness, hardness, speed, force, optimization.

1. INTRODUCTION

In today's competitive world the different mechanical properties, surface quality, low cost and in shorter time period of parts are most vital things to satisfy and attract the customers. Burnishing process is one of the post-processes to reduce the surface roughness of the mechanical components after the conventional machining processes, such as turning or milling. In this process, a rigid ball or roller is used to deform and draw material from the peaks of the surface into valleys due to elastic-plastic contact. This process not only reduces the surface roughness, but also increases the micro hardness, fatigue strength and wear resistance. In the case of ball burnishing, since ball acts as tool to deform the surface, it gives higher pressure, more fatigue strength, and deeper work hardening layer compared to roller burnishing under the same normal force. This processing method is preferred because of its high productivity in mass production compared to the grinding process [1-2]. Traditional finishing processes such as grinding, lapping polishing and honing are commonly employed to improve the surface finish. **Table 1** illustrates gradual improvement of surface roughness produced by various processes ranging from precision turning to super finishing including lapping and honing.

Table 1: Comparison of Finishing Processes

Process	Diagram of resulting surface	Height of micro irregularity (µm)
Precision Turning		1.25-12.50
Grinding		0.90-5.00

Honing		0.13-1.25
Lapping		0.08-0.25
Super finishing		0.01-0.25

SURFACE INTEGRITY

The surface integrity notion, as it is understood is manufacturing processes, was defined by Field and Kahles, as the inherent or enhanced condition of a surface produced in machining or other surface generation operation. This term concerns many parameters:

- Topological characteristics (surface roughness, geometric aspects, etc.);
- Mechanical characteristics (microhardness, residual stresses, etc.);
- Metallurgical characteristics (phase transformation, grains size, etc.);
- Chemical characteristics (changes in the chemical composition of the surface, etc.).

Table 2: Different levels of Surface Integrity (SI) data set. [*Source: Field et al. (1972)]*

Minimum SI data set	Standard SI data set	Extended SI data set
Surface finish	Minimum SI data set	Standard SI data set
Macrostructure (10X or less)	Fatigue tests (screening)	Fatigue tests (extended
Macrocracks	Stress corrosion tests	obtain design data)
Macroetch indications	Residual stress and distortion	Additional mechanical
Microstructure		Tensile
Microcracks		Stress rupture
Plastic deformation		Creep
Phase transformation		Other specific tests (e.g., bearing performance, sliding friction evaluation,
Intergranular attack		sealing properties of surfaces)
Pits, tears, laps, protrusions		
Built-up edge		
Melted and redeposited layers		
Selective etching		
Microhardness		

BURNISHING

Burnishing is one of the methods of finish machining, yielding significant improvements in the service properties of machined parts. It provides efficient machining of machined parts made of most of the engineering metallic materials, including the high-strength alloys of practically any hardness. The method is used in machine production, especially for finishing of precision and plastic deformation of the processed surface is accomplished by the pressure of a burnishing tool with a workpiece surface. During burnishing, the surface roughness caused by the previous machining is flattened and leveled, and the surface acquires a mirror like finish. The surface layer strength increases and compressive residual stresses are generated. After burnishing, the surface becomes smooth and clear of metallic splinters or abrasive grains that usually occur during machining. Combination of properties of the burnished surface determines its high working specifications including wear resistance, fatigue resistance, etc. [2, 3].

A smooth surface alone is insufficient; however, to protect the component against the wear and tear of regular usage, surface enhancement is to be carried out. Since all machined surfaces consist of a series of peaks and valleys of regular height and spacing, the plastic deformation created by ball burnishing is a displacement of the material in the peaks which cold flows under pressure into the valleys. This process improves surface finish, hardness, corrosion resistance and wear. When the burnishing pressure exceeds the yield strength of the component, localized plastic deformation at the surface will take place. This action leads to the spreading out of the valleys; causing an improvement of surface roughness. The grain structure is condensed, producing a hard surface with superior load-carrying and wear-resistance characteristics [1-3].

CLASSIFICATION OF BURNISHING PROCESSES

Burnishing process can be typically classified into two categories as:

1. Based on deformation element
    a. Ball burnishing
        i. Flexible
        ii. Rigid
    b. Roller burnishing
2. Based on the motion of the tool, on the surface
    a. Normal or ordinary
    b. Impact
    c. Vibratory

a. BALL BURNISHING

In this process the deformation element is hard ball. Alumina carbide ceramic, cemented carbide, silicon nitride ceramic, tungsten carbide, chrome-plated steel, high-speed steel, high-hardened steel, silicon carbide ceramic, bearing steel, titanium, stainless steel, carbon steel and synthetic diamond is the material used for ball. Ball burnishing is a process in which the ball rolls on the surface and causes elastic, elastoplastic, and plastic deformations of the surface layer of the workpiece. As a result, the workpiece changes shape, dimensions, roughness, hardness, stresses, etc. This process can provide excellent geometric condition and high dimensional accuracy.

Ball burnishing can significantly increase wear resistance, fatigue resistance, corrosion resistance, etc. This process can used for various materials such as steel, aluminum, copper, brass, polymers, titanium, nickel–chromium–molybdenum, etc. Ball burnishing tools use various functional mechanisms to generate burnishing force. Burnishing force is most often generated with the spring, pressurized fluid, and high stiffness tools. There are also hybrid ball burnishing tools, such as vibration assisted ball burnishing tools, magnetic-assisted ball burnishing tools, etc. Burnishing force is usually generated by a single ball, although ball burnishing tools with multiple balls also exist [1-6].

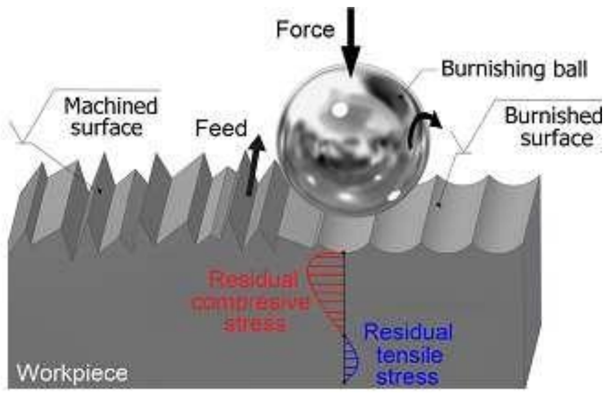


Figure 1: Principle of ball burnishing [6].

The ball burnishing process has the following advantages over other machining processes:

- A high surface finish (0.05 Ra – 0.2 Ra) can be achieved easily.
- Very close and consistent dimensional tolerance can be achieved.
- Increase surface hardness and fatigue life. The greater depth of work-hardening and beneficial compressive stresses on the surface will improve fatigue strength.
- Ball burnishing gives a better wear resistance on the rubbing surfaces thereby the increases the part service life
- Simplicity and stability of the process characteristics, thus making it suitable for mass production.

2. PROCESS PARAMETERS:

As shown in the Fig. 2 Ishikawa diagram of ball burnishing it can be seen and understood that various parameters and properties are responsible for the surface integrity of the workpiece being machined. The parameters and properties have it own importance and when they are employed in relation with each other the correlation must be considered in the quality of the final product. So an exhaustive study is required to understand the effect of each parameter in single and collectively.

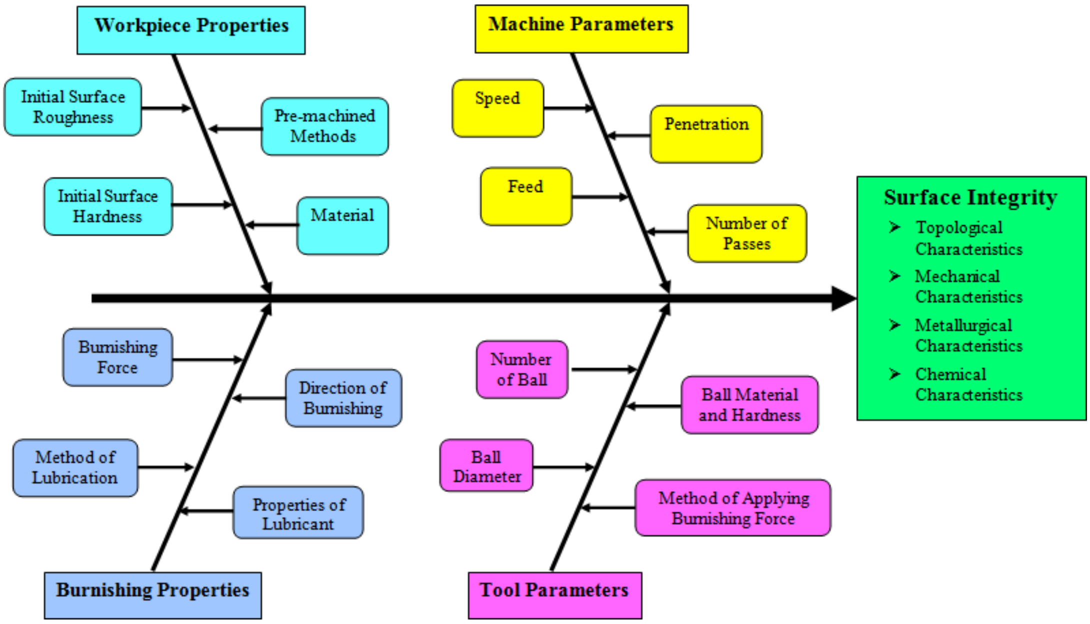


Fig. 2: Ishikawa diagram of ball burnishing.

2. MATERIAL OF WORKPIECE

The burnishing process is applied using different materials such as steel (plastic formwork steels, steel, heat-processed and tempered steel, hardened steel, AISI 5140, St37, X5CrNiMo17-12-2) [4- 6, 8, 11, 13, 15, 18, 19, 21, 24, 25, 30, 31, 33, 36, 37, 38, 40- 42, 44, 46, 48-51, 53, 54], aluminum and its alloys (cast Al-Cu alloy, 5083 Al-Mg, 7075 T6, AA2014, AA 7178, AA 7075, 6061--T6, Al 6061) [1, 2, 8-10, 12, 17, 20, 23, 35, 45, 52] , titanium [22, 26, 32, 34], brass [3, 14, 49], magnesium alloy [27, 28, 39], nickel-chrome [29, 47], polymers [8, 43] and copper [49].

The process has been widely used for various materials for a different of industrial applications. In accordance with the literature, the steel and aluminium is the material most used of applications, subsequently; brass, magnesium alloy and titanium alloys, respectively and literature related the polymers, nickel-chrome and copper are least referred [7].

3. ANALYSIS OF PROCESS PARAMETERS

The most studied parameters by the researchers are the burnishing load (*Fb*), forward speed (*V*) and feed (*f*) [1- 5, 7-9, 11, 12, 14- 53, 54]. The parameters such as number of passes (*n*) [1, 16, 18, 19, 21, 25, 26, 28, 34-36, 41, 42, 46, 48, 49, 54] and the diameter of the ball (*Db*) [2-5, 9, 16, 24, 33, 34, 46, 51, 52, 54], the lubricant used (*lb*) [10, 11, 54] and the burnishing depth (*Pb*) [4, 14, 20, 23, 24, 29, 35, 49] are also studies and least studied parameters are the initial superficial finish (*Rai*), the initial surface hardness (*Hsi*), the material of the ball [52], the number of revolutions (*Nr*) [27, 38] linked to the diameter of the workpiece and the burnishing orientation [6, 8].

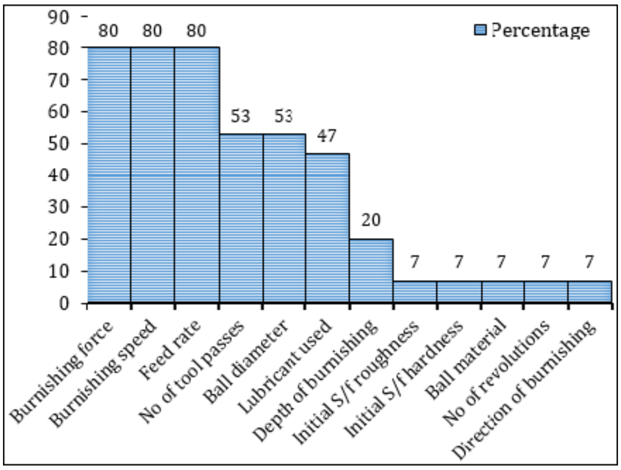


Fig. 3. *Importance percentage of ball-burnishing parameters according to literature* [7].

The researchers have considered the burnishing load and the burnishing depth as independent variables, even when they are dependent parameters and can be considered as the same one. At this point, it is important to mention that in the analysis already made, no difference between the parameters of the ball burnishing process for different machine-tools used was found, considering that the parameters Fb, f, n, lb, Db, Pb, Rai and Hsi are similar either for lathe or milling machine. Note that the V and Nr parameters are exclusive for turning. Though this work considers these parameters as similar, the characteristics of the machine-tools used certainly might influence the results of the process [1-7, 9, 11, 12, 14- 21, 23- 30, 32-46, 52, 54].

3.1. BURNISHING LOAD [1- 5, 7-9, 11, 12, 14- 53, 54].

The applied load (Burnishing load, *Fb*) can be found in the literature in four different units (kilogram-load, Newton, Pascal and Bar), according to the kind of burnishing equipment used (mechanical or hydrostatical). For the applied loads as pressure, different researchers show an expression to determine the load in function to some other factors. Eq. (1) shows a relationship of pressure and geometry of the ball. Additionally, some researchers argue that the real *Fb* are 11% less than the calculated due to loss of pressure between the ball and the support, as it is expressed in the Eq. (2). In other studies, furthermore the reduction of 11% of load, a contact angle of 15º between the tool and the workpiece is considered for an experimental system. Hence, the *Fb* is determined through the Eq. (3). The Eqs. (2) and (3) were used to estimate the load in Newtons, where *p* is the pressure, *r* and *d* are the radius and the diameter of the ball, respectively.

$$Fb = \pi r^2 p \quad (1)$$

$$Fb = 0.89\ (\pi/4)\ d^2 p \quad (2)$$

$$Fb = 0.89\ (\pi/4)\ d^2 p \cos(\pi/12) \quad (3)$$

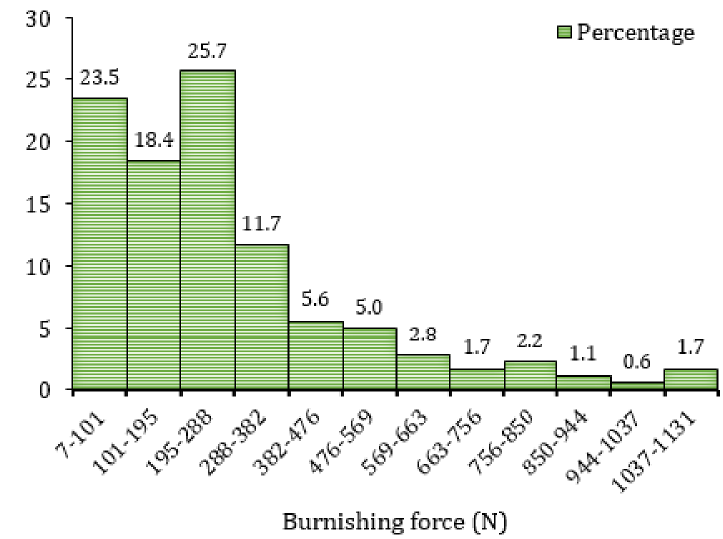


Fig. 4: Importance percentage of ball-burnishing force according to literature [7].

The applied load *Fb* varies between 7 and 1,131 N, whereas the 80% of the studies were carried out with a lower load than 382 N, as shown in Fig. 4. The load is a parameter that influences inversely to the roughness. However, there is a maximum loading value that is exceeded, a trace marks are formed, with a width equivalent to the diameter of the ball (plastic deformation), on the surface of the workpiece. As a consequence, a higher plastic deformation and accumulation or stacked material takes place, which results in an increase of the final roughness of the surface of the workpiece. These contrasting results might be attributable to the mechanical properties of the material that is burnished, for instance, the auto-hardening coefficient that will determine if the material gets stacked or sinked on the surface and that it is also related to the width of lateral pass. On the other hand, an increment of loading *Fb* will increase the hardness. According to the literature, the parameter *Fb* is the main parameter with higher influence (between 39.9% and 71.6%) on the superficial quality (hardness and roughness) in comparison with other parameters as shown in Fig 5.

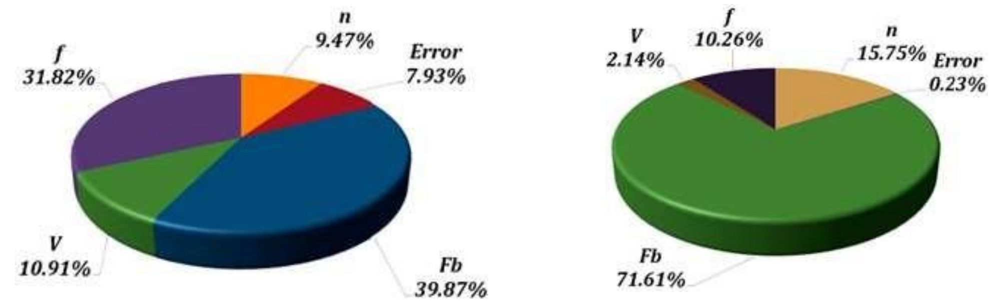


Fig. 5: Parameters that contribute on the surface quality improvement [7].

The literature supports this latest argument, high values of *Fb* result in lower roughness and higher residual compression stresses on the surface. Recent studies show the development of new mechanisms such as burnishing tools assisted by vibrations which allow the improvement of the control of *Fb*.

3.2. BURNISHING FEED [1- 5, 7-9, 11, 12, 14- 53, 54].

The burnishing feed varies between 0.01 and 0.80 mm/rev, as shown in Fig. 6. However, more than 84% of the feed used are located within 0.01 and 0.27 mm/rev and more than 95% are within 0.01 and 0.41 mm/rev. Different researchers has point out that low feed values cause a decrease of roughness, some others support the same behavior, but argue a range of feed where the roughness increases, between 0.1 and 0.25 mm/rev. This range is attributable to the conditions at which the process is carried out and the properties of material being processed. When high feed is applied the burnishing tool creates scratches on the surface with long gaps in comparison with the ball-workpiece contact area, due to which a higher superficial roughness is obtained. In order to avoid these scratches the feed value should be lower than the length of the contact area, attempting the overlapping of trace marks and low feed speed in function of the diameter of the ball. Certainly, the increase of feed reduces the efficiency of burnishing process. Additionally, it is expected to reduce the superficial roughness of the workpiece by using high Fb (around to the critical value) with low feed.

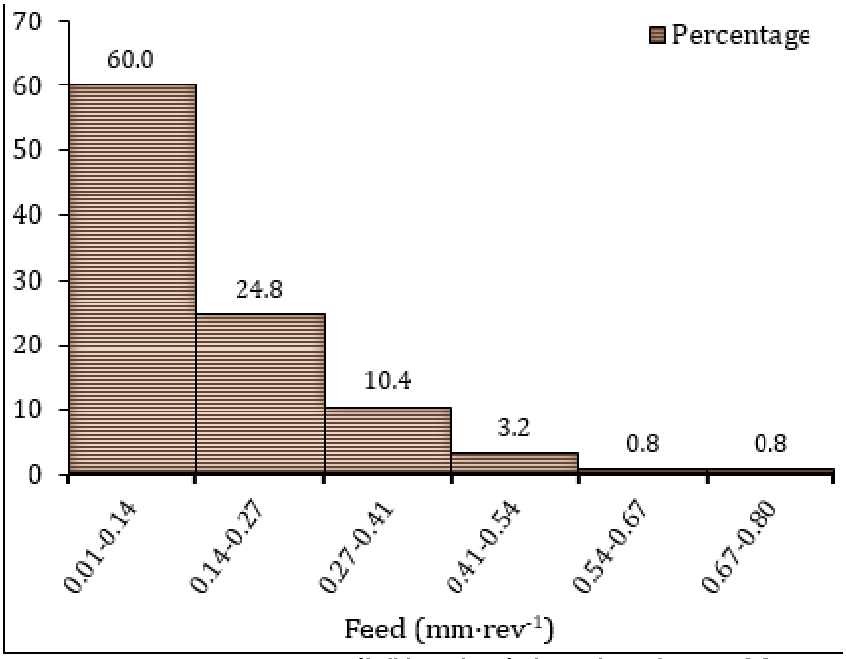


Fig. 6: Importance percentage of ball-burnishing feed according to literature [7].

Some studies state that by increasing the feed factor, the roughness even decreases. However, this parameter is not significant as some literature claim. This is due to high feed range values on a given cylindrical workpiece that results in a non-uniform compression on its surface.

3.3. BURNISHING SPEED [1- 5, 7-9, 11, 12, 14- 53, 54].

The maximum burnishing speed reported in the literature, was around 158 m/min, as shown in Fig. 7. Approximately 70% of the speed values shown in different studies are less than 53 m/min. Some others, instead of tangential speeds, angular speeds of the burnishing process are reported in revolutions per minute (rpm).

$$v = r\omega \qquad (4)$$

The studies state that as the speed increases, the roughness decreases. However, beyond a given speed value, the roughness tends to increase. The maximum value, according to the literature, varies from 1.5 to 60.3 m/s. The variation shown within this threshold is given to the kind of material and different magnitudes of the parameters employed.

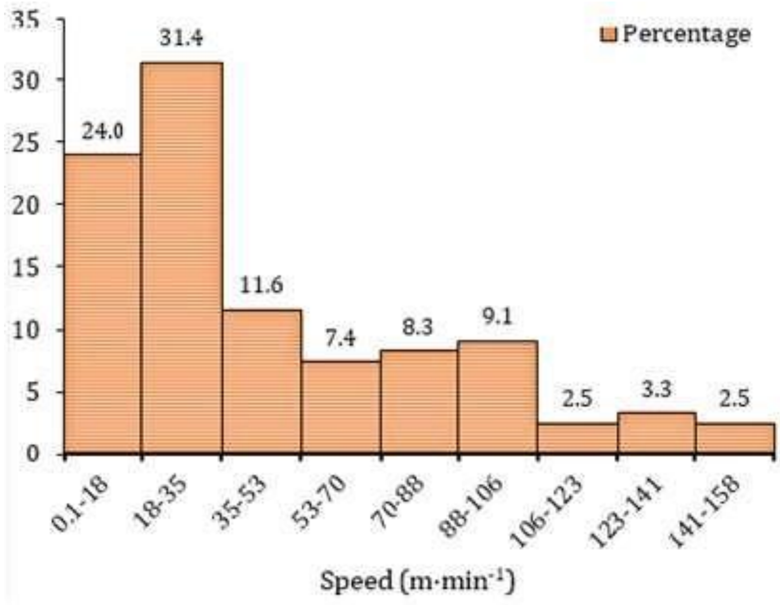


Fig. 7: Importance percentage of ball-burnishing speed according to literature [7].

Some studies show that for a given range, the roughness increases when the speed increases. Nevertheless, other analyses claim this parameter as negligible for this effect. Speed above 10 m/min the superficial roughness of the burnished piece starts to decrease. This phenomenon is attributable to the peeling process above mentioned, caused by the load *Fb* and an excessive number of passes.

3.4. MATERIAL AND DIAMETER OF THE BALL [2-5, 7, 9, 16, 24, 33, 34, 46, 51, 52]

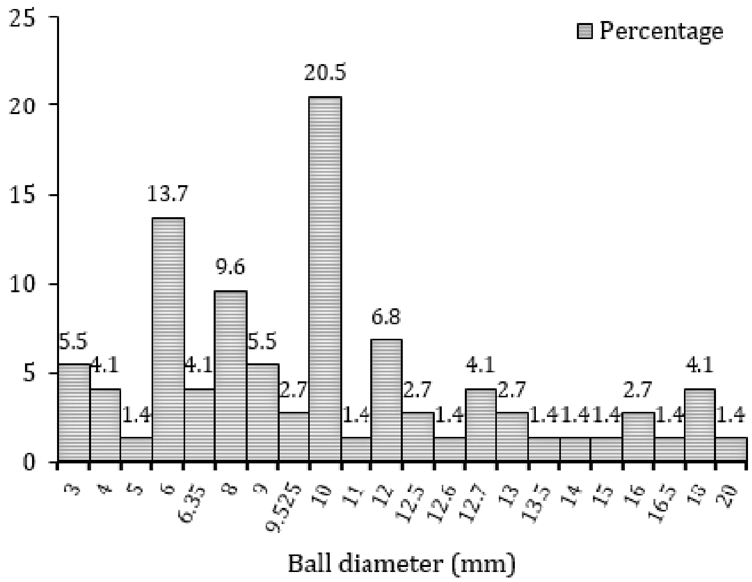


Fig. 8: Importance percentage of burnishing ball diameter according to literature for [7]

The diameters of the ball (*Db*) commonly used in studies were 10 mm (20.5 %), 6 mm (13.7%) and 8 mm (9.6%), as shown in Fig. 8. Diameters *Db* were analyzed from 3 to 20 mm, finding that the change of ball size has an effect on the superficial roughness and hardness. The big ball diameters have a lower penetration on the workpiece in function of *Fb*. For example, a ball with 10 mm provides an improvement of roughness due to a larger contact area on the surface, which results in a greater overlapping of trace marks, in comparison to balls with smaller diameters subjected to the same conditions along the process. A ball with diameter of 6 mm improves the hardness given that with the same burnishing load *Fb* will result in a deeper penetration, this causes a higher compression of the superficial layer of the material. In some works, diameters such as 10, 13, 16, 18 and 20 mm were analyzed, finding that roughness also decreases and on the contrary, the hardness of the workpiece increases. Hence, the increasing of *Db* requires a higher *Fb* in order to attain adequate roughness values.

3.5. NUMBER OF PASSES [1, 7, 16, 18, 19, 21, 25, 26, 28, 34-36, 41, 42, 46, 48, 49, 54]

The numbers of passes (n) suggested by around 40% of the literature are either 2 or 3. The maximum *n* reported was 7 passes as shown in Fig. 9. As the *n* increases, the superficial roughness decreases, hence, the suitable numbers of passes suggested are between 1 to 4. However, there is an optimum *n* that depends on the studied material and parameters of the process that in case it is exceeded, the roughness increases again (around 2 to 4 passes). This effect might be attributable to the excessive hardening of the superficial layer due to compression, overpassing the optimum value of *n* passes and leading to a superficial peeling on the workpiece.

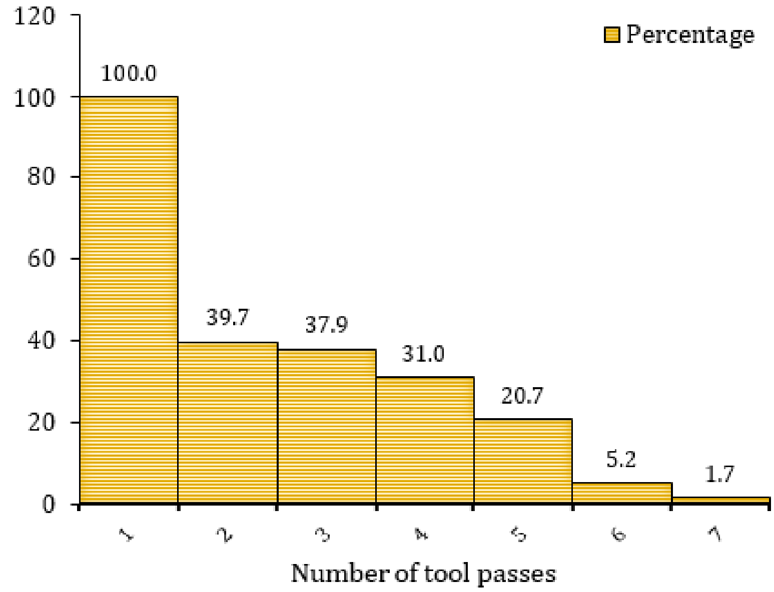


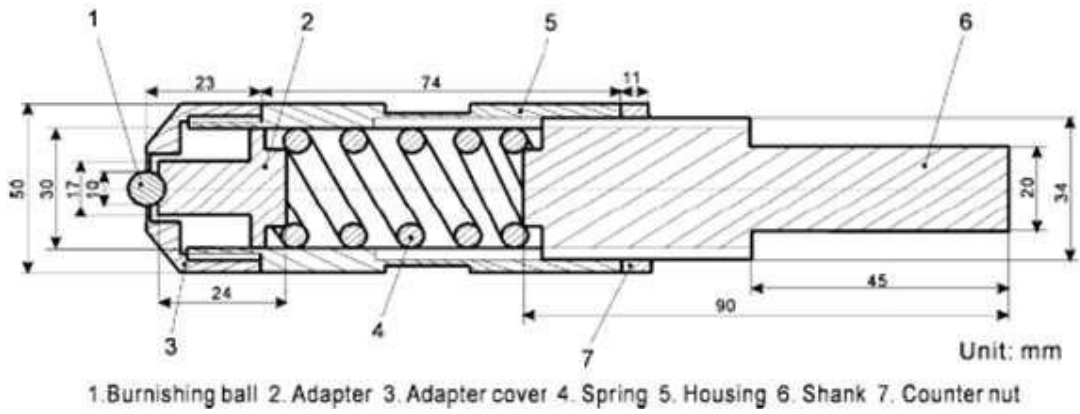
Fig. 9: Importance percentage of ball-burnishing number of passes according to literature [7].

Different researchers have claimed that by increasing *n*, the superficial hardness also increases. They agreed that *n* is an important factor with a sensible effect on the roughness and superficial hardness. Thus, with a low speed (15 m/min) or low feed (approx. 0.015 mm/rev) combined with a high *n* value (between 4 and 5) results in a significant improvement of roughness. On the contrary, with a high speed or high feed combined with a high *n* value results in an adverse effect on roughness due to the superficial peeling.

In the literature it is determined that *n* is the second factor with more influence on the process with a 15.75%, also with a significant effect on the roughness.

4. KIND OF BURNISHER AND MACHINE [1, 7, 16, 18, 19, 21, 25, 26, 28, 34-36, 41, 42, 46, 48, 49, 54]

Some researchers from the reviewed literature reported two kinds of mechanisms commonly used for the ball burnishing process such as the mechanism by mechanical spring, as shown in Fig. 10 (a) and the hydrostatic spring as shown in Fig. 10 (b). The mechanism most used is the mechanical spring, according to 59% of the total of the reviewed studies.



(a)

(b)

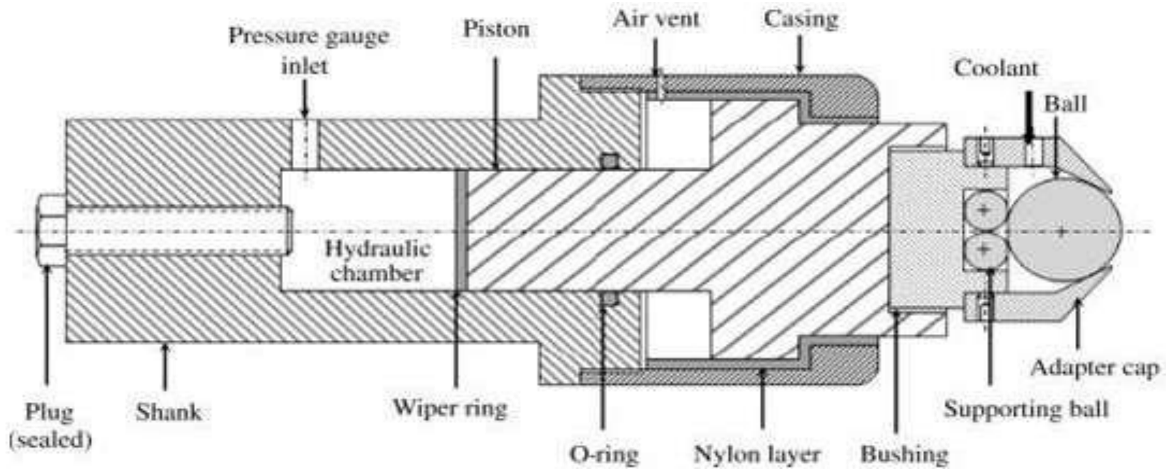


Fig.10: Equipment for ball burnishing, a) Mechanical spring, b) Hydrostatic spring [7].

In accordance with the studies where the hydrostatic spring was used, the tools frequently used balls with diameters of 6 and 13 mm, whereas in studies with mechanical spring the researchers developed their own tool for ball burnishing. This special tool consists in a circular array with three independent balls, with orientation of 120º to each other that can be enabled to work 1, 2 or 3 balls simultaneously. Current studies of ball burnishing suggest the use of novel designs like a burnishing tool assisted by vibrations that provides a better control on the load *Fb* and a better performance in function with the number of passes *n* in comparison with a conventional burnishing tool. Also, a burnishing tool has been developed with double balls that allow burnishing cylindrical workpieces simultaneously with a turning process, in other words, this tool performs both processes simultaneously with no need to exchange tools, allowing therefore optimizing timing in the manufacturing process. These kinds of tools have been used either in conventional lathe, CNC machines or CNC milling machines.

5. GEOMETRY OF THE WORKPIECE [1-54]

The analysis of the ball burnishing process has been carried out in different geometries, where the most studied have been the cylindrical. As mentioned before, the roughness and hardness are two of the parameters most used for determining the surface integrity of the workpiece. In 58% of the studies cylindrical bars were used, 9% were rectangular blocks and 7% were moulds, however, in a small percentage the burnishing was carried out in convex, concaves or inclined surfaces. For cylindrical bars, diameters and lengths were used in ranges of 12.4 to 80 mm and 40 to 400 mm, respectively. The cylindrical bars were selected to carry out the experimental burnishing tests at diverse conditions. Friction stir welded components were considered for studying the effect of burnishing process on the surface roughness, hardness and strength.

6. TYPE OF LUBRICANT [7, 10, 11, 12, 21, 25, 30, 34, 43, 45, 49, 54]

The kinds of lubricant most used in the ball burnishing process are soluble oil, kerosene and other kinds of SAE oils. In a study, four kinds of lubricants were analyzed, finding that with different values of load, speed and feed the kerosene provides a better superficial finish than the pure oil SAE-30 and with 5% and 10% of graphite. In other studies, three kinds of lubricants were considered, concluding that the burnishing using grease achieves a greater hardness than the kerosene and a mixed lubricant.

7. BALL BURNISHING STRATEGIES [1, 6, 8, 26, 47]

According to tribological aspects, the burnished surfaces are different, so with high probability there are differences among the surface flatness, too. Fig. 11 shows different burnishing strategies (1 – Adaptive, 2 – Cycloid, 3 – All-round, 4 – Zig-zag, 5 – Line and 6 – Stepping- swinging) has a significant positive effect on the Rsk (skew parameter) and Rku (flatness parameter) indicators characterizing the tribological properties of surfaces. Non-straight burnishing strategies also have a beneficial effect on the surface roughness. Surface roughness results are better without a rough change of direction in the strategy path. From a tribological point of view, the burnishing of C45 steel is the most favourable – the "2 – Cycloid" trajectory providing the best results.

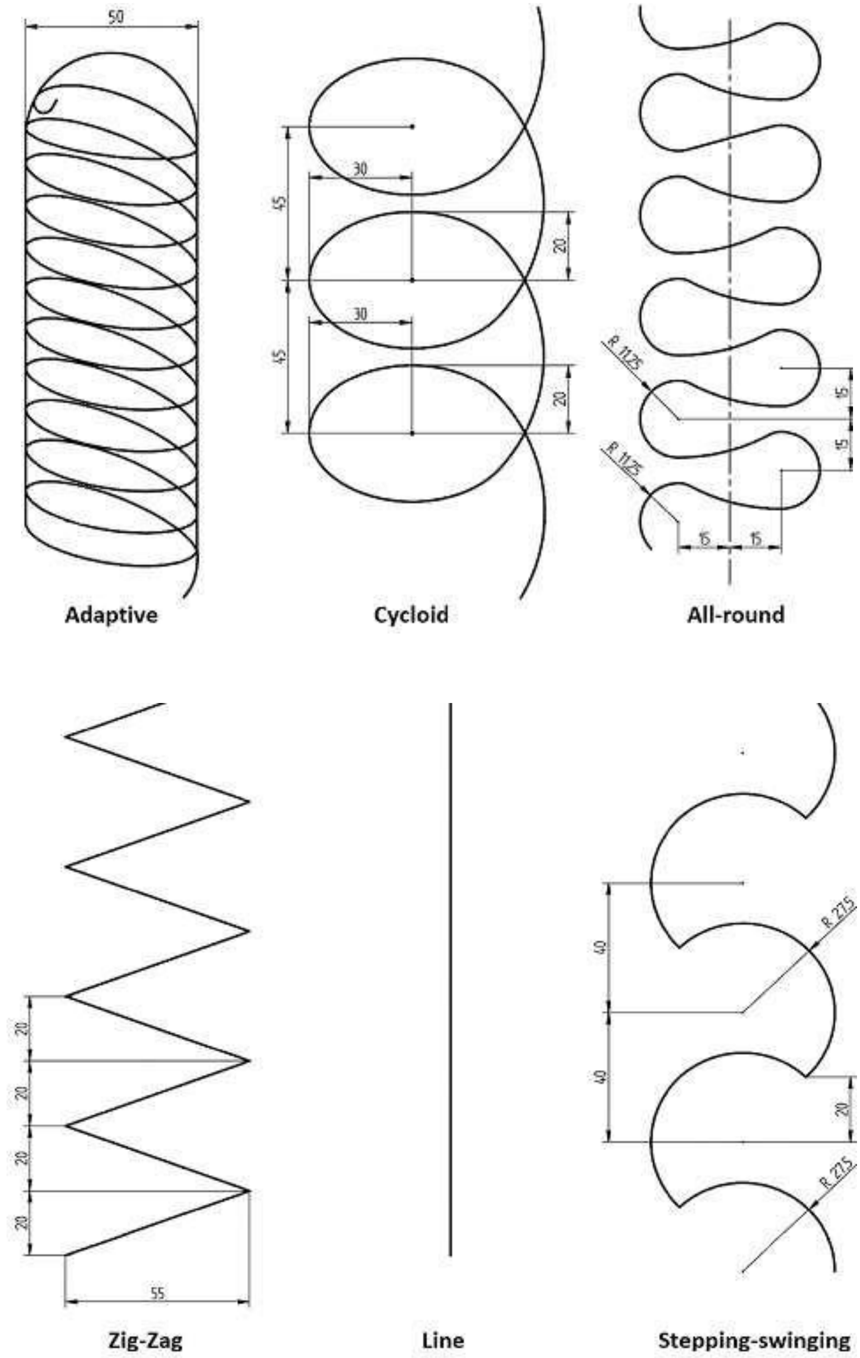


Fig. 11. Ball burnishing strategies [8].

8. EFFECTS OF THE BURNISHING PROCESS ON THE WORKPIECE

8.1. RESIDUAL STRESSES [1, 17, 22, 26, 31, 34, 36, 39, 46, 51]

From the literature researchers have proved that the residual stresses after the ball burnishing process are compressive stresses. These compressive stresses are the key for improving the wear, fatigue and corrosion resistance of the burnished workpiece. In most of the studies, the higher stresses are shown on the surface and decrease as the depth of the workpiece increases until a point where the stresses change from negative to positive. Fig. 12 shows a schematic of distribution of residual stresses of the burnishing where: 1) Ball, 2) Surface before burnishing, 3) Surface after burnishing, 4) Compressive residual stress. A) Pressure area, the ball makes contact with the surface of the piece and the pressure increases progressively, B) Plastic deformation area, the contact pressure exceeds the elastic strength of the material and causes a local plastic deformation, C) Softened area, D) Compression area, the material is compressed by the ball, E) Elastic distortions, after the ball passes the material suffers an elastic recovery.

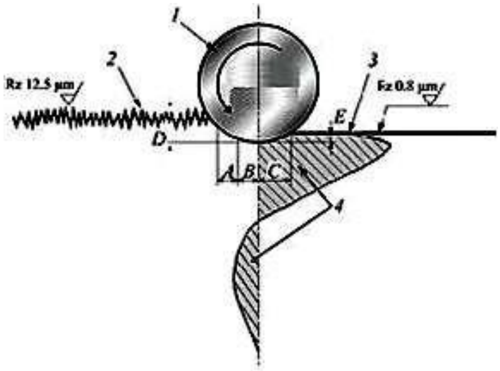


Fig. 12: Schematic of distribution of residual burnishing stresses [7]

The experimental technique most used in the burnishing studies to quantify residual stresses is the technique of X-ray diffraction (XRD). This technique allows measuring the field of stresses on or nearby the surface. The residual stresses measured are mainly axial and tangential at different depths of the burnished workpiece. The distance where the compressive residual stresses are found varies between 0.4 and 2 mm from the surface.

PERCENTAGE IMPROVEMENT OF SUPERFICIAL ROUGHNESS AND HARDNESS [1-9, 11, 12, 14-16, 18-28, 30, 33, 35, 38- 50, 52, 53, 54]

The analysis of the literature shows that the ball burnishing process improves the roughness of pre-mechanized workpieces, increasing their hardness. In analyzed studies in this work, improvements in the superficial finish between 40% and 95% are found for metals with improvement of hardness between 17% and 60%. However, in other studies the application of this process was studied in a number of polymers, finding that the superficial roughness is slightly reduced, whereas the hardness is a parameter barely affected.

ROUNDNESS AND FLATNESS OF SURFACE [6-8, 15, 24]

The roundness is a relevant geometrical tolerance for a mechanical workpiece assembly, obtaining as the difference between the maximum and minimum radius of the measured profile. The concept of out of roundness depends on the required tolerance and varies for each application reasonably. An error of roundness is considered as one of the typical geometrical errors in cylindrical components, so that it has negative effects on the precision and other important factors as wear on rotational elements. Moreover, it is known that the plastic deformation takes place on the surface during the burnishing process, which is one of the causes of variation of roundness.

In two works on roundness before and after the ball burnishing was measured, using an arithmetic mean of 3 iterations each for obtaining better results. One of this study showed that the magnitude of parameters that allows to obtain the lowest out of roundness (around zero) were speed of 1 m/s, a feed of 0.12 mm/rev and a burnishing load of 150 N. In the other study, show that burnishing speed of 15 m/min and feed of 0.58 mm/rev leads to a reduction of out of roundness (near to zero). However, if the speed kept constant and the feed rises to 2.32 mm/rev, results in an increasing of out of the roundness (higher than 20 µm). On the other hand, the out of roundness near to zero is obtained from combinations of other parameters of the process such as: the number of passes (4 - 5) and a feed of 0.015 mm/rev, a depth of penetration of 0.025 mm and a feed of 0.015 mm/rev. Finally, a minimal value of out of roundness near to 10 µm was obtained with 4 passes and a depth of penetration between 0.025 and 0.035 mm.

The different burnishing strategies (1 – Adaptive, 2 – Cycloid, 3 – All-round, 4 – Zig-zag, 5 – Line and 6 – Stepping- swinging) has a significant positive effect on the Rsk (skew parameter) and Rku (flatness parameter) indicators characterizing the tribological properties of surfaces. The adaptive strategy served with the best results concerning the flatness; however, the cycloid strategy improves the average surface roughness significantly. This diverse effect indicates further research, the cycloid path's loops are promising for ensuring with an optimal, compromise strategy for both the average surface roughness (on micro-level) and flatness (on macro-level).

CHARACTERISTICS OF FRICTION AND WEAR [7, 10, 29, 32, 44, 51, 53]

In the literature, a design and manufacture of a disc for wear testing was proposed. This study revealed that by increasing the rotational speed of the disc, the loss of weight increases, as long as the contact load remains constant. The same effect is observed when the burnishing load increases and the speed is kept constant. If the load and the number of burnishing passes overpass certain limits, then a greater resistance to wear is obtained.

Another study presented tribology tests, obtaining a significant decreasing on the friction coefficient and loss of weight under the condition of lubricated contact. The researchers obtained a reduction of 46% in the coefficient of friction when the sliding takes place in a parallel orientation with respect to the burnishing.

Some researchers assessed the characteristics of friction in terms of coefficient of friction through the sliding of two polymers as: poliximetile (POM) and poliuretane (PUR) on stainless steel. Thus, a decreasing of coefficient of friction was observed with an increasing of burnishing load reaching up to

33% and 29% of reduction for POM and PUR, respectively. Both polymers subjected to a burnishing load of 124 N. If this burnishing load increases, the coefficient of friction increases. This similar behaviour was also observed for speed, feed rate and diameter of ball.

EFFECT OF BALL BURNISHING ON THE FATIGUE BEHAVIOUR [7, 11, 37, 51]

Diverse studies have been focused on the effect of ball burnishing on fatigue strength, showing that the process increases the fatigue behaviuor. According to reviewed literature, the ball burnishing induces three main effects that increase the fatigue strength (increasing of hardness, compressive residual stresses and high quality surface finish). In one of the studies, fatigue testing was made by rotational bending in specimen of steel AISI-1045. The fatigue strength of the specimen subjected to burnishing improved from $3x10^4$ to $1x10^6$ cycles, the maximum limit of fatigue by bending increased around 21.25%, a high quality surface finish was obtained (reduction of 50% of the size of superficial grain) and an increasing between 20% and 25% of superficial hardness HBN. These parameters were compared with not burnished specimens.

Also, rotational fatigue testing with specimens of aluminium AA5083 were performanced, finding that the ball burnishing certainly improves the fatigue strength up to 100% (in both, air and corrosive environments) in comparison with a control specimen (specimen non-treated). Similarly, these kinds of tests were made in specimens of stainless steel 15-5 PH, where the ball burnishing increased the fatigue strength up to 25%, in conditions of high residual stresses and low roughness.

Further in other studies, tests of fatigue traction in specimens of plane surface of steel AISI 1010 were carried out, showing that, under the conditions and material specified, the ball burnishing has no significant effect on the fatigue strength. Additionally, testing of traction on burnished specimens was carried out, achieving up to 49% of improvement in ductility of the material. This improvement might be due to the ball burnishing process improved the surface finish, fading also micro-cracks on the edges of the specimen and decreasing significantly any flaws on the surface where eventual cracks might initiate.

In accordance with the reviewed literature, the ball burnishing leads to increase the resistance of the specimen subjected to rotational fatigue testing, whereas for the fatigue traction testing this statement may not be possible to do.

9. OPTIMIZATION AND ANALYSIS TECHNIQUES:

In the burnishing process the quality of the parts is highly depends upon the various process parameters such as process parameters such as speed, feed rate, burnishing force, ball diameter, strategy and a number of revolutions, etc. This is the big challenge, so it is necessary to optimize the process parameter of respective machines. Process parameter optimization of burnishing process was been carried out to improve the quality of functional parts. There are different methods of optimization of process parameter like factorial design, Taguchi method, response surface methodology, central composite design, etc. which are used by the researchers. From these different methods of optimization, Taguchi approach is more powerful technique. From the literature the different optimization techniques used by the researchers are Taguchi method [8, 12, 14, 20, 22, 27, 28, 30, 32, 33, 39, 41, 43, 54], FEM [19, 23, 24, 31, 34, 51], regression analysis (RA) [2, 4], artificial neural network (ANN) [2, 4], Response surface methodology [3, 40], support vector regression (SVR) [4], Surface Texture Analysis [38], principal component analysis [45, 49] and Bacterial Foraging Optimization [52].

10. CONCLUSION:

This work provides insights from a number of studies about the ball burnishing process parameters and conditions for improvement of superficial physical-mechanical properties. Hence, some key points of the ball burnishing process are:

1. The most preferred workpiece materials by the researchers are aluminum alloy and different steel whose main applications are plastic injection moulds, cutting and stamping tools for automotive, aeronautical and aerospace pieces whereas a much scope is there to work on titanium, brass, magnesium alloy, nickel-chrome, polymers and copper.
2. The most considered ball burnishing process parameters are burnishing force, speed, feed and no. of passes as compared to ball material, ball diameter, No. of revolutions and direction of burnishing. The researchers have recommended using a combination between parameters with higher influence: high loads between 288 and 382 N, with low feed from 0.01 to 0.14 mm/rev and a number of passes n between 2 and 3. These recommendations are given with the purpose of obtaining a significant improvement on the superficial integrity of the workpiece.
3. Surface roughness and microhardness are the most measured variables. The ball burnishing process might improve the surface finish between 40% and 90%, whereas the hardness might increase between 17% and 60%.
4. Various studies showed that the ball burnishing process induces compressive residual stresses, which increase the fatigue strength of the working pieces.
5. Mainly the ball burnishing is carried out with mechanical and hydrostatical springs; however, some researchers have developed novel tools to improve the process such as: burnishing tool assisted by vibration and with multiple balls.
6. SAE-oils are mostly used as lubricants but use of diesel and grease effects maximum hardness followed by kerosene and soluble oil.
7. Mathematical modeling and design of experiment are the commonly used methodologies. In the recent years, researchers are using Taguchi Method, Response surface Methodology, ANN and Fuzzy Logic for optimizing burnishing process parameters.

As can be observed, there is a difference of results from different researchers, nevertheless, note that these differences are due to the different magnitude ranges of the parameters studied, to the mechanical properties of the materials and to the type of machine-tool employed. This provides an important scope for experimental researching of the different process parameters through redesigning advance tools that allow to improve surface integrity and reduce costs as well as to study innovative materials with industrial applications.

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