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SHAFTS HARDENING BY ROLLING - A SHORT REVIEW

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Abstract: Rolling process, as one of the processes of Cold Surface Plastic Deforming of metals (CSPD), leads to mechanical, physical and structural transformations in the depth of the material or only at the surface layer, similar in effect, but with different weights in comparison with operations such as rolling, drawing, extrusion, forging, or machining by cutting (grinding, superfinishing), due to the lower values of the degree of deformation of the metallic material, generated by the much lower values of the parameters of the working regime. The condition of the surfaces resulting from the CSPD process is generated and influenced by a number of factors and can be assessed by a set of indicators such as: surface roughness, hardness of the deformed surface layer, depth of the roughened surface layer, residual stresses and machining productivity. The paper presents the advantages and process parameters and details the qualitative indicators of the CSPD process with the presentation of some experimental results from the technical literature.
Keywords: hardening, CSPD, roughness, residual stresses.

1. INTRODUCTION

Cold plastic surface deformation, as an "environmentally friendly" process, without chip detachment from the metal surface, occupies a high place in innovative technologies, due to the possibility of applying it either as a surface finishing process or for hardening purposes (depending on the working regime and tool geometry used), [1, 2].

It should also be borne in mind that the process can be applied to a wide range of materials [1] (steels, from general steels to alloy steels, but not heat-treated, cast iron, non-ferrous steels and their alloys), used in the manufacture of a wide range of machine parts that are used in the manufacture of machinery in the machine building, shipbuilding, automotive, aeronautics, textile, food, agricultural, etc. industries. The process can be applied regardless of the shape of the surfaces, external or internal revolution - cylindrical, conical, profiled, flat, or complex surfaces.

Rolling hardening is accomplished by rolling bodies with the application of normal forces on the machined surface. The rolling elements may be balls, cylindrical, truncated conical, or barrel-shaped rollers, single or enclosed in rolling heads. The rolling is carried out in the vast majority of cases on lathes, using special devices, having several rollers, Figure 1a, c. [2].

During the rolling, the workpiece executes a rotational movement n_p, and the rolling device, composed of body (1) in which roller (2) is mounted, executes a feed movement s_l and a rotation n_s due to the contact with the workpiece. The rolling device provides a pressing force F for pressing the roller against the workpiece to cause deformation and roughening of the surface layer.

Cold rolling is the process best suited to improve the fatigue strength of dynamically stressed parts, especially in the area of stress concentrators such as threads and shoulders that can lead to cracking.

Cold rolling plasticizes the surface layer of the material and forms microstructures on the part surface. In general, the surface is machined before rolling by a suitable honing process (turning, drilling, boring, etc). The rolling force generates high Hertzian compressive stresses at the contact of the roll with the part surface. After the rolling process, residual compressive stresses remain in the surface layer of the part.

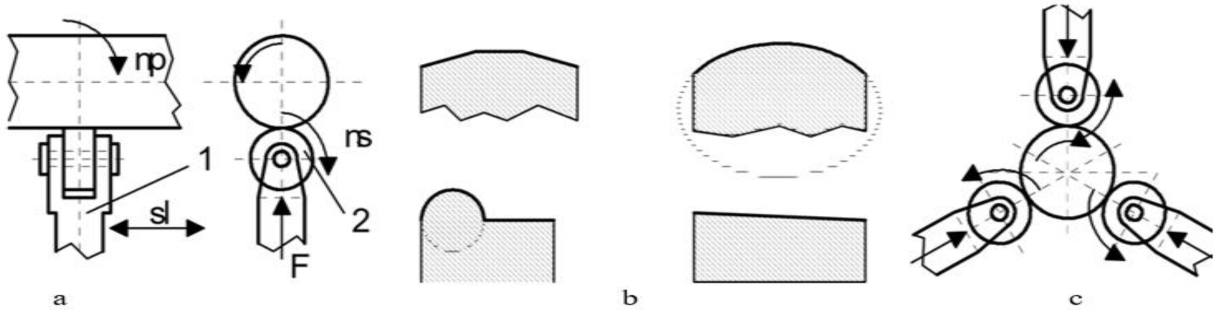

Fig.1. Rolling surface deformation schemes, [2]

The rolling force is based on three physical effects: inducing compressive residual stresses; increasing the strength of the workpiece material in the surface layer; and smoothing the surface.

There are four major advantages of cold rolling: improving surface quality R_a = (0.1-0.2)μm; improving dimensional control (tolerances of 0.1mm or less); increasing workpiece hardness by up to (5-10)%; and increasing fatigue life by up to 300%. Also, other advantages can be mentioned such as: reduction of friction; reduction of noise level; increase in corrosion resistance; elimination of cutting tool marks; replaces other costly operations such as grinding, honing, honing; no waste is generated during manufacturing and thus no additional costs are incurred, which has a positive repercussion especially on expensive or scarce materials. These technologies are also clean (ecological) and approved by the new standards in terms of environmental protection, and in particular industrial environmental protection.

The cold roll finishing operation has wide applicability to a wide variety of parts, including machining of inside diameters, outside diameters, machining of flat, tapered, spherical surfaces, inside fittings, and shoulders, (Figure 2).

Fig. 2. Examples of cold-rolled parts: 1- bearings; 2- connecting-rod; 3- bushings; 4-piston, [3, 24]

2. QUALITATIVE INDICATORS OF THE CSPD PROCESS AND THE INFLUENCE OF THEIR MAGNITUDE ON THE CONDITION OF SURFACE DEFORMED SURFACES

The quality of the contact surfaces of friction couplings can be characterized by: surface roughness; the physical-mechanical state of the surface layer, and the residual stresses caused by previous machining or final heat treatment.

The contact surfaces intended for friction couples are obtained by different technological processes, processes which contribute to the generation of the total surface profile. On this profile, the following deviations from the ideal profile are highlighted (Figure 3):

- deviations from the microgeometry defined by SR EN ISO 5459:2012 as deviations of order 1 or shape;
- Wavinesses (W) is defined as the set of periodic irregularities whose pitch is several times their depth;
-rugosities, the set of irregularities which form 3rd order geometrical deviations, striations, periodic or pseudoperiodic rhytids, and 4th order geometrical deviations, tears, tool marks, and aperiodic voids and whose pitch is relatively small about their depth.

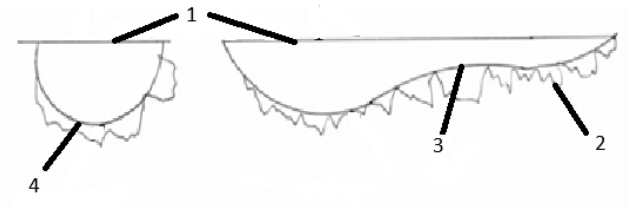

Fig. 3. Surface condition: 1 - general profile direction; 2 - roughness; 3 - waviness; 4 - shape deviations, [4]

The condition of the surfaces resulting from the CSPD process is generated and influenced by a number of factors and can be assessed by a set of indicators (Figure 4), which present the following aspects:

-surface roughness, formed by the displacement of the elastoplastic wave at the front and back of the tool during the combined rolling motion due to frictional contact between the tool and the workpiece and sliding along the axis, or towards the axis of the workpiece. The roughness size defines the nature of the CSPD process through the following effects on the surface: smoothing (at low values of roughness, below 0.2 µm), with positive influence on the quality of the shafts, corrosion resistance; hardening (at high values of roughness, generally above 0.4 µm) when the aim is to increase wear resistance, fatigue, [5, 9];

-hardness of the deformed surface layer, due to the internal stresses that arise as a result of the blocking of the displacement of dislocations during the sliding and rotation processes at the level of the crystals in the metallic material and whose size has a direct proportional influence on the ability of the part to function under the operating conditions required by the customer. By increasing the hardness to high values (at least comparable to those obtained by thermochemical treatments), large manufacturing cost savings can be realized due to the possibility of using cheaper materials (e.g., ordinary carbon steels) instead of heat-treated high-quality and alloy steels. This also contributes to a corresponding increase in the durability (reliability) of the parts subjected to CSPD, [5];

-the depth of the surface hardened layer, depending on the same initial factors and the same characteristics of the deformation process that give the material optimal properties in service. This depth can, in many situations, exceed the penetration depth obtained by heat treatment, [6, 9].

-Residual stresses, due to the plastic characteristics of the material subjected to deformation under external stresses and the internal stresses that occur and whose magnitude influences the dimensional accuracy of the machined parts, making it necessary to take them into account when determining the machining allowance for the DPSR operation, [6, 7].

-The machining productivity, which is influenced by the behavior of the material subjected to this mechanical treatment and the size of which, limited by the number of passes allowed to maintain the surface condition, is an indicator of the efficiency of RPSR compared with other finishing or surface hardening treatment processes, [6-8].

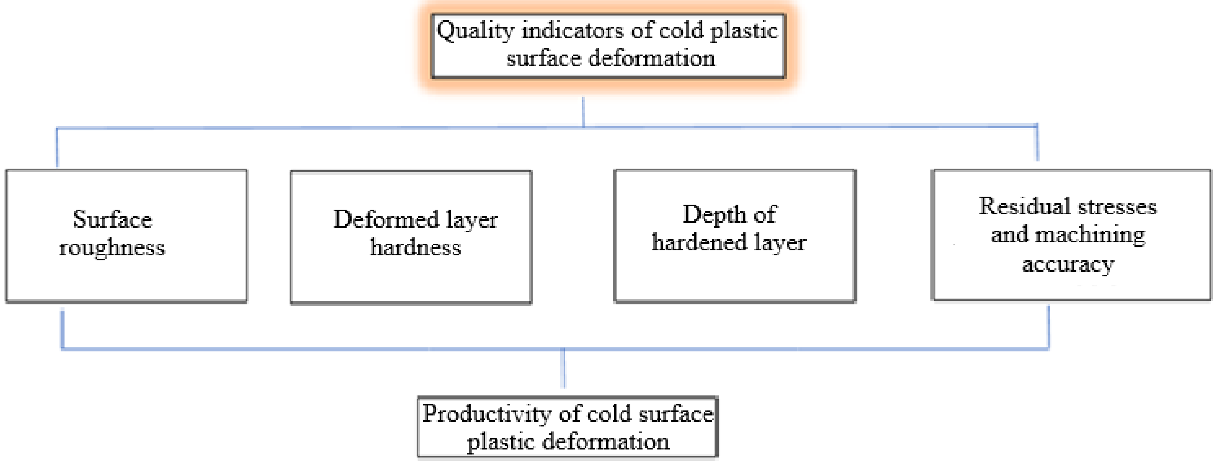

Fig. 4. Characteristic indicators of the CSPD process, [1]

Knowing about the phenomenon of strain-hardening helps to control the deformation process and broadens the range of uses of metals. For example, without the occurrence of work-hardening, operations such as drawing and forming would not be possible. At the same time, work hardening can be used to enhance certain mechanical properties of some metals and alloys, such as aluminum and its alloys, copper, some brass and bronze, and some stainless steels (Table 1).

Table 1. The influence of hardening on the mechanical properties of some metals and alloys

Material	Condition	Breaking strength, r_m [MPa]	Elongation A_t, [%]	Hardness [HB]
copper	annealed hardened	200 440	45 6	38 105
aluminum	annealed hardened	80 180	42 5	20 47
brass	annealed hardened	270 380	50 15	80 140
soft steel	annealed hardened	420 840	31 6	130 250
stainless steel with 18% Cr; 8% Ni	annealed hardened	610 1820	8 5	200 650

3.1. Roughness and accuracy of machined surfaces

From the study of the literature in actual production, to obtain a roughness Ra=(0.04-1.6)µm, the common machining technologies are grinding, rolling, broaching, and honing.

The main objective of CSPD finishing is to achieve smooth, high-quality surfaces with a predefined surface finish. This process is used when the machining objective is either to achieve a high-quality surface finish or when a predefined surface finish cannot be achieved by machining. As the ball or roll travels across the surface of the workpiece, the surface tips are pressed, nearly vertically, onto the surface, and the material then flows into the voids between the tips (Figure 5).

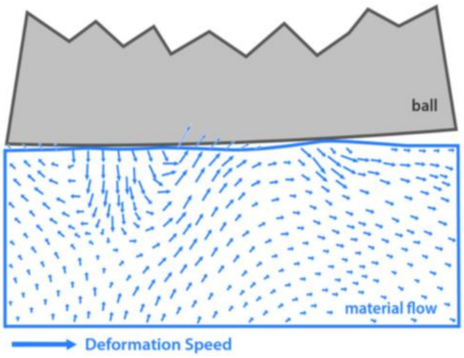

Fig. 5. Curgerea materialului, [10]

The resulting smooth surface is not because the peaks are flattened, but because the material flows, thus reducing the surface roughness (Figure 5), [10].

These diagrams show a surface profile of the parts before and after roll-finishing. The ultimate goal, as in any finishing process (abrasive or otherwise), is to reduce the height differences between peaks and voids. Abrasive finishing breaks the metal from the tips, while roller finishing achieves the same result without removing the metal.

Almost all high-quality surface fabrication processes can be replaced by roller finishing (e.g., fine turning, honing (superfinishing, polishing, etc). This process has considerable technological and economic advantages for surfaces in the roughness range R_z <10 µm.

The geometry of surfaces processed with traditional processes additionally requires, in most cases, surface finishing. Surface roughness of 0.1µm [11] is required to reduce friction and increase fatigue resistance.

In order to increase production efficiency it is necessary to identify new tools that allow to obtain better machining results, either cheaper operations with the possibility of optimization of machining parameters, [11].

Most of the investigations for fine machining process improvement are related to the process outcomes: surface roughness and surface hardness. An improvement in wear resistance can be very easily achieved by rolling, but very few actual studies have analyzed the environmental implications, [12]. Roller roll finishing is a low-cost surface machining/treatment method whereby residual stresses are induced in the surface layer of the material.

In their paper [13], Stoić et al. defined roller rolling as a fine machining process by which certain physical and mechanical properties such as surface roughness, coefficient of friction, wear and fatigue resistance are improved. Thus, Figure 6 shows the surface profile changes after the rolling operation. A significant reduction in the surface roughness from 15µm to less than 1µm can be observed after rolling, and Figure 7 shows the surface roughness profiles after the first and second pass of the rolling operation.

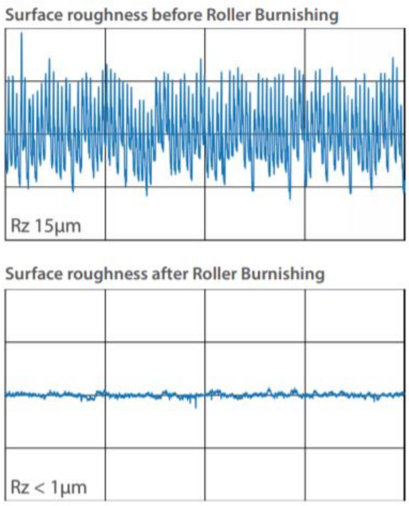

Fig. 6. Shape profile before and after rolling, [13]

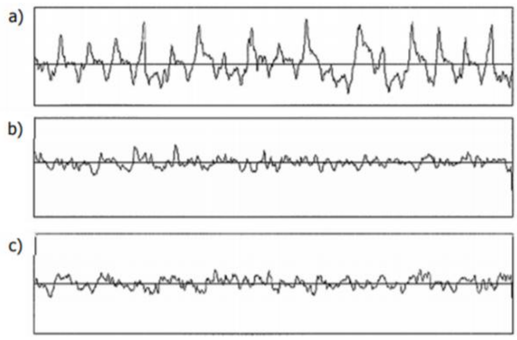

Fig. 7. Example of roughness shape: a) before machining, b) after the first pass of the roller; c) after the second pass of the roller, 12]

Research carried out so far indicates that the geometrical state, characterized by the amount of surface roughness obtained and the undulations that occur, significantly influences the in-service behaviour of the parts, in particular on:

-wear resistance: the friction-rubbing regime is influenced by the binding energy of the molecules on the surfaces of the coupling, surface roughness, local temperature, etc. Friction and wear are influenced by the physico-chemical characteristics of the materials and lubricants used, the surface treatments of the friction coupling surfaces, surface roughness, speed, load, and temperature. The extent of wear is due in particular to the increase in mechanical adhesion, shearing and uniformization of microasperities;

-resistance to fatigue: the undulations in cold plastic deformation by rolling and abrasive polishing are greater than in machining by chipping, the dents and scratches remaining on the surface after chipping are stress concentrators;

-corrosion resistance: the process of tribochemical corrosion, favored by the abrasion and adhesion of the microasperities in the rolling friction process, is influenced both by the surface roughness and by the creation of galvanic microcells in the asperity recesses as their depth and sharpness increase.

3.2. Hardness of the surface hardened layer

Hardness increase is the hardening of a metal or polymer by surface plastic deformation. This increase in hardness occurs due to sliding motions and the generation of dislocations in the crystalline structure of the material, [14]. Many non-fragile metals with a reasonable melting point as well as several polymers, can be hardened in this way, [15]. Alloys not intended for heat treatment, including low-carbon steel, are often hardened. Some materials cannot be hardened at low temperatures, such as indium, [16], while others can be hardened, such as pure copper and aluminum.

As the material is hardened, it becomes increasingly saturated with new dislocations, which are prevented from nucleating (a resistance to the formation of new dislocations develops), [17].

The influence of hardness on the physical-mechanical condition of the rolled surface is manifested in:

-wear resistance, it favors the diffusion of oxygen from the air into the metal and the formation of hard chemical compounds: FeO, Fe_2O_2, Fe_3O_4, and helps to decrease wear, both in the case of mechanical and molecular interaction, [2];

-the fatigue resistance, increasing it by approximately 20%, also indicated by the curves in Figure 9, the cause of this favorable action being not so much the hardness of the surface layer as the residual compressive stresses accompanying the strain hardening;

-rezistenței la coroziune, conform [2] cercetările recente evidențiază îmbunătățirea acesteia la atingerea gradului optim de durifcare,creșterea fiind ce cca. 3,5-4 ori la arborii durificați prin rulare față de cei nedurificați.

After [18] figure 9 shows an unexpected variation in the microhardness values. This may be due to the compressive residual stresses on the finished surface, where the compressive residual stresses were not uniformly distributed along the surface. This can be further explained by the possibility that the pressure exerted by the tool on the unit area for each segment along the specimens may not be at the same value and magnitude. This may lead to uneven distribution of compressive residual stresses, hence the stresses were not applied uniformly and this makes the stratigraphy of the grains inhomogeneous (i.e. the grain correlation at a specific point on the segment is stronger than at another place on the same segment) which makes the metal penetration resistance uneven along the entire segment, which imparts irregular hardness values.

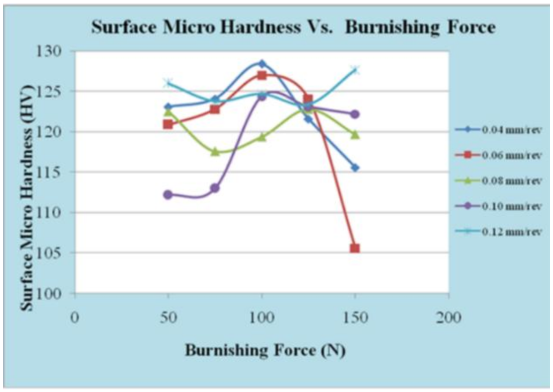

Fig. 9. Microhardness value variation, [18]

According to the article 'Effect of Ball Burnishing Process on the Surface Quality and Microstructure Properties of AISI 1010 Steel Plates', the authors F. Gharbi, S. Sghaier, K.J. Al-Fadhalah, and T. Benameu show in Figures 10a,b the variations of surface hardness with rolling speed at different speeds and forces. It can be seen in them that the relationship between surface hardness and firing velocity is parabolic. The results also indicate that at low advance, an increase in speed significantly decreases the surface hardness. Whereas, at high advance, there is little effect on the surface hardness when varying the velocity. Furthermore, Figure 10b indicates that there is an increase in surface hardness with increasing force magnitude at a fixed feed rate. In the velocity range used in this work, it can be seen that an increase in feed rate up to 0.18 mm/rev leads to a slight increase in surface hardness. However, an increase in feed rate above 0.18 mm/rev. causes a significant decrease in surface hardness, [19].

Figure 10b shows the influence of the rolling force F on the surface hardness for different feeds at a rolling speed of 235rpm. When a high rolling force is applied, the amount and depth of plastic deformation are expected to increase at the workpiece surface. This, in turn, causes an increase in the hardness of the surface layers. Moreover, at a given force, the surface hardness increases and then decreases. In this case, the maximum surface hardness is reached at a feed rate of 0.18 mm/rev at the optimum speed of 235rpm, [19].

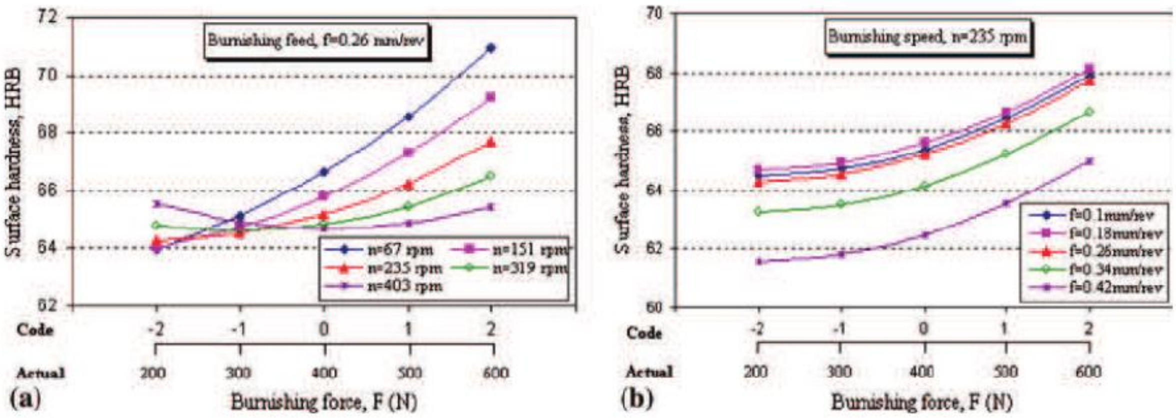

Fig. 10. Effect of rolling force on surface hardness: (a) at different speeds (rpm) and (b) different feeds (mm/rev), [19]

3.3. Depth of penetration of the roughening

The operating properties of the parts are also largely determined by the depth of roughening obtained.

One of the most well known benefits of hardening rolling in comparison to other surface treatments refers to the large depth of the roughened layer that exhibits hardness changes and compressive residual stresses (Figure 11), [20].

Hardness hardening grinding generates lower costs and investment, and is suitable for almost all metal surfaces. All mechanical (e.g., shot peening), thermal (e.g., laser hardening), and thermochemical (e.g., nitriding) processes to increase the fatigue resistance of a part can be replaced by hardening rolling, [10].

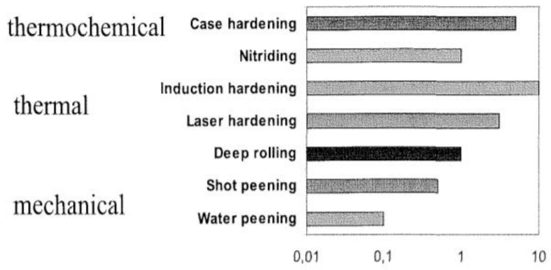

Fig. 11. Surface hardening treatments, [20]

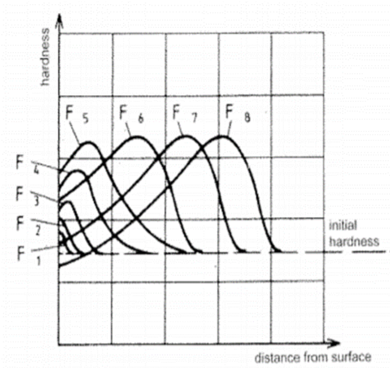

Fig. 12. Influence of rolling force on hardened depth, [20]

Typically, especially for hard materials, deep rolling leads to a subsurface maximum of residual stresses, as expected from the Hertzian theory [20] predicting maximum equivalent subsurface stresses. It should be noted that the position of the maximum residual stress not only depends on the rolling force but also on the contact geometry of the workpiece and the rolling tool involved (Figure 12). With the rolling force, the compressive residual stresses also increase until a saturated level of compressive residual stress is reached; however, a further increase in rolling force moves the compressive zone into greater depths, and finally, higher rolling forces can lead to subsurface compressive residual stresses but tensile residual stresses at the surface.

The near-surface microstructures induced by deep rolling can be very numerous and strongly depend on the process parameters chosen as well as on the material itself.

Depending on the material, deep rolling can lead to the formation of cellular structures, nanocrystallites, twinning, or martensitic transformations, [20].

Cold plastic surface deformation finishing by rolling is used as a finishing procedure and ensures a favorable contact height and shape for the surface. The problem arises when dealing with a surface with complex geometry. 'Deep rolling' stands out against a background of the others due to the high values of hardness, residual stresses and hardening depth reached, [21].

In contrast to CSPD deep rolling burnishing, which is carried out with lower pressures and mainly serves to achieve high surface quality, the aim of DRB (deep rolling burnishing) treatment is to induce high hardened layer thicknesses.

3.4. Productivity of machining

The cold rolling finishing method does not require the use of special machines; existing machines can be used in the production departments, such as: milling machines, lathes, drilling machines, CNC lathes, machining centers, etc. The machining method is used in a single clamping of the workpiece, thus increasing productivity and accuracy of execution.

The quality performance provided to the rolled parts allows the successful replacement of similar machining, such as grinding, polishing, etc. or hardening, simplifying not only the technological sequence but also the time spent on machining, [2].

Roll finishing has long been used on a large type of parts for the automotive industry (brake system parts, transmission elements and converters, etc.). This method is also widely applied in non-automotive applications for a number of advantages: to provide larger and longer-lasting sealing surfaces; to decrease wear; to reduce friction and noise levels in rolled parts, and to improve aesthetics. Examples include valves, hydraulic or gas cylinder pistons, pump shafts, bearing rings, and plumbing fixtures, [22].

From the literature surveyed it appears that rolling tools can be designed and built for any part configuration. Standard tools are offered for running inside and outside surface diameters.

Cycle time is shorter: in the machining industry, the longer the machining time, the higher the cost to make a product, so the more money the company loses. Fortunately, roller burning tools do exactly that. Compared to other methods, the roller finishing method performs a single-pass operation and can significantly decrease cycle time.

Maximizes product quality: in mass production, it can be difficult to control surface finishes and tolerances. However, roll-rolling allows accurate sizing and finishing, even in mass production. By doing so, the process can decrease the number of parts that fail inspection and are rejected.

Dimensional accuracy: dimensional tolerance can often be a concern when parts require assembly.

Increased surface hardness: for metal blanks, such as aluminum components, a durable surface is important. The roll rolling method hardens the material surface by using a cold rolling process.

Electrical conductivity: this particular factor of electrical conductivity is not constant and varies from material to material. However, some general factors frequently affect conductivity in a significant manner. Some of these factors are temperature, impurities, porosity, etc. When the other factors are held constant, reducing porosity can improve the electrical conductivity of materials. Due to the high force applied by the rolling tool, the component surface material is compacted. This leads to a reduction in the porosity of the machined part, [23].

4. CONCLUSIONS

From the literature review, it is concluded that there is a wide relevance of the process parameters in the field of roller finishing process, which improves the metal surface quality and hardness.
It can be observed that the penetration depth has the greatest influence on the surface roughness improvement. The second factor influencing roughness is the number of passes of the burning tool on the workpiece. This finishing method can be used effectively in several areas such as automotive manufacturing, machine tool production, aerospace, etc.
Compared to alternatives (e.g. peening shot), depth rolling generates lower costs and investment and is suitable for almost all metal surfaces. Depth rolling tools can be used on existing customer tooling machines (conventional and CNC). Set-up and transportation costs can be eliminated. This process can be used with a wide variety of components to increase fatigue resistance or allow for easy design solutions.
All mechanical processes (e.g. peening shot), thermal (e.g. laser hardening), and thermochemical treatments (e.g. nitriding) to increase the fatigue resistance of a part can be replaced with depth rolling.
Roll finishing is a faster, cleaner, more efficient and economical method of sizing and finishing parts to prescribed dimensions.
Any ductile or malleable metal can be finished by cold plastic surface deformation by rolling (steel, stainless steel, alloys, cast iron, aluminum, copper, brass, bronze, etc.).
The tools used for roll-form cold plastic deformation finishing are used in sectors such as Automotive, Aircraft, Defense, Spacecraft, Railways, Textile, Machine Tools, Machine Tools, Motors and Pumps, Hydraulic and Pneumatic Stationary Equipment, Household Appliances, etc.
Cold plastic deformation finishing/hardening is extremely reliable, fast, and easy to perform. It can be easily adapted to a regular manufacturing process.
The rolling cold plastic surface forming process achieves the following technical and economical effects: reduction of production cost and time; improvement of surface quality and therefore of the service life of the components, compared to conventional turning or surface treatments such as shot peening and high flexibility of the system, which can be easily adapted to existing turning or turning/grinding machining centers.
From the literature review, it is concluded that there is a significant influence of process parameters in the area of roll finishing process, which improves the metal surface quality and hardness
Many researchers have studied the process of DPSR by rolling in terms of the effects of feed, speed, and rolling force (Dabeer and Purohit, 2010; Ei-Tayeb et al., 2008; Malleswara Rao et al., 2011). The residual stresses in the workpiece before and after the rolling process have been investigated (El-Axir et al., 2008a; El-Axir et al., 2008b; Luo et al., 2005). The results of previous works revealed that the compressive residual stresses on the surface, which are advantageous in improving the component life, can be obtained after the rolling finishing process.

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