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State of the art of Deep Rolling

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ABSTRACT

It is vital to control fatigue life in different industrial sectors, and to improve this, surface treatments are usually used. Some of the most important surface treatments are Shot Peening (SP), Laser Shock Peening (LSP) or Deep Rolling (DR), which are used to improve the surface properties and resistance to cyclic loading of the components. The idea of this article is to focus on Deep Rolling and revise the state of its development at the present time, with a particular emphasis on implementation and changes in materials. A comparison of Deep Rolling versus other surface has been made, and different processes that can improve the effects of Deep Rolling, such as heat treatments, are shown. It can be concluded that the pressure of the tool during the process is the most important control parameter for Deep Rolling and that the residual stresses and strain hardening have the greatest influence in terms of fatigue life. Moreover, selecting the correct values of the other control parameters for DR, depending on the material on which DR is to be done, allows increased compressive residual stresses, a hardened layer near the surface and lower surface roughness, all of which produce an improvement in fatigue life.

Contents

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1. Introduction

The behaviour of metallic components regarding cyclic loading, and therefore against fatigue phenomena of components operating in industries such as the aerospace (Sticchi et al., 2015; Klocke and Mader, 2005), power generation (Ma et al., 2015), or automotive industries (Matlock et al., 2009), is very important because in many cases their useful life is determined by cyclic performance. The industrial sectors, where fatigue is of great importance, are always in a process of continuous evolution with the aim of improving the fatigue life of their components. One of the most common ways to increase the useful life against cyclic phenomena is the realization of surface treatments on the components.

Surface treatments are a set of processes by which residual compressive stresses are attained on the surface of components to increase their life against cyclic phenomena (Sticchi et al., 2015; Manouchehrifar and Alasvand, 2009; Perenda et al., 2015; Altenberger, 2005a). The most commonly used surface treatments include Shot Peening (SP), Laser Shock Peening (LSP) and Deep Rolling (DR).

Laser Shock Peening is based on the action of one or several short high-energy laser pulse on the surface of the material, so that strain hardening and the introduction of residual stresses occur there. Shot Peening is the bombardment of the surface by small diameter spherical particles with sufficient force to cause plastic deformation and the introduction of residual stresses.

Deep Rolling is a process by which a mechanically or hydraulically (Klocke and Mader, 2005) controlled ball or roller applies a specific pressure on the surface of a component, causing plastic deformation of the surface and subsurface area and introducing a layer (1–2 mm) of compressive residual stresses. Besides these residual stresses, two beneficial phenomena for increasing fatigue life are produced: strain hardening and lower surface roughness (Groche et al., 2012). The influence of these effects on the crack growth and propagation is shown in Table 1 (Wagner, 1999).

However, both residual stresses as well as strain hardening can decrease over the life of the component, either due to the effect of temperature, the effect of mechanical stresses from fatigue (Michaud et al., 2006) or a combination of both (Juijerm and Altenberger, 2007a). Therefore, studies of the relaxation of the values of residual stresses and strain hardening are needed (Altenberger et al., 2012; Juijerm and Altenberger, 2007b).

The parameters for Deep Rolling – pressure, speed, number of passes, etc. – directly influence the state of residual stresses, strain hardening and the final roughness, so their correct determination, depending on the material, is a key to maximizing the benefits of DR (Manouchehrifar and Alasvand, 2009; Abrão et al., 2014a). Numerical simulation offers the possibility to study the optimal configuration of DR parameters, eliminating the need to test various operating conditions (Manouchehrifar and Alasvand, 2009; Perenda et al., 2015; Yen et al., 2005; Balland et al., 2013a; Bouzid Saï and Saï, 2004; Balland et al., 2013b).

The aim of this article is to review the state of DR nowadays. First, different procedures for the execution of the DR, as well as parameters that control the process and the influence on material parameters such as microstructure, surface hardness or yield strength are presented. Then, the numerical simulation of DR is addressed, and the materials most commonly subjected to this treatment and their industrial applications are reviewed. Finally, new procedures for the implementation of DR, especially related to DR at high and low temperatures, as well as a comparison between DR and the most common surface treatments are presented.

2. Deep Rolling process

2.1. The process of Deep Rolling

The process of DR can be carried out in different ways, mainly depending on the shape of the element on which it is to be performed. For components with axial symmetry, it is often carried out by a DR machine consisting of three balls equally spaced at 120° around the axis of the workpiece. The component undergoes a rotation about its longitudinal axis and a displacement in the direction of this axis, while the three balls of the DR machine don't move at all. This way, DR is produced by subjecting the workpiece to a certain pressure exerted by the balls on the workpiece due to the movement of the latter (Perenda et al., 2015; Wagner, 1999; Abrão et al., 2014b).

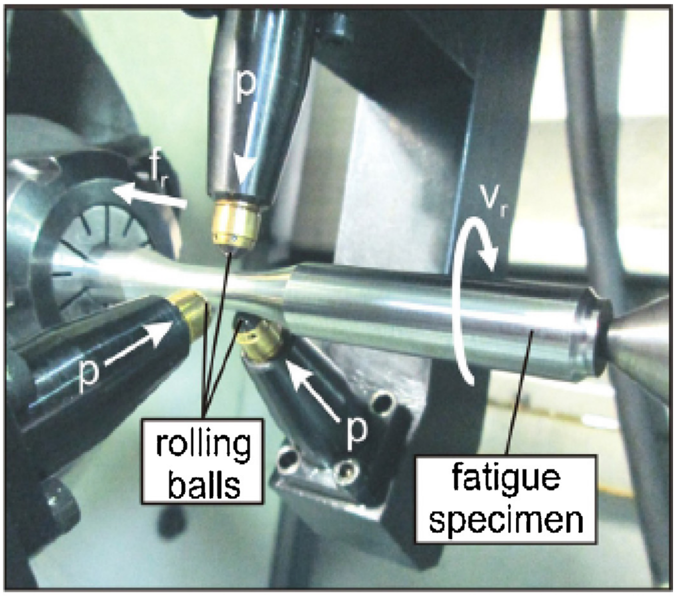
In elements without axial symmetry, for example planar elements or with more complex geometries (Altenberger et al., 2012; Wong et al., 2014; Nikitin et al., 2004; Nikitin and Altenberger, 2007), applying pressure is performed by a ball or roller whose required pressure is transmitted hydraulically or mechanically, while moving along the surface (Fig. 1). In order to prevent thin elements from bending, DR might be accomplished by two opposed rolling tools (Klocke and Mader, 2005). DR on more complex geometries can be applied in a similar way, designing tools with special shapes adapted to the geometry of the component and attaching them to another tool to provide the movement, such as a robotic arm (Wong et al., 2014).

2.2. Measurable parameters

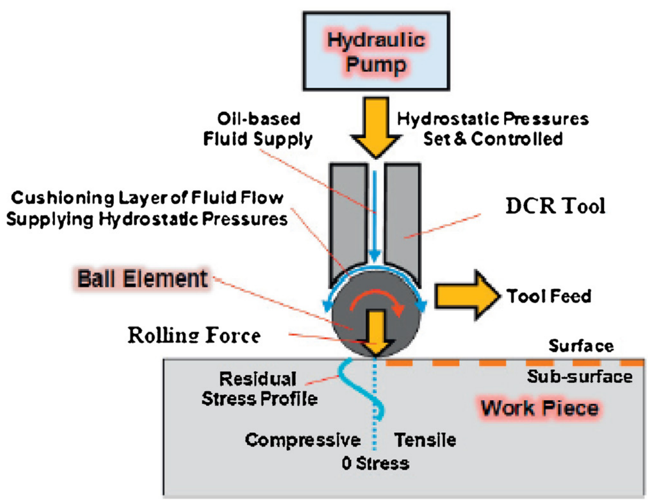
Measurable parameters are those material variables or properties that undergo changes due to DR. Their values condition the component behaviour during its lifetime.

2.2.1. Residual stresses

They are one of the most important parameters caused by DR. Residual stresses are often measured by X-ray diffraction (XRD) (Achmus et al., 1997; Galzy et al., 2005) (e.g. $\sin^2\psi$ method with CrKα radiation for steels). Another way to measure residual stresses is the use of the Central Hole Drilling (CHD) method (Wong et al., 2014; Nau et al., 2014). CHD measures the near surface residual stresses by strain release corresponding to a small shallow drilled



a)



b)

Fig. 1. (a) DR on axisymmetric components (Abrão et al., 2014a). (b) DR on flat components (Wong et al., 2014).

hole with a strain gauge rosette. This method allows to measure residual stresses over a depth of 1 mm while XRD only reaches a few μm (Valentini et al., 2011).

2.2.2. Surface hardness

Like residual stresses, surface hardness influences the fatigue life of the components (Fig. 2). Increasing surface hardness leads to higher compressive residual stresses after mechanical surface treatment (Perenda et al., 2015) and thus higher fatigue life. Rolled surface are tested by different standard indentations: Rockwell (Prabhu et al., 2010), Vickers (Abrão et al., 2014b), Vickers microhardness (Nalla et al., 2003), etc.

2.2.3. Strain hardening

Its magnitude is measured in terms of FWHM (Full Width at a Half Maximum) (Nalla et al., 2003; Maawad et al., 2011) by means of X-ray diffraction and the $\sin^2\psi$ method with CrKα radiation. Maawad et al. (2011) proposed the determination of FWHM using energy dispersion diffraction of X-rays by means of X-ray reflection

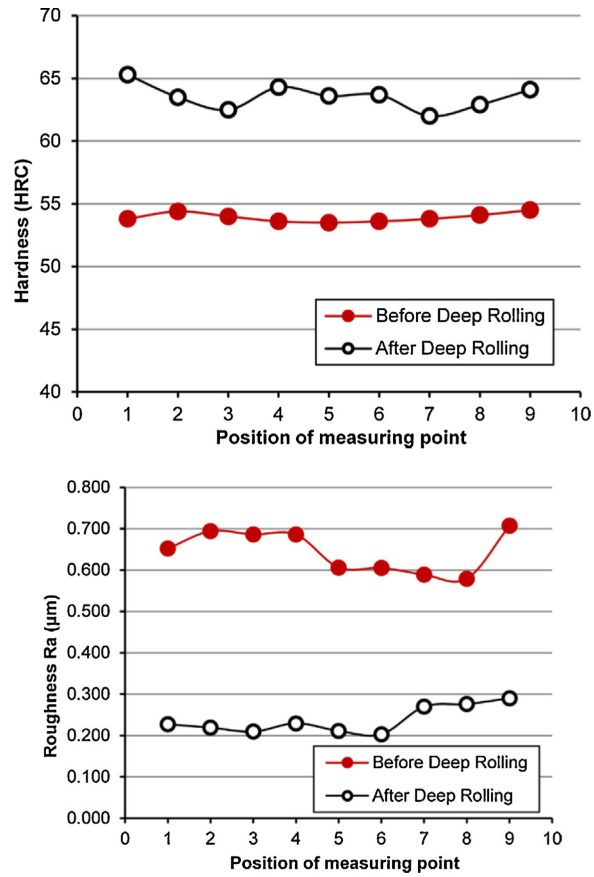


Fig. 2. Hardness and roughness measurement before and after Deep Rolling treatment (Perenda et al., 2015).

and then fitting a pseudo-Voigt function set (Maawad et al., 2011). It is considered to be one of the most important parameters, and in some cases even more important than that of residual stresses. For example, when the components are subjected to high temperatures and there is practically a complete relaxation of residual stresses, extended fatigue life prevails provided that the strain hardening relaxation values are small (Nikitin et al., 2004).

2.2.4. Roughness

It is generally reduced with DR (Fig. 2), which is beneficial (Mohseni et al., 2014). Profilometers are normally used to measure the average roughness depth, R_z, defined as the average of the five highest peaks and the five deepest valleys in a given length (Nalla et al., 2003). Surface geometry is evaluated sometimes by means of SEM observations (Li et al., 2009). Roughness reduction has also beneficial influence on the corrosion fatigue behaviour (Timmermann et al., 2013).

2.2.5. Microstructure

The microstructure obtained after DR depends on the material, which may consist of dislocation cell structures (carbon steel) (Abrão et al., 2014a,b), martensitic transformations (Nikitin et al., 2004; Nikitin and Altenberger, 2007) (suffered by austenitic stainless steels due to plastic deformation (Brinksmeier et al., 2008)), nanocrystals (austenitic steels, titanium or magnesium alloys) (Nikitin et al., 2004; Nalla et al., 2003) or micro-twins (Nikitin and Altenberger, 2007). The stability of the microstructure when mechanical fatigue loads or thermal loads are applied determines to a great extent the effectiveness of DR (Altenberger et al., 2003a). In hardened steels the stability of residual stresses is crucial for fatigue life.

Table 1
DR effects on crack behaviour.

	Crack nucleation	Crack propagation
Surface roughness	Accelerates	No effect
Cold work	Retards	Accelerates
Residual compressive stress	Minor or no effect	Retards

2.2.6. Yield strength and ultimate tensile strength

Plastic deformation due to DR produces different changes depending on the material. On the one hand, Nikitin and Altenberger (2007) found that the yield strength and ultimate tensile strength increase with DR in stainless steel AISI 304. On the other hand, Abrão et al. (2014a) found that in the case of an AISI 1060 steel, the yield strength and the ultimate tensile strength can decrease with DR, depending on the heat treatment.

2.3. Process parameters

Process parameters are those conditions (pressure, speed, etc.) under which DR is performed. The values of these process parameters determine the values of the measured parameters. Some of the most important process parameters are those shown below:

2.3.1. Friction coefficient

Increasing the friction coefficient decreases the residual stresses generated longitudinally, as Manouchehrifar and Alasvand (2009) studied for titanium alloys with numerical simulations.

2.3.2. Speed

Its influence depends on the strain-rate sensitivity of the material, so it can increase, decrease or have no affect on residual stresses. Trauth et al. (2013) carried out various tests on different materials with different DR speeds, noting that higher speeds produce higher residual compressive stress values in a nickel alloy (IN718), lower values in chrome-molybdenum steel (42CrMo4) and hardly any influence in ductile cast iron GGG60.

2.3.3. Pressure

It should be high enough to cause plasticization of the surface of the material, increasing the number of dislocations. The higher pressure produces larger and deeper residual stresses, as seen in studies by Abrão et al. (2014a) on AISI1060; in studies by Zinn and Scholtes (1999) on magnesium alloy AZ31; and in studies by Trauth et al. (2013) on a nickel alloy (IN718), chrome-molybdenum steel (42CrMo4) and ductile cast iron (GGG60). Increasing pressure also increases the surface hardness. However if the pressure exceeds a certain value the material is overloaded leading to a degradation (Scheil et al., 2013), hence the surface hardness could decrease, with even lower values than those of the core values (Abrão et al., 2014a). Likewise, with increasing pressure, roughness decreases and strain hardening increases, although in the case of roughness, Abrão et al. (2014b) observed that for AISI1060 steel, high pressure values produce higher roughness than more moderate pressure values.

2.3.4. Number of runs

As a general rule, an increase in the number of passes increases the hardness and residual stresses, with the roughness decreasing according to Abrão et al. (2014a,b).

2.3.5. Diameter

By performing DR with different ball size diameters, Meyer et al. (2011) and Prabhu et al. (2010) demonstrated that residual stresses and hardness increase with the diameter of the ball in AISI D3 steel and AISI4140 steel. This was confirmed by Scheil et al. (2013) by means of finite element simulations. However if the diameter is reduced, a reduction in the roughness values can be observed (Prabhu et al., 2010).

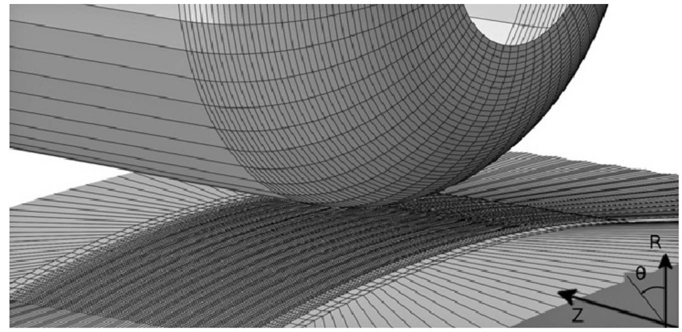


Fig. 3. Example meshing for DR simulation (Balland et al., 2013a).

2.3.6. Feed speed

In terms of productivity, this is the most important parameter, but its influence on measureable parameters is relatively small and is usually negligible for both hardness and residual stresses, something which can be checked in the studies of Abrão et al. (2014a,b) on AISI1060 and Wong et al. (2014) on Ti-6Al-4V.

Other parameters with less influence mentioned by various authors are: vibration (Manouchehrifar and Alasvand, 2009), overlap (Manouchehrifar and Alasvand, 2009; Wong et al., 2014), lubricants (Abrão et al., 2014a) and tool material (Abrão et al., 2014a).

3. Numeric simulation

Numerical simulation is a useful tool for determining residual stresses, strain hardening and surface roughness in a workpiece, so it is necessary to use correct modelling for the problem. Performing a correct simulation of DR, accompanied by a proper characterization of the material properties, can complement and in some cases replace DR testing to obtain the best combination of process parameters (Baecker et al., 2010). Those simulations can validate the measured residual stress profiles too (Majzoobi et al., 2010). Afterwards, fatigue crack propagation in service might be also simulated in order to quantify the beneficial effects of preceding induced residual stresses (Hassani-Gangaraj et al., 2015; Bertini and Santus, 2015).

Despite being a simplification of the 3D model, 2D models allow comparisons to be made with fairly good correlation between the simulation and testing and allow a first estimation of the process parameters (pressure, velocity, speed advance, ball diameter, etc.) to be made as well (Rodríguez et al., 2012). Current models increasingly tend towards 3D simulation models and also towards the use of hexahedral elements instead of tetrahedral elements (Bouzid Saï and Saï, 2004; Balland et al., 2013b) in order to improve the accuracy of the numerical results.

An appropriate description of roughness and strong deformation gradient generated by DR necessitates the use of a very fine mesh near the surface of the workpiece, as Balland et al. (2013a) showed (Fig. 3). Thus, the surface area affected directly by the DR pressure should always be meshed with sufficiently small elements, whereas the areas of the workpiece unaffected directly by the DR pressure may be meshed with a coarser mesh. In axisymmetric elements (Perenda et al., 2015; Balland et al., 2013a) or other geometries (Bouzid Saï and Saï, 2004) only a part of them can be meshed, since the contact between the tool and the workpiece always occurs in the same way. This allows a great reduction in the number of elements and nodes, and a revolution volume of less

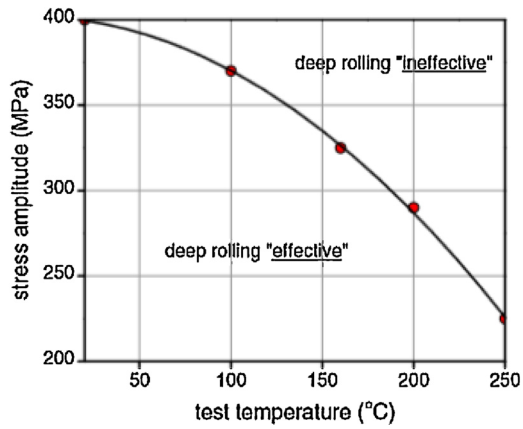


Fig. 4. Optimum conditions for DR application in alloy Al–Mg–Si–Cu (Bouzid Saï and Saï, 2004).

than 45° may be meshed in the case of workpieces with revolution symmetry.

In axisymmetric elements (Perenda et al., 2015; Trauth et al., 2013) where DR is performed on a rotating specimen in contact with 3 balls, some changes can be made to decrease the simulation time. Transmitting the rotational movement to the tool component allows the piece to be fixed while the tools around it are rotating. Fixed deformable elements are more suitable for applying a special modelling technique called "mass scaling" (Trauth et al., 2013).

Mass scaling means to increase the mass of the elements to prevent the calculation steps from being very small, which reduces the total simulation time. Consequently, artificial inertia forces are added, which influence all natural frequencies, including rigid body modes. This additional mass should be used carefully so that the resulting nonphysical inertia effects do not dominate the overall solution (Perenda et al., 2015; Trauth et al., 2013).

A material model of the component is also very important for the correct simulation of the DR process, and the most usual material models are isotropic hardening, kinematic hardening or the Johnson–Cook model. In addition, a nonlinear combined isotropic/kinematic hardening is able to take Bauschinger effects into account (Baecker et al., 2010). The higher the precision in reflecting the stress and strain in the component, the better the simulation. The tools are usually modelled as a rigid element in order to reduce the computation time (Manouchehrifar and Alasvand, 2009; Balland et al., 2013a), although the use of 2D models allows the material to be considered as linear-elastic, assigning a very high value of Young's modulus (Rodríguez et al., 2012) or directly its own value.

4. Materials and industrial applications

The tools with which DR is done must be composed of materials with high stiffness, the most common materials being ceramic or tungsten carbide. DR has different effects on different materials which it is applied to depending on their properties (Abrão et al., 2014a). Listed below are some materials that are commonly subjected to DR.

4.1. Titanium alloys

The most common alloy on which DR is applied is Ti-6Al-4V, an alloy with good mechanical properties: high strength, low density, as well as good fatigue behaviour, corrosion and wear. It can be used both in surgical implants and the aviation sector; other titanium alloys often subjected to Deep Rolling are Ti-Al6-Nb7 (Schuh et al., 2007) in surgical implants and Ti-10V-2Fe-3Al (Drechsler et al., 1998) in aerospace industry. Monitoring the evolution of fatigue on components in the aircraft industry, such as turbine blades and components of jet engines, is critical, and applying surface treatments allows increased fatigue life (Nalla et al., 2003). The usual method used to be Shot Peening, but in recent times research has been done with DR (Altenberger et al., 2002), something made possible by the design of tools with forms adapted to the geometry of the components. These are then applied together with the action a robotic platform which allows DR to be performed on certain workpieces with complex geometries (Wong et al., 2014).

DR may produce a thin layer of nanocrystals and ultra-fine grains (Altenberger et al., 2014; Li and Zhu, 2010) on the surface by severe plastic deformation, and it increases the dislocation density in the vicinity of the surface. Since the process induces plastic deformation, it is necessary to consider this small change in the geometry of the workpiece, especially with very small geometric tolerances, such that no stress concentration due to the geometry change occurs during its lifetime.

4.2. Carbon steels

The results and effectiveness of DR in carbon steels are clearly dependent on the heat treatments which they have been subjected to, that is to say the microstructure of the material (Abrão et al., 2014a,b). Both the properties of the steel and the effect of DR depend on whether the heat treatment consists of a partial annealing, full annealing or quenching and tempering.

The ultimate strength of the annealed steels increases with pressure and the number of passes, but the opposite occurs in quenched and tempered steels; in both cases the yield strength decreases. Residual stresses increase up to a certain point with the number of passes and pressure in annealed steels (Abrao et al., 2015), so any value above this limit causes damage to the material, although these limit values do not appear to exist in martensitic steel (Abrão et al., 2014a). However, hardness values increase for any treatment with pressure and number of passes.

With the above in mind, the most effective heat treatment prior to DR process on carbon steels is quenching and tempering because the generated martensite promotes higher surface hardness and higher residual compressive stresses (Zhang et al., 2014).

An interesting application is given in materials formed by powders (Nusskern et al., 2014). In these materials, a carburizing treatment cannot be performed because its porosity can cause carbon diffusion to the core, producing embrittlement. DR allows porosity to be reduced near the material surface (Nusskern et al., 2014), so that the carburizing heat treatment can be performed by keeping carbon on the surface. Thus, the surface properties of the material experience an improvement due to DR as cementation.

4.3. Stainless steel

The most studied stainless steel on which DR effect has been done is AISI 304 (Abrão et al., 2014a; Yen et al., 2005; Altenberger et al., 1999; Nikitin and Besel, 2008a; Nikitin et al., 2005a). This steel is characterized by a fully austenitic structure before DR. After DR, a surface layer of nanocrystals appears, besides the appearance of strain-induced martensite near the surface and micro-twins, as well as high dislocation density.

DR may cause the emergence of nanocrystals when applied to certain materials, such as IN 738LC nickel superalloy or stainless steel AISI 304. Altenberger et al. (1999) reported the existence of a layer of 1–2 μm and a grain size of 15 nm. Metals having nanocrystals have many beneficial properties such as greater biocompatibility, greater hardness, and increased wear, corrosion and crack initiation resistance (Nikitin et al., 2005b; Pan et al., 2011). However, bulk production is more expensive both in

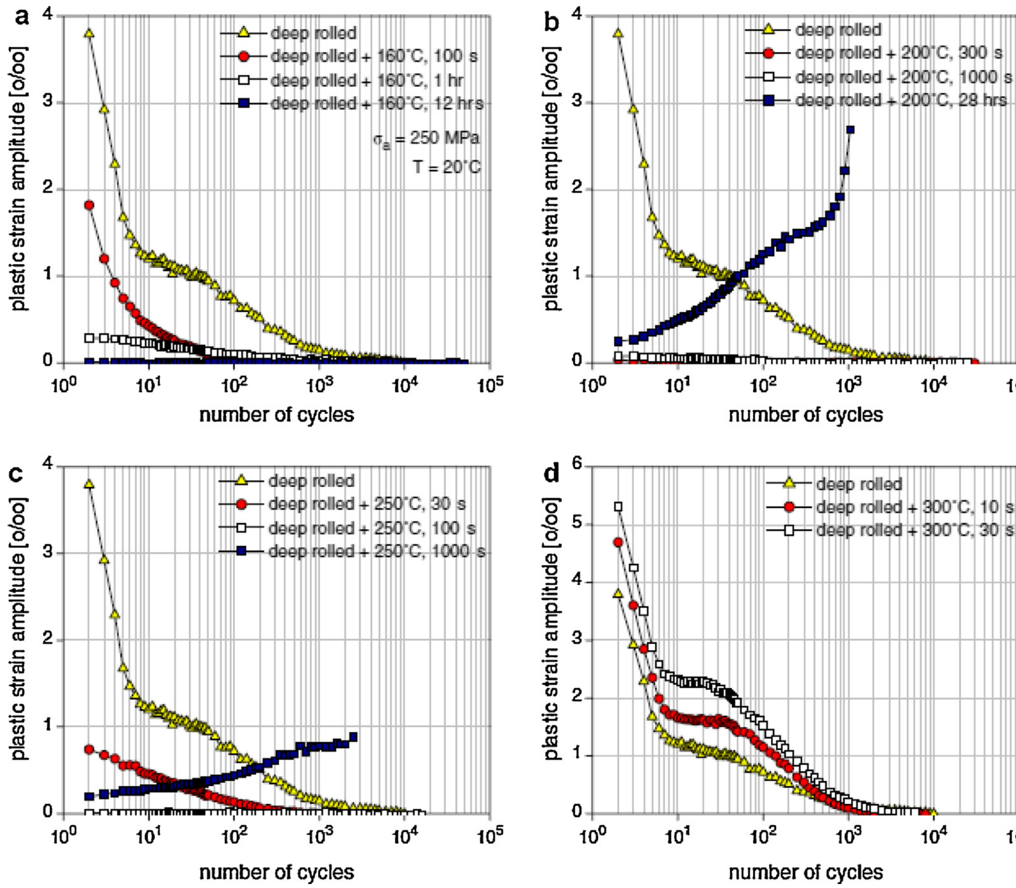


Fig. 5. Cyclic deformation curves of deep rolled as-quenched AA6110 after ageing treatments for different ageing times and temperatures of (a) 160 °C (b) 200 °C (c) 250 °C and (d) 300 °C at an applied stress amplitude of 250 MPa (Juijerm et al., 2006).

time and money, so that the cost-effective alternative is to produce a nanocrystalline microstructure on the surface (produced by mechanical treatments such as DR).

4.4. Aluminium alloys

Aluminium alloys (for example AA6610, AA6013, AA6111 or AA7075) can be used sometimes to replace other materials like copper or steel in certain industries such as the automotive sector. DR leads to improved fatigue life, because of the appearance of residual compressive stresses and especially the strain hardening produced. Relaxation of these parameters exists, as well as in other materials, thus there are determined temperature and stress combinations for which DR is not effective (Juijerm and Altenberger, 2006a,b; Juijerm et al., 2004). This relaxation happens due to cyclic loads, which have their greatest influence during the initial phase of fatigue, and due to thermal loads, whose influence becomes more important after a certain number of cycles (Juijerm and Altenberger, 2007d) (1000 in the case of aluminium alloys).

When fatigue cycles are performed at high amplitude stress and/or high temperatures, DR has been shown to be ineffective as can be observed in Fig. 4. Any combination of temperature and stress amplitude above the line is in an area where the performance of DR is ineffective, while combinations below that line are in a DR effective area to increase the fatigue life components (Bouzid Saï and Saï, 2004). In situations of fretting fatigue DR is also more effective in high-cycle fatigue regime (Majzoobi et al., 2016).

Aluminium alloys are commonly subjected to aging heat treatments to improve their mechanical properties, and such heat treatments have a combination of temperature versus time which is considered optimal. The study of Juijerm et al. (2006) on DR in combination with aging shows that the number of life cycles for a given stress amplitude is very similar both in the case of not quite reaching the optimum time for aging and when treatment is performed during the optimal time, however, over-aging causes a decrease in fatigue life (Fig. 5).

Some authors, such as Juijerm et al. (2007), have studied the possibility of performing the aging treatment after the execution of DR. Although an increase in fatigue life is observed, with respect to a subject with only DR surface treatment, increased fatigue life is less than if the aging treatment is performed prior to treatment of DR. This is because if DR is performed after heat treatment, the benefits of both treatments can be exploited to the max, whereas conducting DR before aging does not allow the sum of the benefits of both treatments, because some relaxation of residual stresses and hardness will occur because of the aging treatment.

Laser cladding is a state of the art filler material technique based on the deposition of material in order to create functional layers which improve the characteristics of the treated piece (Zhuang et al., 2014). It is used for wear and corrosion protection as well as repair and restoration. After application, a narrow heat affected zone appears. To reduce the possibility of tensile residual stresses in the heat affected zone, DR can be used. The result of this treatment is the appearance of compression residual stresses in the area between the base material and the deposited material so that a substantial increase in fatigue life occurs.

5. DR versus other surface treatments

5.1. DR versus SP

Shot Peening is one of the treatments commonly used in the aviation industry to improve surface properties and to introduce compressive residual stresses, although the surface roughness after treatment requires the use of an additional polishing or other surface treatment methods to reduce such roughness. Depending on the material, surfaces are shot peened with steel, glass or ceramic particles (Hennig et al., 2014).

Wagner (1999), Maawad et al. (2011) and Altenberger et al. (1999) have studied the behaviour of titanium and magnesium alloys (Ti-3Al-8V-6CR-4Mo-4Zr and AZ80), copper alloy Ti-2.5Cu and stainless steel AISI304 respectively, all of which were subjected to DR and SP treatments. Depending on the alloy studied, the values of surface residual stresses and FWHM could be greater in DR or SP. However, from a few hundred microns deep, both values are higher in the case of DR, which also achieves greater depths. This fact, coupled with an improvement in the surface roughness of DR as compared to SP, explains the increase in fatigue life of DR over SP. However, Majzoobi et al. (2009) showed that, for low cycle fretting fatigue in Aluminium 7075-T6, SP improvement in fatigue life is superior to DR.

DR tools are simpler than those for SP, however, their use is limited to less complex shapes, and when they are more complex, only SP can be performed (Leitner et al., 2007). As previously discussed, some researchers (Wong et al., 2014) are studying the use of DR in more complex shapes, like in the aviation sector.

5.2. DR versus LSP

As previously mentioned, Laser Shock Peening (LSP) is a surface treatment used to improve the properties of materials, especially their fatigue behaviour, based on the action of a high-energy laser pulse on the material surface (Zhang et al., 2010). Although both DR and LSP have similar beneficial effects on the fatigue life of components, there are significant differences between them. DR is capable of producing significantly higher residual compressive stresses in surface. The depth of these residual stresses can be greater in either mechanical treatment depending on the alloy. DR produces an improvement in the surface roughness, while the LSP either does not or produces a very small improvement (Nalla et al., 2003).

Differences in microstructure depend on the material on which the treatments are applied: in materials such as austenitic stainless steel AISI304 (Nikitin et al., 2004; Nikitin and Altenberger, 2007) (Fig. 6) or titanium alloys such as Ti-6Al-4V (Nalla et al., 2003), DR creates a surface layer of nanocrystals and martensitic transformations in the vicinity of the surface, which cannot be produced by LSP. The dislocation density is higher near the surface using DR which explains the increase in hardness and FHWM values as Nikitin and Altenberger (2007) observed in previous studies (Fig. 7).

Nikitin and Altenberger (2007) conducted studies on the fatigue life of stainless steel AISI 304, noting that DR provides higher values of fatigue life in high cycle fatigue (HCF), while the LSP appears to be superior in low cycle fatigue (LCF) for the process parameters chosen. Both DR and LSP are strongly affected by an increase in temperature during fatigue loading (Nikitin et al., 2005a), however DR provides greater number of cycles at high temperatures (100–600 °C) while LSP performs better at ambient temperature (because LSP provides greater residual stresses and FWHM with the increase of the depth). This can be explained because after the plastic strain amplitude reaches 1%, the LSP treated material quickly softens due to a reorganization of dislocations, which are more volatile. Strain hardening provided by LSP is generated only by

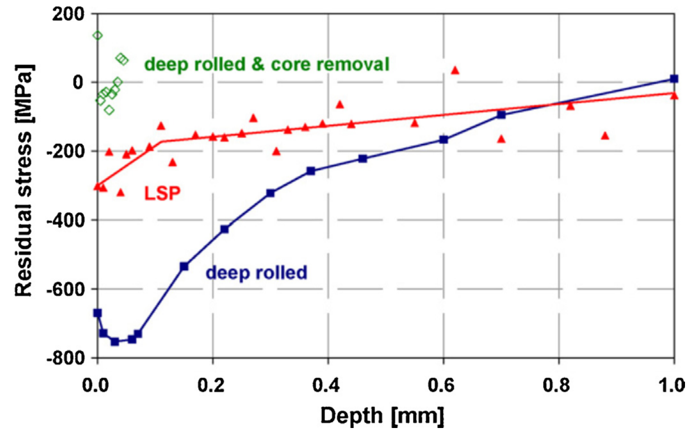


Fig. 6. Residual stress of laser-shock peened and deep rolled AISI 304 (Nikitin and Altenberger, 2007).

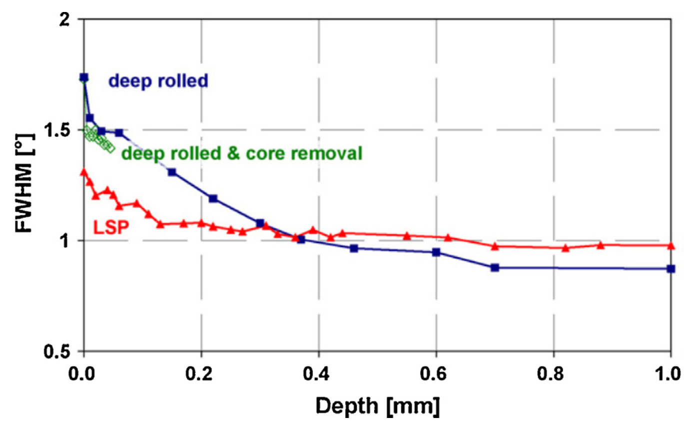


Fig. 7. Full width at half maximum for deep rolled and laser-shock peened AISI 304 (Nikitin and Altenberger, 2007).

cold working (no formation of martensite, or nanocrystals, or micro "twins") and when the deformation reaches a certain level, dislocations begin to move, increasing strain (Nikitin and Altenberger, 2007).

The difference in affected depth makes comparison complicated. To overcome this drawback, drilling and removing the central part ensures that the microstructure near the surface can be investigated without interaction of the core surface, although in DR a relaxation of macroscopic residual stresses occur, so this method only serves to compare the influence of the microstructure in cyclic behaviour. Thus, it has been demonstrated (Nikitin and Altenberger, 2007) that DR microstructure is responsible for more stable compressive residual stresses and FWHM with temperature and cyclic strain, which explains the improved fatigue life of DR at high temperatures and high cycle fatigue. The greatest depth of compressive residual stresses and strain hardening in LSP explains the increase in fatigue life of LSP at low temperatures, despite its lower stability and values of residual stress. Nevertheless, under thermal fatigue, roughness and crack initiation are the predominant parameters (Krauss and Scholtes, 2004).

In titanium alloys (particularly Ti-6Al-4V), Nalla et al. (2003) found that DR produces higher values of compressive residual stress and strain hardening than LSP in and near the surface, whereas LSP values are higher far from the surface. Both surface treatments suffer relaxation of residual stresses and strain hardening due to cyclic loading and temperature, showing a more pronounced relaxation in DR. Despite this relaxation, residual

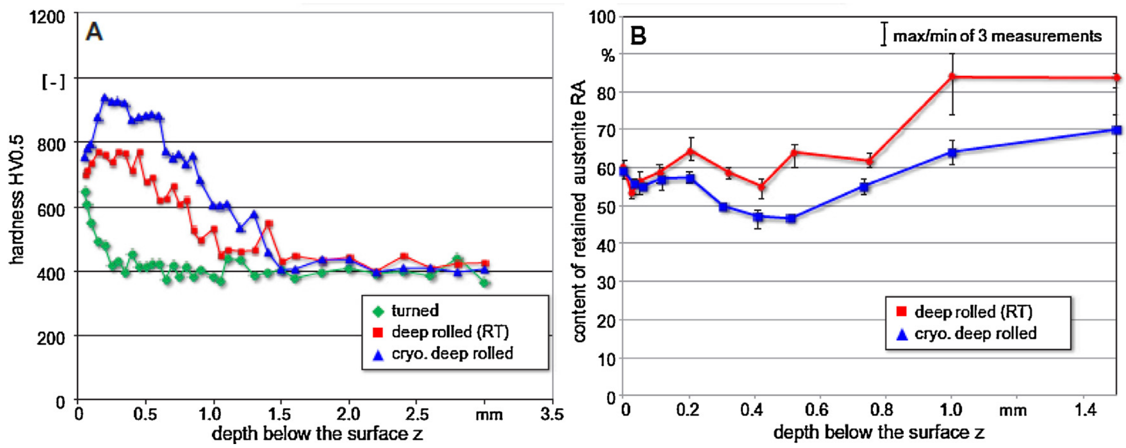


Fig. 8. Hardness (A) and contents of retained austenite (B) resulting from turning and Deep Rolling processes (Meyer et al., 2011).

stresses and strain hardening values remain higher in DR near the surface.

The density of dislocations and strain hardening depth are similar in DR and LSP, which explains that, at least at room temperature and a low number of cycles, fatigue lifetimes are similar. However, as indicated by Altenberger et al. (2012) the emergence of nanocrystals induced by DR produces an increase in fatigue life partly due to increased resistance to crack initiation of nanocrystalline microstructures up to temperatures of 400 °C (0.4 T_m, where T_m is the melting temperature). However, when such temperatures are exceeded and creep becomes the dominant mechanism, DR may provide worse results due to increased susceptibility and worse behaviour of nanocrystals against creep, with the use of LSP as a surface treatment being advisable in this case.

6. New techniques of Deep Rolling

6.1. DR at high temperatures

As seen above, performing a heat treatment after DR improves fatigue life compared to only doing DR, although the improvement is greater if the order is reversed, that is if the heat treatment is performed before DR (Juijerm et al., 2007).

Other authors like Nikitin and Besel (2008b) have contemplated the possibility of performing DR at high temperature in materials such as ferritic–pearlitic steels and stainless steels. Strain hardening by conventional DR occurs by increasing the density of the dislocations, thus impeding the movement of those same dislocations. When heat treatment is performed after DR, it decreases the number of dislocations and the movement thereof is prevented primarily by interstitial carbon or nitrogen atoms. In studies of fatigue with stress-controlled fatigue tests (Juijerm et al., 2007; Nikitin and Besel, 2008b), the number of cycles to failure increases. However, the number of cycles can be further increased performing DR at high-temperature, because strain hardening is produced both by the precipitation of interstitial solid solutions and by increasing dislocations and their intersections. Juijerm and Altenberger (2007c) found an analogous phenomenon in a heat-treated aluminium alloy (AA6110), subjected to DR at high temperatures, in which precipitation occurs.

For fatigue under constant load amplitude, a decrease in the amplitude of plastic deformation, and consequently an improvement in fatigue life occurs. However, for fatigue cycles under deformation control in the LCF regime, there is a sharp reduction in fatigue life. Because of the plastic deformation experienced during high temperature DR or DR followed by heat treatment, the maximum possible plastic amplitude decreases and thus decreases the fatigue life under controlled deformation or plastic deformation (Nikitin and Besel, 2008b).

6.2. DR at low temperatures

This procedure, unlike the previous one, seeks to perform DR at low temperatures or even cryogenic temperatures to obtain more stable microstructures. The main limitation of this treatment is the small range of possible materials for application, since the material must allow cold transformation to martensitic microstructure and must be stable against the stress induced in the machining process and also against microstructural changes during its useful life. With this in mind, Meyer (Meyer et al., 2011; Meyer, 2012) proposes metastable austenitic steels as the main candidates.

After the machining process, the workpiece is subjected to DR while at the surface the temperature is reduced by means of liquid nitrogen and through the projection of CO_2 snow.

The thermodynamic stability of the microstructure before cryogenic DR is important, since the greater the stability the lower the amount of martensite that will be produced. In metastable austenitic steels like AISI D3 for low austenitization temperatures (1105 °C), the microstructure is unstable, and undesirable changes can occur in its lifetime. However, at more elevated austenitization temperatures (1165 °C, 1185 °C) the microstructure is too stable to allow martensitic transformation caused by DR, so there is a narrow austenitizing temperature range for which the metastable austenitic steels, at low temperatures, are likely to be subjected to DR. It should be mentioned, that the martensitic phase in metastable AISI 304 steels shows very highly compressive residual stresses (exceeding 1200 MPa or more).

The application of DR at low temperatures results in an increased surface roughness, with values that differ little from DR at room temperature, and a greater martensitic transformation (Meyer et al., 2011) (Fig. 8). This results in increased hardness and residual stresses, both in absolute value and depth, so for the moment, despite the slight increase in roughness, low-temperature DR has a positive influence on fatigue, although it requires further testing.

7. Fatigue behaviour

To study fatigue behaviour (Altenberger, 2005a; Nikitin et al., 2004; Altenberger et al., 2002, 2003b; Abrao et al., 2015; Juijerm et al., 2004, 2006; Kloos and Adelmann, 1988), the simplest way is to perform tension-compression tests with values of $R = -1$, stress control and different frequencies to check the influence of the cyclic load and thermal loads on the residual stresses and strain hardening. Cyclic tests on real components are less common, however, on components with certain geometries they can be performed, allowing the study of the influence of DR (Regazzi et al., 2014).

The main effect of DR is the increase of fatigue life compared to untreated components. In materials whose yield strength is low, fatigue improvement is mainly due to the work hardening produced (Altenberger, 2005b). An increase in temperature during DR produces a very pronounced relaxation of compressive residual stresses, especially in the area near the surface. Strain hardening, measured by FWHM, remains more stable, so that even with values of relaxation of residual compression stress exceeding 50%, fatigue life can substantially increase if the relaxation of FWHM is small. There are several reasons for the increase in fatigue life by work hardening:

- Work hardening reduces the extent of local plastic deformation by preventing the movement of dislocations, thereby reducing crack initiation.
- Work hardening decreases the early growth of small cracks that start at the surface or near the surface.
- The fine microstructure inhibits crack initiation.

However, since the strain hardening that materials with high values of yield stress can withstand is more limited, the residual stresses are responsible for the increase in fatigue life. In any case, lower surface roughness values result in increased fatigue life by delaying crack initiation (Altenberger, 2005b; Kloos et al., 1987). In addition to a fine microstructure, microstructural gradients present in aged alloys are also beneficial for fatigue life, as shown by Berg et al. (1998).

In general, in components that are free from defects, the fatigue life is controlled by the initiation phase, especially in the HCF regime, whereas in components with defects it is controlled by the crack propagation phase. Strain hardening is the primary mechanism for improving fatigue life in the initiation phase, while residual stresses are the primary mechanism for improving the propagation phase, having a negligible influence on early initiation (Maawad et al., 2011).

8. Conclusions

In this paper the current state of DR has been analyzed, used primarily to improve the fatigue life of components in industries such as aerospace, automotive and power generation. Comparing it with other treatments such as SP and LSP, its simplicity can be highlighted, since it consists of applying a predetermined pressure on a surface by means of a ball or roller. Thus, it has a lower cost than its competing processes, but it is limited by the geometries that it can be applied to.

The execution of DR should be conducted properly, controlling the most important process parameters: pressure, ball diameter, speed, etc. Selecting the correct values of these variables, depending on the material on which DR is to be done, allows increased compressive residual stresses, a hardened layer near the surface and a lower surface roughness to be obtained, which produces a significant increase in fatigue life.

Numerical simulation of the DR process principally allows the possibility for a selection of the optimum process parameters, without resorting to the completion of DR on different components for different parameter settings, as long as the mesh model is established and the material model allows an accurate reflection of the stress-deformation states produced by DR.

Finally, Deep Rolling at elevated or low temperature widens the perspective for generating tailored near-surface properties by promoting aging or phase transformation.

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