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The influence of heat treatment and deep rolling on the mechanical properties and integrity of AISI 1060 steel

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ABSTRACT

This work addresses the influence of distinct microstructures and deep rolling parameters on the behaviour of AISI 1060 steel. For this purpose, the work material was initially subjected to subcritical and full annealing as well as to hardening through quenching and tempering. The specimens were subsequently deep rolled under different rolling pressures and numbers of passes. The findings indicate that plastic deformation increases with rolling pressure and number of passes due to more intense cold working and that under identical deep rolling conditions the fully annealed material presents more severe deformation than the subcritically annealed samples. Moreover, the ability of deep rolling to increase surface hardness decreases with the elevation of the hardness of the original material. The values of the yield and ultimate tensile strength were affected in different manners by deep rolling depending on work material condition and the tensile residual stresses observed after turning were converted into compressive values by deep rolling. Finally, the elevation of rolling pressure and number of passes presented distinct effects on the microhardness distribution beneath the surface depending on the work material condition.

1. Introduction

After shot peening, deep rolling is undoubtedly the process most widely used to induce surface near compressive residual stress by work hardening, thus increasing the fatigue strength of components which will be subjected to cyclic loads. Nevertheless, while shot peening requires specific equipment and may impair the surface finish generated by the previous operation, deep rolling can be conducted on standard machine tools simply by attaching the appropriate device. On the other hand, shot peening can be applied to components with a much larger variety of shapes and dimensions.

An additional advantage of deep rolling is the remarkable improvement on surface finish. Tekkaya et al. (2013) compared the influence of deep rolling and grinding on the surface quality and friction coefficient of WC-12Co thermally sprayed forming tools made of C60 steel and found that grinding promoted lower maximum height of the roughness profile (R_z) and reduced valley depth (R_{vk}) values, while similar reduced peak height (R_{pk}) values were given by both processes. Nevertheless, the quality of the drawn sheets (measured using the same roughness parameters) was superior when formed with the deep rolled tool. As far as the friction coefficient is concerned, similar values were recorded at lower drawing speed (10 mm/s), however, a tenfold increase in the drawing speed resulted in lower friction coefficient values using the ground tool, explained by the perpendicular orientation of the grinding grooves in relation to the sliding direction during drawing (increased bearing capability of the lubricant film). Similar work was performed by Grzesik and Żak (2012), who concluded that superfinishing and deep rolling of hardened steel promote distinct geometric and service properties compared with hard turning. Therefore, the selection of the most suitable route should take into account the required bearing characteristics of the finished component.

During deep rolling, the tool (ball or roller free to rotate) is pressed against the part over a determined number of passes to cause plastic deformation and, in general, longitudinal and rotational movements are simultaneously applied. Although hardened steels can be used as the rolling tool material, tungsten carbide and ceramics are preferred owing to their higher moduli of

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elasticity and wear resistance. Rolling speed, feed, pressure, number of passes, lubricant medium, tool diameter and material are the principal factors affecting the performance of deep rolling.

When deep rolling, the pressure applied by the tool must exceed the yield strength of the work material in order to cause plastic deformation and thus promote the elevation of hardness and the inducement of compressive residual stresses in the outer layers of the workpiece. As a consequence, surfaces subjected to deep rolling are characterized by cell structures with elevated dislocation densities resulting from large amounts of local plastic deformation combined with low strain rates (Schulze, 2006). Obikawa et al. (2009) assert that the magnitude of residual stresses in hypoeutectoid steels is closely dependent on their composition, i.e., the tensile surface residual stress on the pearlitic constituent is twice as large as that observed on ferrite (owing to the higher ductility of the latter) and that the average surface residual stress increases with the volume fraction of pearlite. Moreover, finite element simulation of orthogonal cutting suggests that the peak residual stress increases with the ferrite and pearlite band widths.

The maximum hardness value resulting from plastic deformation after deep rolling is usually not at the work surface, but beneath it where the Hertzian stress reaches its maximum. Nevertheless, an additional increase in yield strength and hardness in the outer layers can be obtained due to grain size reduction (Hall–Petch effect). El-Axir (2000) studied the influence of some deep rolling parameters on the surface microhardness and on the residual stress profile of a medium carbon steel and noted that the hardness increased with pressure and number of passes and decreased with the elevation of rolling feed. As far as the influence of rolling speed is concerned, the findings indicate that it strongly interacts with feed rate, i.e., the microhardness tends to increase with speed when lower feed rate values are employed, whereas the opposite trend is observed at higher rolling feeds. With regard to the residual stress, it typically shifts from tensile to compressive as the applied pressure increases. An appreciable increase in surface hardness (from 400 to 790 HV) was observed after deep rolling cold work tool steel, however, a further elevation to 940 HV (without additional elevation of the rolling pressure) was recorded after deep rolling in a cryogenic environment due to strain induced transformation of metastable austenite into martensite (Brinksmeier et al., 2008).

According to Morimoto (1988), the amount of surface plastic strain gradually decreases as the number of deep rolling passes is elevated, nevertheless, the subsurface microhardness increases considerably after the second and third passes, the latter being comparable to that obtained after using higher pressure and only one pass. Surface and subsurface hardness values also increase as rolling feed is reduced owing to the fact that the work material in the vicinity of the tool is repeatedly subjected to plastic deformation. In contrast, Murthy and Kotiveerachari (1981) report that the influence of number of deep rolling passes on hardness depends on the work material strength, i.e., for lower strength steels the number of passes does not drastically affect hardness to the same extent as in high strength steels.

Srinivasa Rao et al. (2008) state that the increase in surface hardness of a high strength low alloy steel after deep rolling may reach 30–45% depending on the proper selection of the rolling parameters. As far as the influence of rolling pressure is concerned, the authors notice that surface hardness increases to reach its maximum at an intermediate pressure. Seemikeri et al. (2008) report that the most relevant deep rolling parameters affecting microhardness (in decreasing order of importance) are rolling speed, pressure, ball diameter and number of passes. Interestingly, distinct sets of rolling parameters are required for the optimization of either surface hardness or fatigue life.

The relationship between work material properties and deep rolling parameters has not yet been fully explored and understood and this may be the reason why inconsistent results are frequently observed, especially with regard to the influence of the rolling parameters on hardness distribution and surface finish. Optimum pressure, number of passes and feed rate seem to be intimately related and dependent on the yield strength of the workpiece. Chui et al. (2012) report that the ultimate tensile strength of a low carbon steel increased from 354 to 420 MPa after deep rolling, while the elongation to failure was slightly reduced. This behaviour was attributed to the reduction in grain size from 20–50 μm to 8–18 nm on the surface, increasing to 90 nm at a depth of 30 μm. Moreover, the newly formed ferrite grains presented random crystallographic orientation.

An appreciable increase in the fatigue strength of carbon and low alloy steels subjected to deep rolling is reported by Berstein and Fuchsbauer (1982), however, this increase was found to be more pronounced in materials with extreme yield strength values: in the case of lower strength materials the increase in fatigue strength was attributed to the subsurface hardness elevation, whereas the stability of the compressive residual stress was considered responsible for the improvement of the fatigue strength of high strength steels. Furthermore, with the elevation of rolling pressure both maximum workpiece hardness and depth of the affected zone were elevated, however, surface hardness decreases above a critical pressure value and may reach a value lower than the core hardness. Finally, an analogous trend was observed with regard to the behaviour of the residual stress: compressive stresses of increasing magnitude and depth were recorded as pressure was elevated, albeit without further increase in magnitude after a critical pressure value is applied, followed by a decrease in the intensity of the surface compressive residual stress, which may shift to tensile under excessive rolling pressure.

Residual stresses arise from the elastic response of the material to an inhomogeneous distribution of the nonelastic strains such as plastic deformation, precipitation, phase transformation, misfits, thermal expansion strains, etc. (Noyan and Cohen, 1987), therefore, their assessment constitutes an useful tool to establish the extent of the influence of deep rolling on the component. Schulze (2006) reports that the residual stresses measured in the axial and tangential directions (relatively to the rolling path) are affected in different manners by the elevation rolling pressure: while the axial residual stress become slightly more compressive at the surface, the tangential residual stress value is not affected, albeit the penetration depth increases considerably in both cases.

Sartkulvanich et al. (2007) compared experimental and numerical data regarding the residual stress distribution after deep rolling of a hardened bearing steel. Consistent results were found using both approaches with more compressive stresses being generated after deep rolling at higher pressure and lower feed rate. Additionally, the authors claimed that, within the tested range, the residual stresses obtained after deep rolling were not affected by the different residual stress states previously induced by turning with fresh and worn tools. Similar results were reported by Klocke and Liermann (1998), who added that the white layer present after hard turning was not altered by deep rolling.

To date, extensive literature has been published regarding the influence of deep rolling on the surface quality and on the profile of the residual stress and microhardness distributions beneath the surface of metals and their alloys. In contrast, limited information is available concerning the effect of this surface mechanical treatment on the microstructure and mechanical properties of the processed material, which may be the reason why conflicting information is frequently reported. Therefore, the principal goal of this work is to investigate the influence of two of the most important deep rolling parameters (namely rolling pressure and number of passes) on the behaviour of AISI 1060 steel with distinct characteristics obtained by means of three

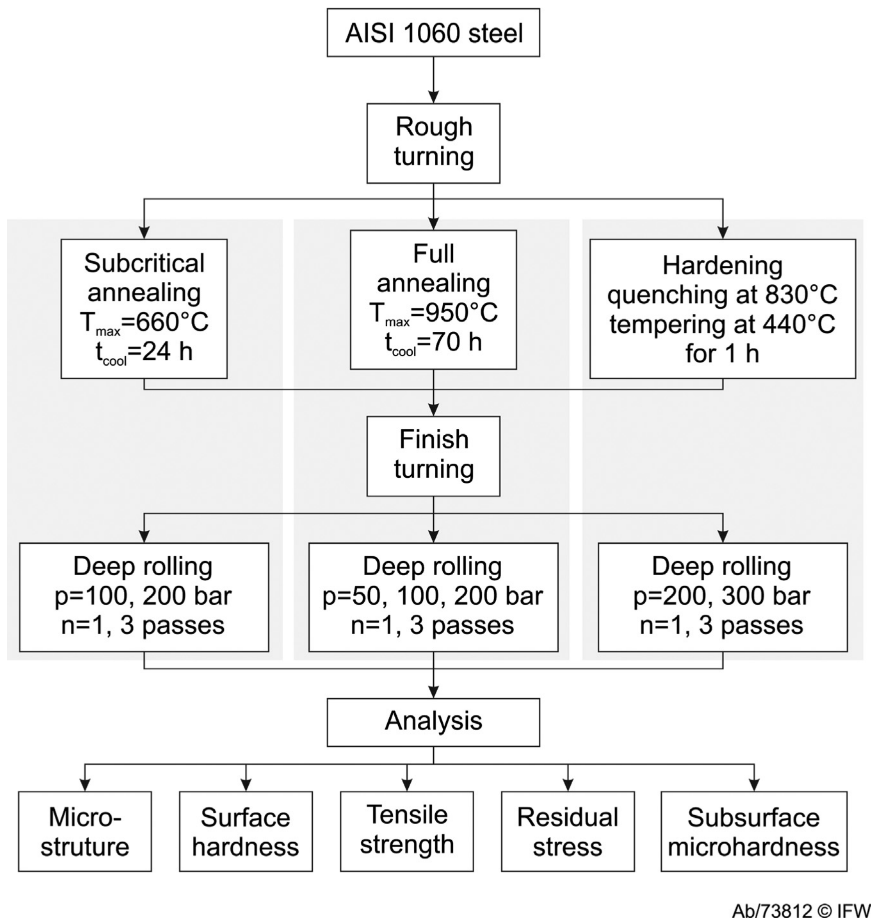


Fig. 1. Experimental design.

heat treatment routes (subcritical and full annealing and hardening).

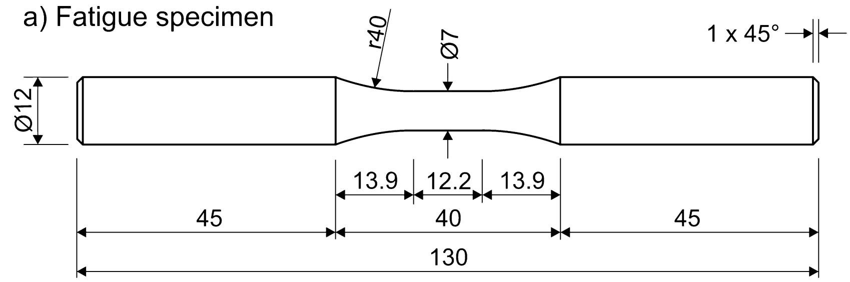
2. Experimental procedure

Fig. 1 shows a schematics of the experimental design. AISI 1060 high carbon steel was selected as work material owing to both the facts that the high carbon content allows hardening by quenching and tempering and the absence of alloying elements yields a better understanding of the influence of deep rolling on the material behaviour. Tensile and fatigue specimens were produced in accordance with DIN 50125 (2009) and DIN 50113 (1982) standards, respectively. The final geometry and dimensions of the fatigue specimens are presented in Fig. 2(a), together with the chemical composition of AISI 1060 steel used in this work (obtained through energy dispersive X-ray analysis), see Fig. 2(b), and its mechanical properties prior to heat treatment (Fig. 2c).

After rough turning, the specimens were subjected to the following heat treatments (Wegst and Wegst, 2007): subcritical annealing (heating to a maximum temperature of 660 °C followed by furnace cooling for 24 h), full annealing (heating to a maximum temperature of 975 °C followed by furnace cooling for 70 h) and hardening (quenching at 830 °C followed by tempering at 440 °C with a soaking time of one hour). These three distinct heat treatments were selected in order to generate distinct microstructures (pearlite and ferrite after annealing and martensite after hardening) and grain sizes (by annealing at different temperatures and cooling times) for the further investigation of the influence of deep rolling on the behaviour of the material.

After heat treatment the samples were finish turned in a high stiffness CNC lathe (Gildemeister CTX 520 linear) using Al_2O_3 + TiCN coated tungsten carbide inserts ISO grade P15 (cutting edge angle of 62.5°, negative inclination angle of −9°, negative rake angle of −5° and clearance angle of 5°) and the following cutting parameters: cutting speed of 100 m/min, feed rate of 0.1 mm/rev and maximum depth of cut of 0.15 mm, see Fig. 3(a). Tool grade/geometry and machining conditions were selected in order to allow the production of specimens with distinct hardness levels under identical conditions.

Finally, deep rolling was performed in the same machine tool by attaching an Ecoroll HG6-20-5.5-SL20 deep rolling device (maximum rolling pressure of 400 bar), manufactured by Ecoroll AG Werkzeugtechnik (Celle, Germany). This particular model operates with three tungsten carbide balls (diameter of 6.35 mm) equally spaced by 120° around the circumference, which allow deep rolling of rotationally symmetrical components with diameter ranging from 5.5 to 12 mm, see Fig. 3(b). This equipment was selected in order to avoid deflection of the slender specimens. The hydraulic fluid possesses a viscosity of 46 mm^2/s at 40 °C and was also used as lubricant during the operation. Deep rolling speed and feed were kept constant at, respectively, v_r = 100 m/min and f_r = 0.07 mm/rev. Although relevant, the influence of these factors was not investigated owing to the fact that including these factors would turn the experimental procedure prohibitive considering the proposed outputs to be analyzed. According to Klocke and Liermann (1998), it is important to set the rolling feed with a distinct value from that used in the previous machining operation in order to obtain optimum improvement on the surface finish, otherwise the rolling path will be parallel to the feed grooves and the ridges will not be flattened.



b) Chemical composition (wt%)

C	Al	Si	P	Mo	S	Cr	Mn	Ni	Cu	Fe
0.76	0.02	0.31	0	0	0.03	0.05	0.74	0.07	0.06	97.97

c) Mechanical properties prior to heat treatment

Hardness: 325 HV0.5

Yield strength $R_{p0.2}$= 440 MPa

Ultimate tensile strength R_m= 830 MPa

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Fig. 2. (a) Geometry and dimensions of the fatigue specimens, (b) chemical composition of AISI 1060 steel and (c) mechanical properties prior to heat treatment.

Additionally, the lower the rolling feed, the better the surface finish (El-Axir, 2000) and the lower the ball diameter, the higher the Hertzian pressure exerted on the workpiece (Klocke and Liermann, 1998).

Deep rolling pressure and number of passes varied during the experimental work as indicated by the grey areas in Fig. 1: while different pressure (p) values were selected depending on the material strength resulting from heat treatment (100 and 200 bar for subcritical annealing, 50–100 and 200 bar for full annealing and 200 and 300 bar for hardening), one and three rolling passes (n) were applied to all specimens. The selection of such pressure values was based on the fact that the rolling force, which depends linearly on applied pressure, must exceed the yield point of the work material to promote plastic deformation (Klocke and Liermann, 1998). In order to allow direct comparisons among the distinct heat treatments, a rolling pressure of 200 bar was applied to all heat treatments. Nevertheless, the same pressure range could not be applied to the three conditions owing to the fact that low rolling pressure values may not promote appreciable plastic deformation on the hardened specimens, whereas extremely high pressures may result in overrolling and its deleterious effects (such as cracks and softening) on the annealed samples.

The analysis of the influence of heat treatment and deep rolling on the properties of AISI 1060 steel was based on microstructure assessment, measurement of surface hardness, yield and ultimate tensile strengths, surface near residual stress and full width at half maximum (broadening of the diffraction peak associated with the microstress, i.e., the stress caused by inhomogeneous plastic deformation at a microscopic scale, such as dislocations) and the microhardness profile beneath the surface. Microstructure

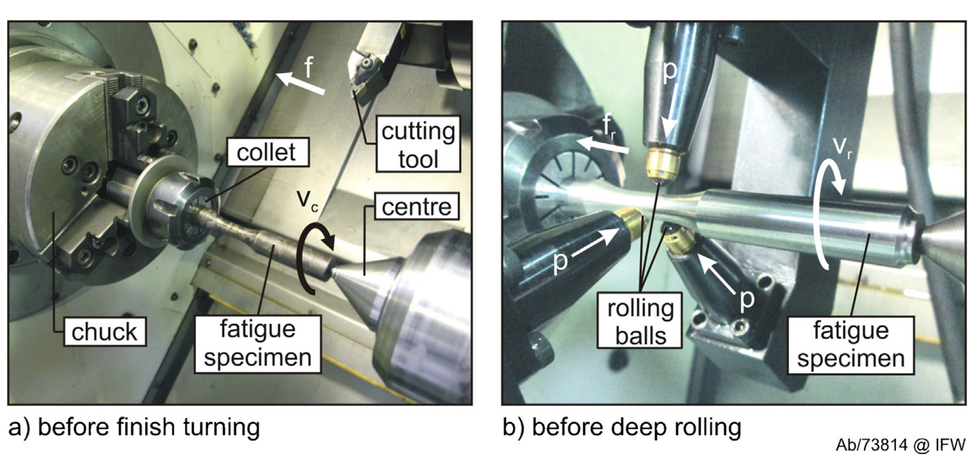

Fig. 3. Experimental setup: (a) before finish turning and (b) before deep rolling.

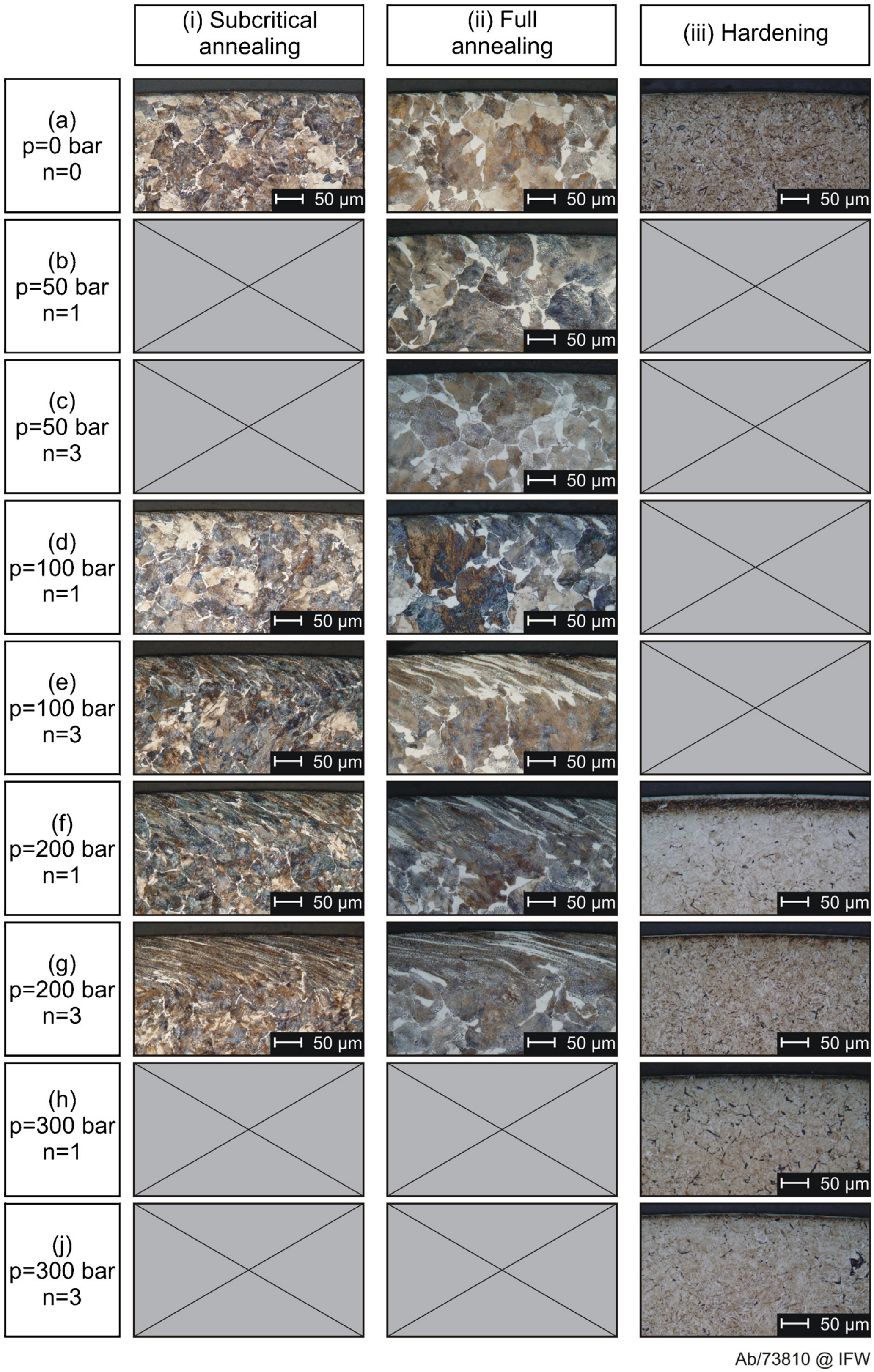

Fig. 4. Influence of heat treatment and deep rolling parameters on the microstructure of AISI 1060 steel.

analysis was performed on a Leitz Aristomet reflected light microscope after grinding (SiC paper with mesh sizes of 220, 500, 1200) and polishing (3 µm and 1 µm diamond suspension) the specimens cross sections and etching them for 5 s in a solution of 2% Nital in ethanol. Surface hardness and subsurface microhardness distribution were evaluated with a Struers Duramin-5 hardness tester with loads of, respectively, 500 and 100 g applied during 10 s. In the case of microhardness measurements, a distance of 45 µm was kept from the border and between adjacent indentations. A Zwick/Roell Z250 universal testing machine (250 kN) was

Table 1
Effect of heat treatment on selected features of AISI 1060 steel.

	Subcritical annealing	Full annealing	Hardening
Average grain size (μm)	20	35	Not available
Grain size number G	8.3	6.7	
Surface hardness ($HV_{0.5}$)	295 ± 12	291 ± 21	756 ± 16
Yield strength $R_{p0.2}$ (MPa)	402 ± 10	331 ± 7	1606 ± 94
Ultimate tensile strength R_m (MPa)	763 ± 9	713 ± 4	2005 ± 62

employed to measure the yield and ultimate tensile stress values. The surface near residual stress and full width at half maximum values were assessed with a GE XRD 3003 TT X-ray diffraction system with a 2 mm diameter collimator. The $\sin^2\Psi$ method (Macherauch and Müller, 1961) was employed using CrKα radiation on 2 1 1 planes of the ferrite phase and varying Ψ from −45° to 45°. This technique is universally applicable to all polycrystalline materials and possesses the advantage of being a non-destructive method to determine near-surface residual stresses (Noyan and Cohen, 1987).

3. Results and discussion

Table 1 summarizes the influence of the employed heat treatments on the characteristics of AISI 1060 steel before deep rolling. According to ISO 643 (2003), the grain size number G is obtained through the following relationship: $m = 8 \cdot 2^G$, where m is number of grains per square millimetre. Larger average grain size was obtained after full annealing in comparison with subcritical annealing as the result of the heat treatment parameters. Despite the fact that this difference did not affect surface hardness considerably, the yield and ultimate tensile strength values presented reductions of 18% and 7%, respectively. With regard to the features resulting from hardening by quenching and tempering, it was not possible to determine the grain size of martensite, nevertheless, the mechanical properties presented a drastic elevation compared with the annealed specimens.

Fig. 4 shows the microstructure of AISI 1060 steel after distinct heat treatments (represented in the columns i, ii and iii) and deep rolling under different pressures and number of passes (rows a–j). Fig. 4(i-a) presents the microstructure resulting from subcritical annealing followed by turning. A typical pearlitic microstructure with an average equiaxial grain size of 20 μm (corresponding to $G = 8.3$) is obtained and proeutectoid ferrite is also observed. In general, it can be noted that rolling pressure affects grain deformation more substantially than number of passes, as shown by Fig. 4(i-d) and (i-f). Moreover, there is a great level of interaction between pressure and number of passes, i.e., although the affected depth did not change drastically with the simultaneous elevation of these factors, deformation becomes more intense and homogeneous along the affected layer for $p = 200$ bar and $n = 3$, see Fig. 4(i-g). The microstructure obtained after turning the fully annealed specimens can be seen in Fig. 4(ii-a). As expected, larger grain size was obtained (average diameter of 35 μm, corresponding to $G = 6.7$), however, as far as the influence of deep rolling is concerned, rolling at 50 bar promoted barely visible alterations on microstructure, irrespectively of the number of passes employed, see Fig. 4(ii-b) and (ii-c). In contrast, grain deformation on the surface of the specimens is evident when rolling pressure is elevated to 100 bar and becomes more accentuated when number of passes is increased from $n = 1$ to $n = 3$, as can be inferred by comparing Fig. 4(ii-d) and (ii-e).

When rolling pressure is further elevated (Fig. 4ii-f), the depth of grain deformation increases considerably, especially for $n = 3$, see Fig. 4(ii-g). A martensitic microstructure resulting from quenching and tempering and without evidence of plastic deformation is found in Fig. 4(iii-a) and does not seem to be affected by deep rolling conditions. The presence of thin white and dark layers, generally associated with untempered and overtempered martensite, respectively, can be noted in Fig. 4(iii-f) and, to a lesser extent, in Fig. 4(iii-g), (iii-h) and (iii-j). These structures are frequently found after machining hardened steels due to the fact that the austenitization temperature is reached near the surface followed by rapid cooling, while the subsurface layers achieve lower temperatures and cool at slower rates. Furthermore, if retained austenite is present in the microstructure it may be transformed into martensite due to the transformation induced plasticity effect (TRIP). Griffiths (1987) reports that the white layer observed after machining is the result of a combination of plastic deformation and heat, however, there are circumstances under which the white layer can be generated without evidence of reaustenitisation, i.e., if temperature is low, sufficiently high plastic deformation may promote the formation of the white layer, as shown in Fig. 4(iii-f) to (iii-j).

Comparing the microstructures obtained after deep rolling the subcritically and fully annealed specimens deep rolled under identical conditions one can conclude that while the condition $p = 100$ bar and $n = 1$ promotes similar effect on both materials, see Fig. 4(i-d) and (ii-d), Fig. 4(i-e) and (ii-e) show that deep rolling at $p = 100$ bar and $n = 3$ results in more severe plastic deformation of the grains of the fully annealed specimen. This can be explained by the lower hardness resulting from this heat treatment. Finally, comparing the influence of deep rolling for the three heat treatments shows that the higher the hardness of the specimens (full annealing, subcritical annealing and hardening in increasing order), the lower the grain deformation, see Fig. 4(ii-f), (i-f) and (iii-f), respectively. Fig. 4(i-g), (ii-g) and (iii-g) indicates that this trend remains unaltered when the number of rolling passes is increased to $n = 3$.

The results concerned with the surface hardness of AISI 1060 steel for all deep rolling conditions tested are given in Fig. 5, where the error bars represent the standard deviation ($\pm\sigma$) calculated from three measurements taken from the same specimen. Clearly, the influence of deep rolling decreases as the hardness of the material is elevated (approximately 35% after deep rolling both annealed specimens at 200 bar and three passes and only 6% for the hardened steel deep rolled at 300 bar and equal number of passes). In addition to that, it can be inferred that surface hardness increases with rolling pressure and number of passes as the result of cold working. Similar results are reported by El-Axir (2000), who noticed that the surface microhardness of a medium carbon steel increases with pressure and number of passes. However, a decrease in hardness is noticed under particular deep rolling conditions. In the case of the fully annealed steel, see Fig. 5(b), the surface hardness after rolling at 100 bar and one pass is lower than that recorded before deep rolling. This behaviour can be explained by the fact that deep rolling may promote a more homogeneous distribution of the dislocations previously induced by turning. In general, carbon steels tend to present low stacking-fault energy and, therefore, better distribution of dislocations inside the grain after plastic deformation. As a consequence dislocation slipping in the slip systems may be facilitated (Reed-Hill and Abbaschian, 1992; Keh and Weissmann, 1963).

Nevertheless, a further increase in either pressure or number of rolling passes results in an increase in the dislocation density, and consequently, in surface hardness. A comparison between Fig. 5(a) and (b) shows that similar surface hardness values are produced by identical deep rolling conditions irrespectively of the differences between heat treatments and corresponding microstructures, except for $p = 100$ bar. Deep rolling affects the workpiece surface and the layer immediately beneath it, therefore, as can be seen in Fig. 4, for depths up to 200 μm there is some equivalence in the degree of cold working of the samples processed under identical rolling conditions, but heat treated differently.

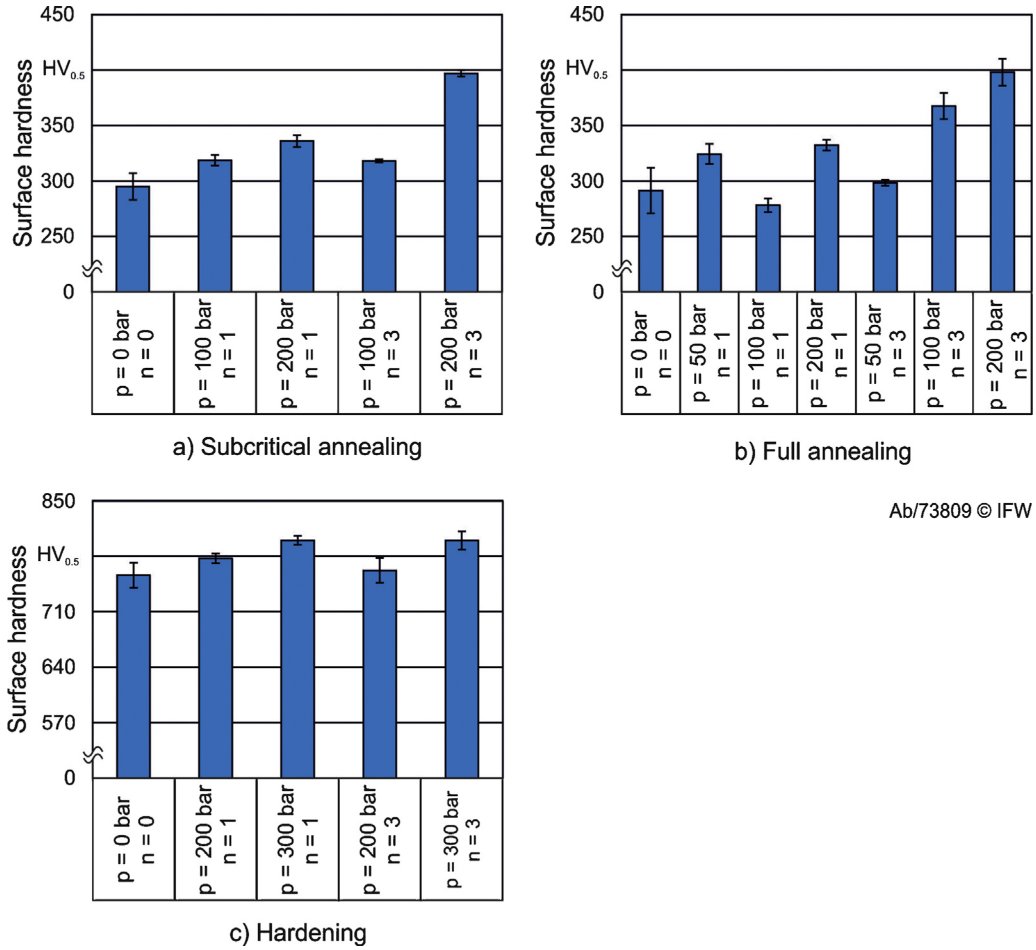

Fig. 5. Influence of heat treatment and deep rolling parameters on the surface hardness of AISI 1060 steel: (a) subcritical annealing, (b) full annealing and (c) hardening.

On the other hand, the microstructure below 250 μm obtained after deep rolling looks similar to that of the non-processed material considering each heat treatment (different grain size and interlamellar spacing). The specimens subjected to full annealing were cooled at a slower rate, thus presenting larger grain size and wider pearlite interlamellar spacing (Reed-Hill and Abbaschian, 1992; Krauss, 1990). It is possible that deep rolling under lower pressure resulted in lower surface hardness values also due to the higher amount of ferrite on the surface in the case of $p = 100$ bar and $n = 1$. However, when the number of passes is increased the softer microstructure tends to work harden at a higher rate, thus resulting in higher surface hardness, as can be seen after deep rolling the subcritically and fully annealed specimens at $p = 100$ bar and $n = 3$. Finally, Fig. 5(c) shows that the quenched and tempered specimens present higher surface hardness values due to the volume fraction of martensite.

The influence of heat treatment and deep rolling parameters on the yield and ultimate tensile strength of AISI 1060 steel is presented in Fig. 6, where the error bars indicate the standard deviations obtained from three trials. Fig. 6(a) and (b) show the influence of rolling pressure and number of passes on yield and ultimate tensile strength of the specimens subjected to subcritical and full annealing, respectively. An increase in both strength values is observed with the elevation of rolling pressure and number of passes, albeit to a lesser extent in the case of full annealing. Similarly to the surface hardness results shown in Fig. 5(a) and (b), the ultimate tensile strength values obtained after subcritical and full annealing increase with rolling pressure and number of passes. Comparable results are reported by Chui et al. (2012), who noticed that the ultimate tensile strength of a low carbon steel increased by 18.6% after deep rolling.

The relationship between hardness and ultimate tensile strength is well known, although in the present work hardness is considered on the surface only. The values of the yield and ultimate tensile strength are lower after full annealing and they increase at a lower rate as rolling pressure and number of passes are elevated. This behaviour can be explained by the fact that, in opposition to surface hardness, the yield and ultimate tensile strength values are mechanical properties which represent the microstructure of the material as a whole. During full annealing (carried out at a higher temperature), static recrystallization and recovery of the grains deformed by rough turning may have taken place, thus promoting a higher degree of softening in comparison with specimens subcritically annealed owing to the elimination of part of the dislocations and keeping their density low. Besides, heat treating the steel at higher temperatures during longer periods favours grain growth, see Fig. 3, and this can impair its strength. Nevertheless, a similar trend is noticed for both yield and ultimate tensile strength: while the ultimate tensile strength increases with rolling pressure and more notably when three rolling passes are employed, the yield strength presents an initial trend towards reduction to recover its original value after deep rolling at the highest pressure and applying three passes. Due to the fact that the yield strength is more sensitive to the presence of dislocations than the ultimate tensile

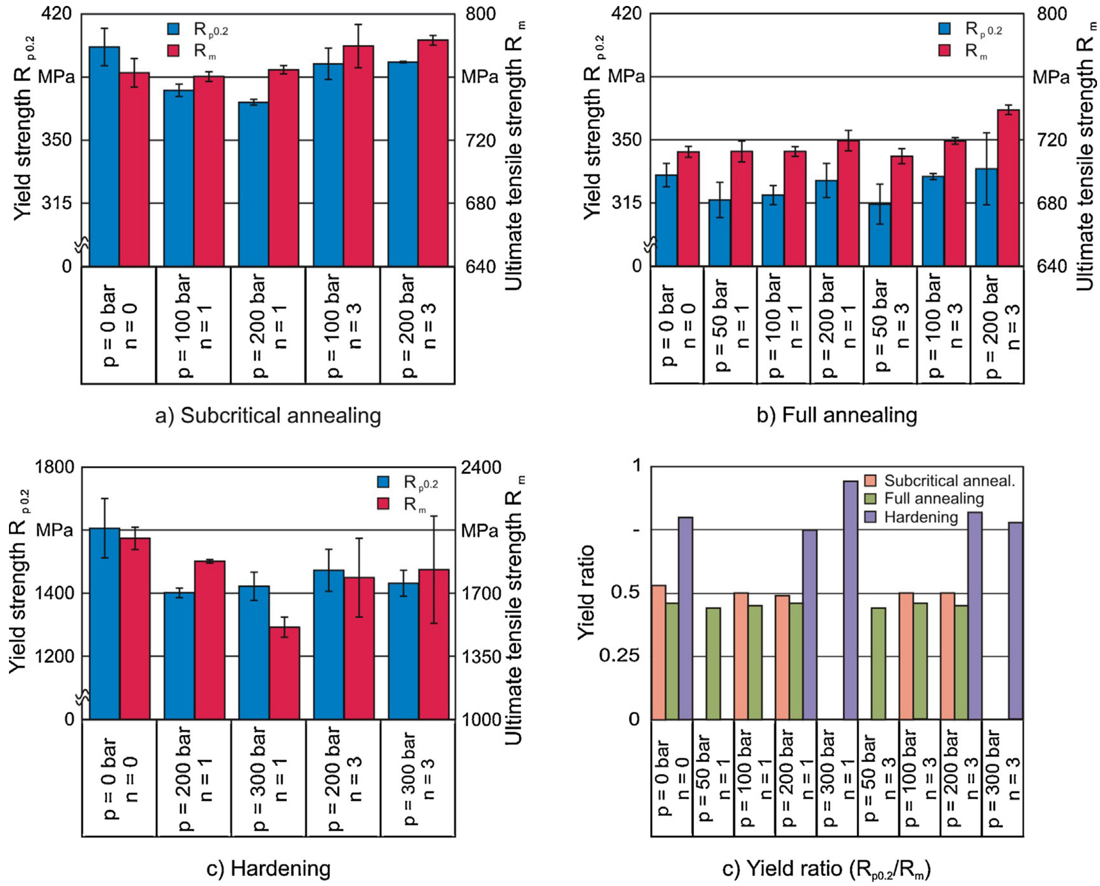

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Fig. 6. Influence of heat treatment and deep rolling parameters on the yield and ultimate tensile strength of AISI 1060 steel: (a) subcritical annealing, (b) full annealing, (c) hardening and (d) yield ratio.

strength (Dieter, 1986), when the tangled dislocations generated after turning are more homogeneously distributed by deep rolling, the yield strength tends to decrease probably because there is an appreciable elevation in the average free path of the dislocations slip in their slip systems before work hardening increases. A different scenario is observed for the hardened steel, see Fig. 6(c). In this case, both yield and ultimate tensile strength values present the same behaviour, however, the tensile strength obtained after turning is not recovered even under the most severe rolling condition owing to the fact that the high dislocation density resulting from the martensite phase transformation is also better distributed in the microstructure by deep rolling. The influence of heat treatment and deep rolling on the yield ratio (ratio of $R_{p0.2}$ to R_m) is shown in Fig. 6(d), where it can be noticed that highest yield ratio values are recorded for the hardened specimens due to its comparatively higher yield strength. In contrast, the lowest yield strength of the fully annealed material resulted in lowest yield ratio values, whereas intermediate yield ratio values were given by the subcritically annealed AISI 1060 steel. Pavlina and Van Tyne (2008) state that the lower the ratio $R_{p0.2}/R_m$, the higher the strain-hardening potential and that the latter decreases with hardness elevation. Moreover, Fig. 6(d) shows that the influence of deep rolling parameters on the yield ratio is slight owing to the fact that rolling pressure and number of passes affect both yield and ultimate tensile strength values in a similar fashion.

Fig. 7(a) and (b) shows, respectively, the surface near residual stress and full width at half maximum values of specimens subjected to the three heat treatments and to selected deep rolling parameters. The error bars represent the standard deviation values calculated from four measurements carried out in different specimens. Tensile residual stresses of similar intensities are obtained after turning specimens of both annealed sets, while tensile stresses near to zero are induced after turning the hardened samples. Gunnberg et al. (2006) describe the generation of tensile residual stress in turning as follows: the high temperature in the cutting zone leads to the thermal expansion of the outer work material layer, while the inner layer which is at a considerably lower temperature is forced to deform plastically. As the temperature on the surface decreases and the outer layer attempts to contract, tensile residual stresses are induced. In contrast, compressive residual stress is mechanically induced by the force equilibrium and geometric compatibility required after the cutting tool action promotes plastic deformation on the surface layer and elastic deformation beneath it (Gunnberg et al., 2006). Therefore, the intensity and depth of the resulting residual stress will depend on the interaction of the thermal and mechanical effects. In the case of the quenched and tempered steel, the formation of martensite reduces the tensile stress state due to the imprisonment of carbon atoms in the structure interstices, thus leading to volumetric expansion and shearing. Tempering attenuates and accommodates expansion gradients and contributes to the reduction of the tensile residual stress.

Cold work hardening caused by deep rolling, however, helps to shift the tensile stresses to compressive values as the work material ahead of the rolling tool is plastically deformed during the operation. According to Berstein and Fuchsbauer (1982), the elevation of rolling pressure induces compressive stresses of increasing

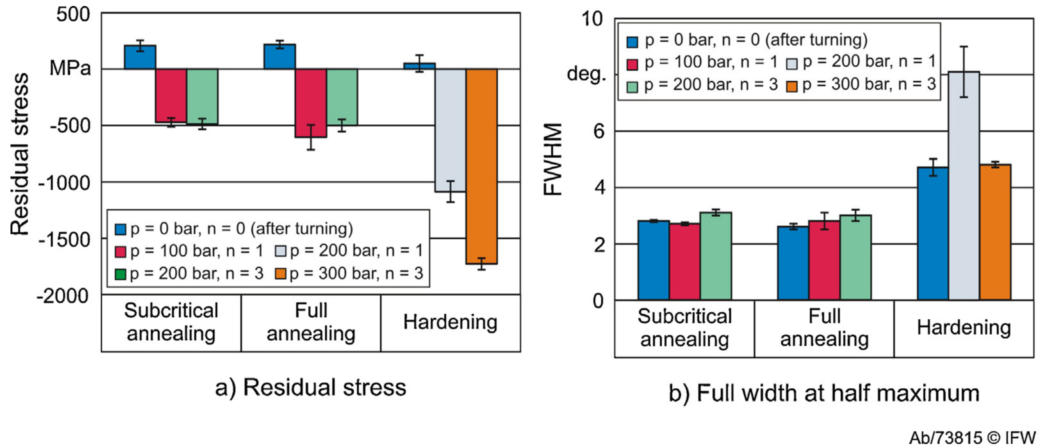

Fig. 7. Influence of heat treatment and deep rolling parameters on: (a) residual stress and (b) full width at half maximum.

magnitude and depth, however, after a critical pressure value there is no additional increase in the intensity of the compressive residual stress, which may decrease on the surface or even shift to tensile stress under excessive pressure. Fig. 7(a) suggests that $p = 100$ bar is near the critical pressure value for the subcritically and fully annealed specimens. In opposition to the annealed samples, the results for the hardened steel indicate that the intensity of the compressive residual stress increases with pressure and number of passes without evidence of saturation within the tested range. The results for the full width of the diffraction peak at its half maximum are presented in Fig. 7(b) and suggest that the elevation of pressure and number of passes leads to more intense microstrains in the case of the annealed samples. Significantly higher values were obtained for the hardened specimens and the reason why the highest value was recorded after deep rolling at 200 bar and one pass may be related to the thicker white layer produced under this particular condition. The white layer observed in Fig. 4(iii-f) after deep rolling at $p = 200$ bar and $n = 1$ may be untempered martensite transformed from the retained austenite present in the microstructure after plastic deformation (Griffiths, 1987) under this specific rolling condition.

Finally, the results concerned with the microhardness distributions beneath the surface are presented in Fig. 8 for the three heat treatments and selected deep rolling parameters. It can be noticed

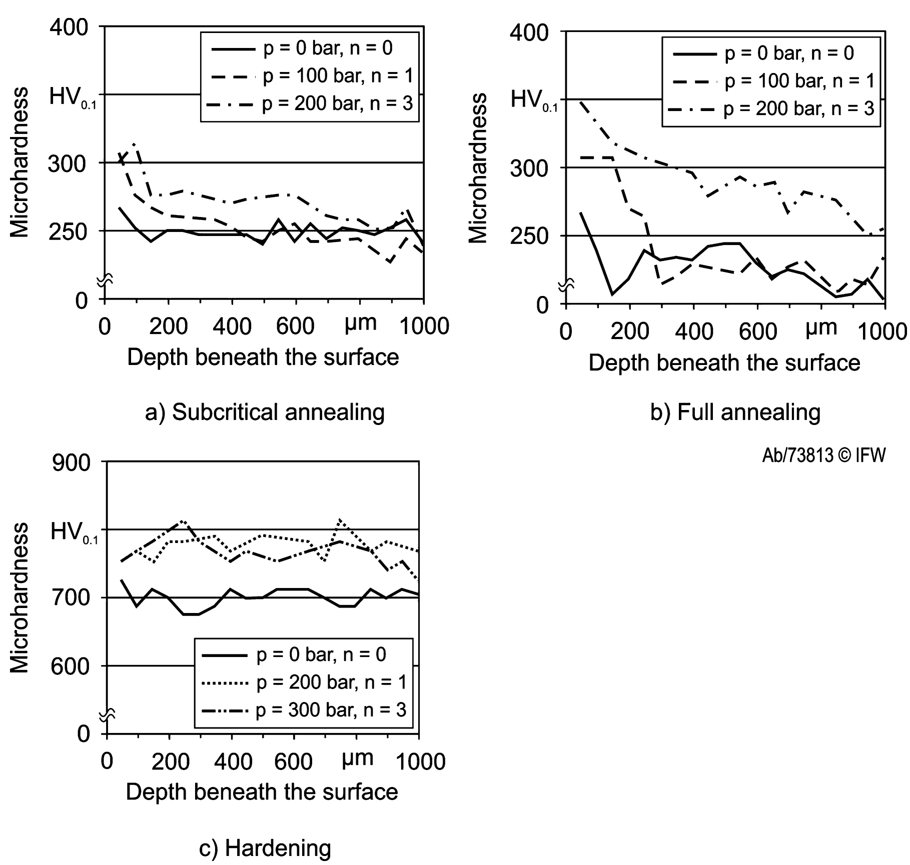

Fig. 8. Influence of heat treatment and deep rolling parameters on microhardness distribution of AISI 1060 steel: (a) subcritical annealing, (b) full annealing, and (c) hardening.

that the microhardness value and the affected depth increase with rolling pressure and number of passes for the subcritically and fully annealed specimens, see Fig. 8(a) and (b), respectively. Similar results are reported by El-Axir (2000) and Morimoto (1988). However, deep rolling the fully annealed AISI 1060 steel resulted in higher values and deeper affected zone compared to the subcritically annealed samples.

These findings confirm the visual analysis of Fig. 3, which suggests more intense plastic deformation in the fully annealed specimens compared with those subjected to subcritical annealing. One must bear in mind, however, that the variation in the grain size distribution may have affected the microhardness measurements, especially in the case of the fully annealed steel, which possesses larger grain size. Furthermore, the finer and more homogeneous microstructure resulting from subcritical annealing aids to attenuate the work hardening depth. As far as the steel in the hardened state is concerned, highest microhardness values beneath the surface were obtained at lower rolling pressure and applying only one pass, see Fig. 8(c). The microhardness decrease near the surface may be related to the presence of overtempered martensite, as suggested by Fig. 4(iiif).

4. Conclusions

The influence of deep rolling pressure and number of passes on the microstructure and mechanical properties of AISI 1060 steel specimens subjected to distinct heat treatment procedures (subcritical annealing, full annealing and hardening by quenching and tempering) can be summarized as follows:

- The grain boundaries of the annealed specimens suggest that plastic deformation increases with rolling pressure and number of passes due to more intense cold working. Additionally, the fully annealed material presents more severe deformation. In contrast, plastic deformation is not visible in the hardened specimens through optical microscopy.
- The higher the hardness of AISI 1060 steel, the smaller the influence of deep rolling on it (maximum elevation of approximately 35% after deep rolling the annealed specimens and 6% after rolling the material in the hardened state).
- While the ultimate tensile strength of the annealed specimens increases with rolling pressure and number of passes, the yield strength presents a decrease under certain rolling conditions associated with the better distribution of the dislocations previously induced by turning. In the case of hardened AISI 1060 steel, both the ultimate and the yield strength decrease.
- Tensile residual stresses are induced near the surface after turning the three materials, however, they are converted into compressive residual stresses after deep rolling irrespectively of the rolling parameters employed. In contrast to the annealed specimens, which do not show significant differences in compressive residual stresses after deep rolling under rather distinct conditions, the results for the hardened steel indicate that the intensity of the compressive residual stress increases with pressure and number of passes without evidence of saturation within the tested range.
- The full width at half maximum results indicate that the elevation of pressure and number of passes leads to more intense microstrains in the case of the annealed samples. Significantly higher values were obtained for the hardened specimens, with their maximum recorded after deep rolling at 200 bar and one pass.
- The profile of the microhardness distribution beneath the surface shows an elevation with both rolling pressure and number of passes for the specimens subjected to annealing. With regard to the hardened specimens, however, the highest rolling pressure and number of passes did not lead to highest microhardness values, probable owing to the better distribution of the dislocations when three passes are employed.
- In general, quenching followed by tempering can be regarded as the most indicated heat treatment owing to the fact that the generated martensite promotes highest surface hardness and tensile strength values. Furthermore, when associated to deep rolling at 300 bar and three passes highest compressive residual stresses are generated near the surface of the component.

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