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The influence of deep rolling on the surface integrity of AISI 1060 high carbon steel

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Abstract

The aim of this work is to study the influence of selected deep rolling parameters (rolling pressure and number of passes) on the surface integrity of fully annealed AISI 1060 high carbon steel. In addition to the mechanical properties, a comprehensive investigation on surface integrity is carried out. The findings indicate that despite the increase in surface hardness and ultimate tensile stress, deep rolling can negatively affect the yield strength. The amplitude and functional roughness parameters show a considerable reduction after deep rolling, however, increasing rolling pressure and number of passes leads to poorer surface finish. Finally, the tensile residual stress generated by turning shifts to compressive values after deep rolling and the microhardness and microstructure analyses indicate that the depth of the layer affected by deep rolling depends on both the rolling pressure and number of passes.

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1. Introduction

Target induced compressive residual stresses aiming to improve the service performance of metallic components have been devised since the dawn of the metallurgical science. Initially, hammering was the only available process, later being followed by deep rolling and shot peening. Currently, a number of alternative techniques (such as laser shock peening, water jet peening and vibration assisted deep rolling) is available to meet the component required properties. Similarly to its counterparts, deep rolling is expected to induce compressive residual stresses by cold work strain, thus increasing the fatigue strength of the component. Moreover, surface finish is significantly improved.

The analytical approach employed to model deep rolling is based on the Hertzian contact between two surfaces, which results in maximum equivalent stress below the surface owing to the change in the contact zone from a point to an area. However, the fact that the Hertz contact stress theory assumes that the solids involved are elastic and strain is small requires the use of numerical approaches to consider plastic deformation and thus, the inducement of residual stresses [1]. Deep rolling devices integrated into turning tool holders have been developed by [2, 3] and despite the substantial reduction in production time, the authors state that special attention must be paid to the static and dynamic stiffness of the machine and hybrid tool due to the increase in the force resulting from simultaneously cutting and deep rolling.

Work by Loh et al. [4] showed that the surface hardness of medium carbon steel increased by an average of 55% after deep rolling with tungsten carbide balls. Furthermore, rolling pressure and feed were regarded as the most significant factors. In order to promote an addition increase in hardness, Meyer et al. [5] recommended the application of cryogenic cooling during deep rolling of components made of steel containing metastable austenite. Under this environment, less energy is required to promote strain induced

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martensitic transformation.

Although the principal goal of deep rolling is to induce compressive residual stresses, its beneficial effect on surface finish cannot be neglected. Luca et al. [6] stated that the principal parameter affecting surface roughness is rolling pressure, nevertheless, the authors point out the importance of the surface finish generated in the previous machining operation to the final quality of the rolled part. Work by El-Axir [7] indicated that except for rolling feed, which increase causes the deterioration of surface finish, the interactions between the remaining factors (rolling pressure, number of passes and speed) strongly affect roughness, therefore, the identification of the most suitable rolling condition relies on the simultaneous selection of the parameters.

As far as the residual stresses induced by deep rolling are concerned, Avilés et al. [8] reported that the compressive stress observed near the surface of deep rolled medium carbon steel was approximately one order of magnitude higher than the values recorded in specimens which were not rolled. The effect of selected rolling parameters on the residual stress induced on a high strength low alloy steel was investigated by Trauth et al. [9] and the findings indicated that the intensity of the compressive stress increased considerably with rolling pressure and tool diameter. In contrast, the influence of rolling feed was found to be negligible and the elevation of rolling speed had a negative effect on the residual stress.

Deep rolling and related processes have been extensively investigated over the last decades, nevertheless, several points have not yet been thoroughly understood. For instance, the interaction effect of deep rolling parameters on the macro and micro residual stress distributions deserves further investigation. The same applies to the influence of the work material properties on the selection of deep rolling parameters. Therefore, the overall aim of this work is to study the influence of deep rolling pressure and number of passes on the surface integrity of AISI 1060 steel. This material was selected owing to the fact that its elementary composition (without alloying elements) is expected to allow the better understanding of the involved phenomena before tackling more complex alloys.

2. Experimental procedure

Bars of AISI 1060 high carbon steel with Ø20.3 mm and 130 mm long were used as work material. After rough turning and heat treatment (full annealing), finish turning to remove an oversize of Ø1 mm was conducted in a high stiffness Gildemeister CTX 520 linear CNC lathe (145 kW power and 10,000 rpm maximum rotational speed) using coated tungsten carbide inserts ISO grade P15 (Sandvik Coromant DNMG 110408-PM 4215) mounted on a tool holder code DDNNN 2020 K11 under the following conditions: cutting speed (v_c) of 100 m/min, feed rate (f) of 0.1 mm/rev and maximum depth of cut (a_p) of 0.15 mm. Finally, deep rolling was performed in the same machine tool using an Ecoroll device model HG6-20-5.5-SL20 with three Ø6.35 mm tungsten carbide balls under the following conditions: deep rolling pressures (p) of 50, 100 and 200 bar and 1 and 3 rolling passes (n). Deep rolling speed and feed were kept constant at, respectively, v_r =100 m/min and f_r = 0.07 mm/rev. Surface hardness and microhardness subsurface distribution were assessed using a Struers Duramin-5 hardness tester. The yield and ultimate tensile stress values were obtained with a Zwick/Roell Z250 universal testing machine and the surface topography was assessed with a Zeiss EVO 60 scanning electron microscope. Surface roughness parameters (Rv, Rp, Rt, Rpk, Rk, Rvk, RPc and Rmr) were measured using a Mahr Perthometer PGK with a sampling length of 0.80 mm. The residual stress and the full width at half maximum near the surface were measured with a GE XRD 3003 TT X-ray diffraction system with a Ø2 mm point collimator. The $\sin^2\Psi$ method was employed using CrKα radiation on 211 planes of the ferrite phase and varying Ψ from -45° to 45°. Microstructure analysis of the cross sections was carried out in a Leitz Aristomet microscope after polishing and etching the specimens in a solution containing 2% Nital in ethanol. The results for surface hardness and tensile stress represent an average of three measurements, whereas the data concerned with surface roughness and residual stress were obtained from four replicates and one measurement was taken to assess the microhardness distribution beneath the surface.

3. Results and discussion

The influence of the deep rolling parameters on surface hardness and tensile strength is presented, respectively, in Fig 1(a) and 1(b), together with the results for the specimens which were not deep rolled (p = 0 bar, n = 0). In general, surface hardness increases with rolling pressure due to work hardening, nevertheless, considerably higher hardness is obtained applying three rolling passes. The reasons why the hardness of the specimens deep rolled at p = 100 bar and n = 1 was not affected by deep rolling and why the hardness decreased as the number of passes was elevated from n = 1 to n = 3 using p = 50 bar are not completely clear, however, they may be associated with a more uniform distribution of the dislocations previously induced by turning when sufficiently high pressure and/or number of passes are applied. As pressure and/or number of rolling passes are further elevated, the introduction of additional dislocations by cold working causes the elevation of surface hardness. As far as the tensile strength results are concerned, Figure 1(b) shows that the yield stress ($Rp_{0.2}$) is reduced after deep rolling under the lowest pressure to gradually increase with pressure and number of passes. In contrast, the ultimate tensile stress (Rm) increases with both rolling parameters. As previously discussed, this behaviour can be explained by the fact that rolling at lower pressures leads to the reduction of dislocations entanglement and, consequently, of the yield strength. Owing to the fact that $Rp_{0.2}$ is more sensitive to dislocation movement, similar behaviour is not observed for Rm. As rolling pressure and number of passes are increased, dislocation density is elevated, as well as the tensile strength of the material.

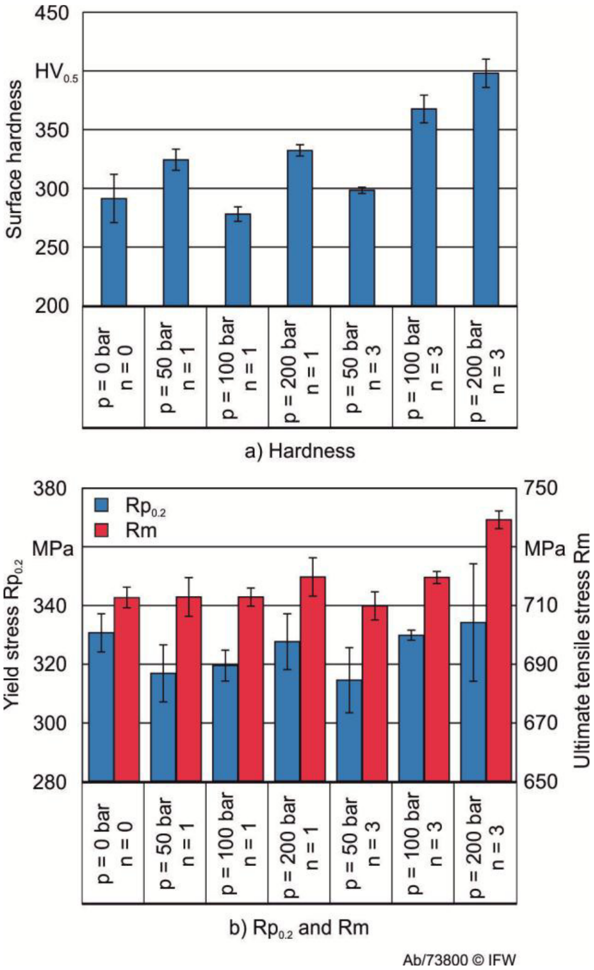

Fig. 1. Effect of deep rolling parameters on (a) surface hardness and (b) mechanical properties of AISI 1060 steel

Fig 2 shows the effect of rolling pressure and number of passes on surface topography. The feed and burnishing marks caused by turning, see Fig 2(a), are flattened after deep rolling under the lightest condition, as indicated in Fig 2(b). The same pattern is observed when pressure is increased to 100 bar, as shown in Fig 2(c). However, applying p = 200 bar results in more severe plastic flow (Fig 2(d)), in addition to spalling (probably due to overhardening) when three rolling passes are employed, as indicated in Fig 2(e) and 2(f).

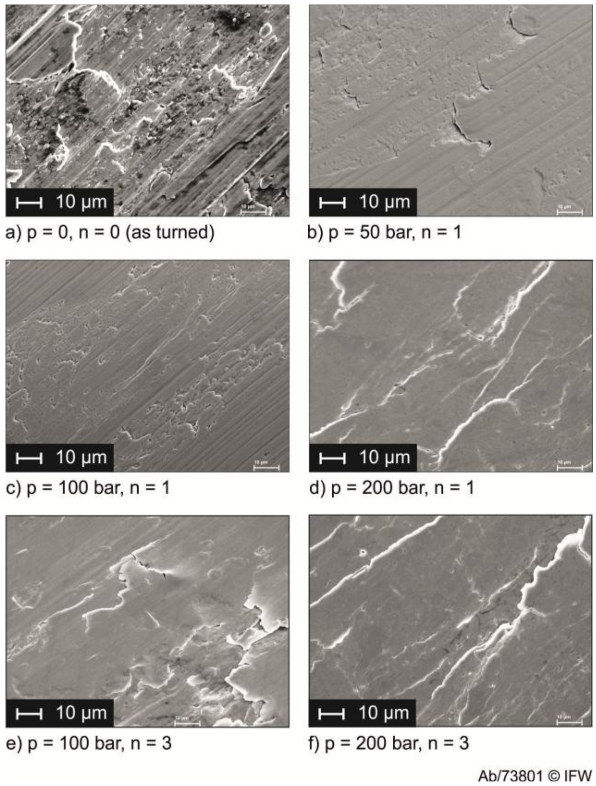

Fig. 2. Effect of deep rolling parameters on the surface topography of AISI 1060 steel

The surface roughness results are given in Fig 3. The presented parameters were selected due to the fact that they were considered suitable to detect the influence of the investigated deep rolling parameters on surface finish within the tested range. Fig 3(a) shows the amplitude parameters Rv (maximum depth of the profile below the mean line within the sampling length), Rp (maximum height of the profile above the mean line within the sampling length) and Rt (maximum peak to valley height of the profile in the assessment length). It is worth mentioning that the sum of Rv and Rp gives Rz (maximum peak to valley height of the profile within the sampling length). These results show a substantial reduction in the roughness parameters after deep rolling at p = 50 bar with lowest roughness recorded after three passes (Rt = 1.25 µm), however, a further increase in pressure leads to the deterioration of the surface due to plastic flow and spalling. Furthermore, the ratio between Rp and Rv increases with the rolling parameters due to the deposit of plasticized material in the valleys.

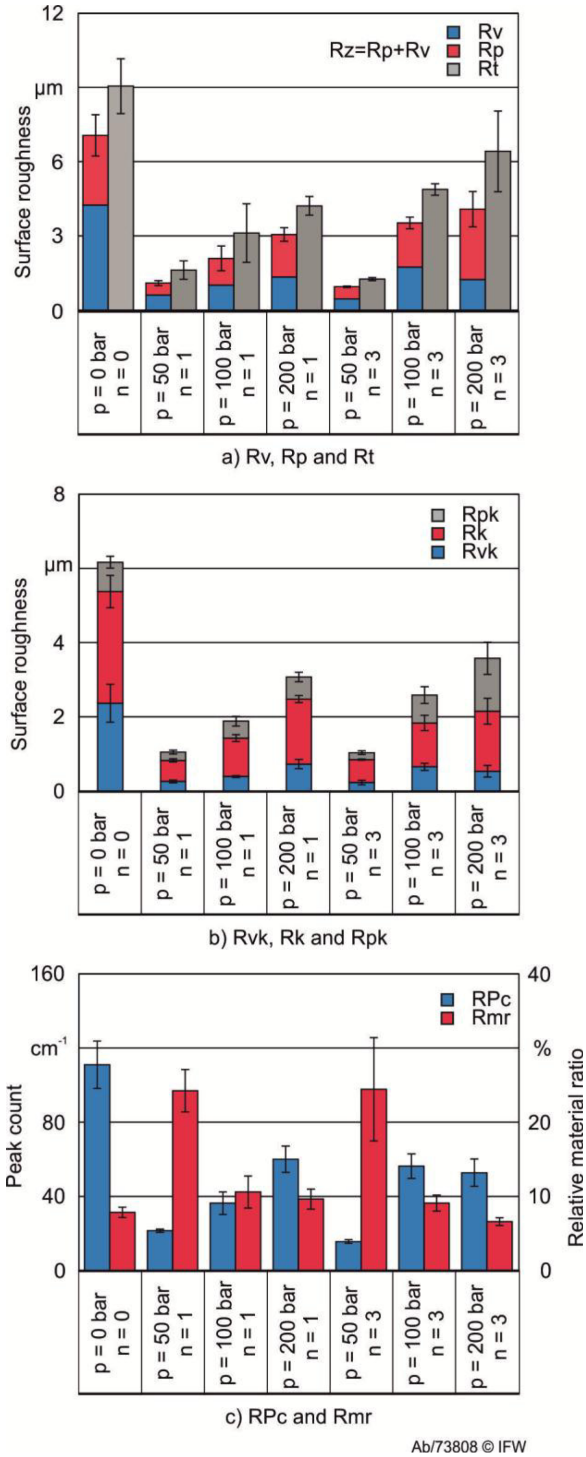

Fig. 3. Effect of deep rolling parameters on the surface roughness of AISI 1060 steel

Selected parameters obtained from the material ratio curve (Rpk - reduced peak height, Rk - core roughness depth and Rvk - reduced valley depth) are presented in Figure 3(b). Similarly to the amplitude parameters previously discussed, the values of these functional parameters decrease after deep rolling at p = 50 bar to increase markedly with the subsequent elevation of pressure and slightly with number of passes. Compared with the turned specimens, the value of Rk is relatively larger after deep rolling, especially when one rolling pass is employed, which is an important feature for bearing applications. Moreover, the elevation of Rpk with pressure for n = 3 suggests that the presence of bulges caused by plastic flow is the main reason for the deterioration of the surface quality. Finally, Fig 3(c) presents the results for RPc (peak count within the range from -0.25 to 0.25 µm) and Rmr (relative material ratio considering a reference sectioning level at 5% and a difference of -0.20 µm). Compared with the surface which was only turned, an appreciable reduction in RPc is noted after deep rolling at p = 50 bar, however, it tends to increase with the elevation of pressure. The opposite trend is observed for Rmr, i.e., after an expected increase caused by deep rolling, the trend is towards its reduction as pressure is elevated. In both cases the influence of number of passes seems to be minimal. The findings presented in Fig 3(b) and 3(c) indicate that material flow may perform a more relevant role than spalling on the surface quality of fully annealed AISI 1060 steel.

The results for the near-surface residual stress and full width of the diffraction peak at half maximum (FWHM) are presented in Fig 4(a) and 4(b), respectively. It can be seen that the tensile residual stress found after turning shifts to compressive values after deep rolling. Additionally, it is noted that rolling pressure and number of passes do not drastically alter the value of the compressive residual stresses induced by deep rolling, except under p = 100 bar and n = 3. The reason for that resides in the fact that with the elevation of the investigated deep rolling parameters more work hardening takes place, thus increasing the compressive stress, however, no further elevation is obtained after the saturation point above the yield strength is achieved. The lowest FWHM values recorded at p = 50 bar for n = 1 and n = 3, see Fig 4(b), indicate that this pressure leads to a more ordered distribution of dislocations, since this parameter represents the microstress, i.e., the stress caused by inhomogeneous plastic deformation at a microscopic scale. Applying pressures of p = 100 bar and p = 200 bar increase the number of dislocations and thus, the value of FWHM. Therefore, the findings presented in Fig 4(b) confirm the proposed hypothesis for the behaviour of the yield tensile strength shown in Fig 1(b).

The microstructure obtained after turning and subsequent deep rolling at selected conditions is presented in Fig 5. Plastic strain, which is hardly noted after turning (Fig 5(a)) or deep rolling using p = 50 bar

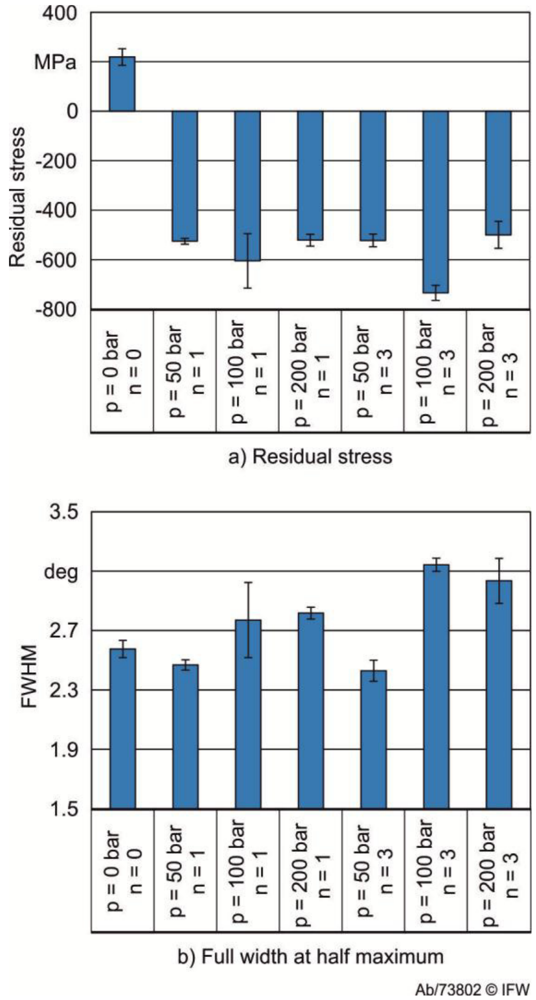

Fig. 4. Effect of deep rolling parameters on (a) residual stress and (b) full width at half maximum of AISI 1060 steel

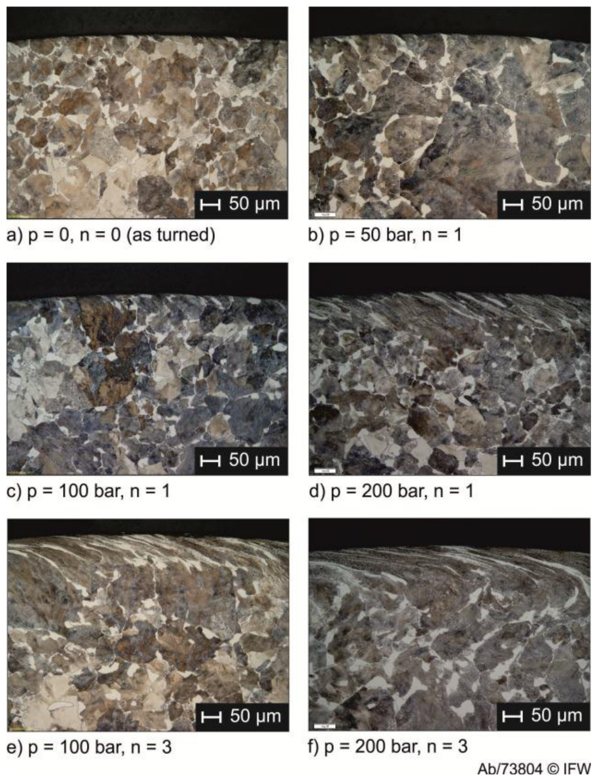

Fig. 5. Effect of deep rolling parameters on microstructure of AISI 1060 steel

and one pass (Fig 5(b)), increases gradually with pressure, as shown in Fig 5(c) and 5(d), to become more intense when three rolling passes are employed, as indicated in Fig 5(e) and 5(f). As a consequence, Fig 6 shows that the profile of the microhardness distribution beneath the surface is altered. Fig 6(a) shows that when one single rolling pass is applied, the depth of affected zone increases with rolling pressure, while the microhardness near the surface is less influenced. However, when three passes are applied, see Fig 6(b), both the microhardness near the surface and the affected depth increase with pressure. Unfortunately the load used in the microhardness measurements (100 g) did not allow the determination of the microhardness profile within a distance of 45 μm from the surface, where the grains boundaries shown in Fig 5(e) and 5(f) suggest more intense plastic strain. Such data would lead to a more comprehensive understanding on the relationship between plastic strain and microhardness variation as well as on the influence of deep rolling parameters on the behaviour of fully annealed AISI 1060 steel.

4. Conclusion

The influence of deep rolling pressure and number of passes on the surface integrity of fully annealed AISI 1060 steel can be summarized as follows:

- In general, the surface hardness after deep rolling increases with rolling pressure and number of passes. The same behaviour is observed for the ultimate tensile stress, while the yield stress is negatively affected when a rolling pressure of 50 bar is used due to a more uniform distribution of the dislocations previously induced near the surface by turning.
- The typical surface topography generated by deep rolling is characterized by a plasticized zone, however, increasing rolling pressure and number of passes leads to spalling and bulging. As far as the surface roughness is concerned, the amplitude and functional parameters as well as the peak count tend to decrease drastically after deep rolling using the lowest rolling pressure. Increasing pressure deteriorates the roughness and the number of rolling passes does not affect surface finish considerably. The relative material ratio value presents an opposite

trend and can also be used to satisfactorily characterize the surface generated by deep rolling.

- The tensile residual stress induced near the surface by turning shifts to compressive values after deep rolling due to cold working. Highest compressive stress was obtained at intermediate pressure (p = 100 bar) and three passes and a further increase in rolling pressure does not result in a compressive residual stress of higher intensity owing to saturation as the yield strength of the investigated material is exceeded.
- The higher the rolling pressure and the more the number of passes, the more intense is the plastic strain beneath the surface. Consequently, both the microhardness value and the depth of the affected zone increase with rolling pressure and number of passes.

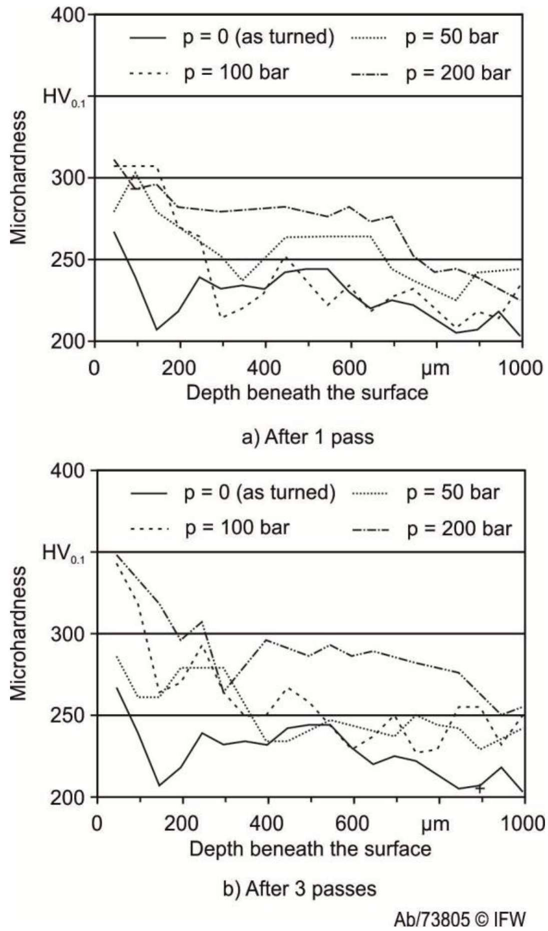

Fig. 6. Effect of the number of deep rolling passes on the microhardness profile after (a) one pass and (b) three passes

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