Residual stresses induced by deep rolling in notched components

M. Guagliano, L. Vergani
Dipartimento di Meccanica, Politecnico di Milano, Milano, Italy

Abstract

Mechanical surface treatments are more and more utilized to improve the fatigue strength of notched machine elements. In these cases the improvement of the mechanical characteristics is mainly due to the residual stress state that the treatments induce in the surface layers of the material. This paper deals with deep rolling: a numerical procedure designed to calculate the residual stress state by varying the treatment parameters is proposed. This procedure was applied to a notched element and the numerical results were verified by means of the experimental measurements obtained by using an X-ray diffractometer. To demonstrate the influence of the treatment parameters a prediction of the fatigue strength of the specimen was made, both the residual stresses obtained with different rolling loads as well as the stresses resulting from the applied load were taken into account.

Riassunto

I trattamenti meccanici superficiali sono sempre più utilizzati per migliorare il comportamento a fatica dei componenti meccanici intagliati. Il miglioramento è principalmente dovuto allo stato tensionale residuo indotto negli strati superficiali del materiale. In questo lavoro è stata considerata la rullatura: viene proposta una procedura numerica, verificata sperimentalmente con misure diffrattometriche, per il calcolo delle tensioni residue. Per evidenziare l'influenza dei parametri del trattamento sulla resistenza a fatica dei componenti intagliati è stata effettuata la previsione della resistenza a fatica di un provino intagliato considerando sia le tensioni residue indotte dal trattamento, sia gli sforzi dovuti al carico applicato.

INTRODUCTION

It is well known that mechanical surface treatments such as rolling or shot peening have a considerable effect on the fatigue behaviour of components. Fatigue improvement is mainly due to the residual stress fields induced by technological treatments while hardening of the material surface layer is not very significative with regard to fatigue behaviour. On the contrary if we consider chemical or thermo-chemical treatments, fatigue improvement is due both to material hardening and to the residual stresses.

The pattern of the residual stresses induced by the mechanical treatments is very important and can significantly influences the fatigue behaviour. In fact it is recognized that this beneficial effect is dependent on the resulting stress field, obtained by the superimposition of the residual and applied stresses. If the specimens are notched the improvement is remarkable, while if the specimens are smooth the effect of the resulting stress field is not as positive owning to the tensile residual stresses in the subsurface layer [1], [2], [3], [4].

In order to improve the fatigue behaviour, the residual stress pattern can be modified by varying the treatment parameters (in particular if surface rolling is considered: roll diameter, rolling load and number of load applications; if shot peening is considered: shot size and impact energy) or following surface rolling by adding a tensile or compressive overloading [5].

The fatigue tests executed subsequently showed the importance of the position of the maximum compressive and tensile residual stresses as well as that of the material layer thickness with the compressive stresses. In fact if there is a notch, that has been surface rolled, due to the presence of compressive stresses, subsurface cracks generally nucleate but do not propagate.

The knowledge of the residual stress pattern allows also to determine the position of the crack initiation, which is strongly influenced by the stress gradient and the applied stress value. In fact, if the net fatigue strength (obtained by superimposing the fatigue strength of the material and the residual stresses) is compared to the applied stress pattern, it is possible to forecast where the cracks initiate [6], [7], [8].

If the notches are strong and the applied stresses are high, the cracks are generally external, on the contrary, if the notches are slight and the applied stresses are low, the cracks initiate in the subsurface region, under the compressed layer. For all these reasons, the knowledge of the residual stress profile is considered necessary to optimize the deep rolling treatment and its effect on the fatigue behaviour of the elements. The implementation of this approach gave rise to several problems such as simulation of the rolling procedure, in fact the non linearity of both the model and of the roll contact were considered.

In previous studies several numerical models of a simple element, a prismatic bar, [9], [10], [11] rolled by a cylindrical roll, which presses and moves on the bar, were built. This model was validated, by first comparing the residual stresses measured on the mechanical element, the different residual stress patterns were then obtained, by varying the load and the roll in order to determine the best distribution of the residual stresses.

In this study, on the contrary, the rolling of a notched specimen is considered. The steps of the work are the same: construction of a numerical model of the roll which presses and moves on the specimen, validation of the model by comparing the numerical results with the experimental ones, execution of other calculations by varying the rolling parameters and study of resulting stress patterns in order to define the fatigue behaviour.

MECHANICAL MODEL

The geometry of the specimens considered is shown in fig. 1. The theoretical stress concentration factor is K_t=1.5 (torsional loading) and the notch radius is equal to 1.5 mm. The specimens, made from steel 40CrMo4, were manufactured by the Centro Ricerche Fiat (a partecipant in this study). All the specimens were quenched and tempered and then rolled by Hegensheidt by means of the roll shown in fig. 1. The rolling load was P=15kN.

The material utilized has the mechanical characteristics shown in Table 1, experimentally found by CRF.

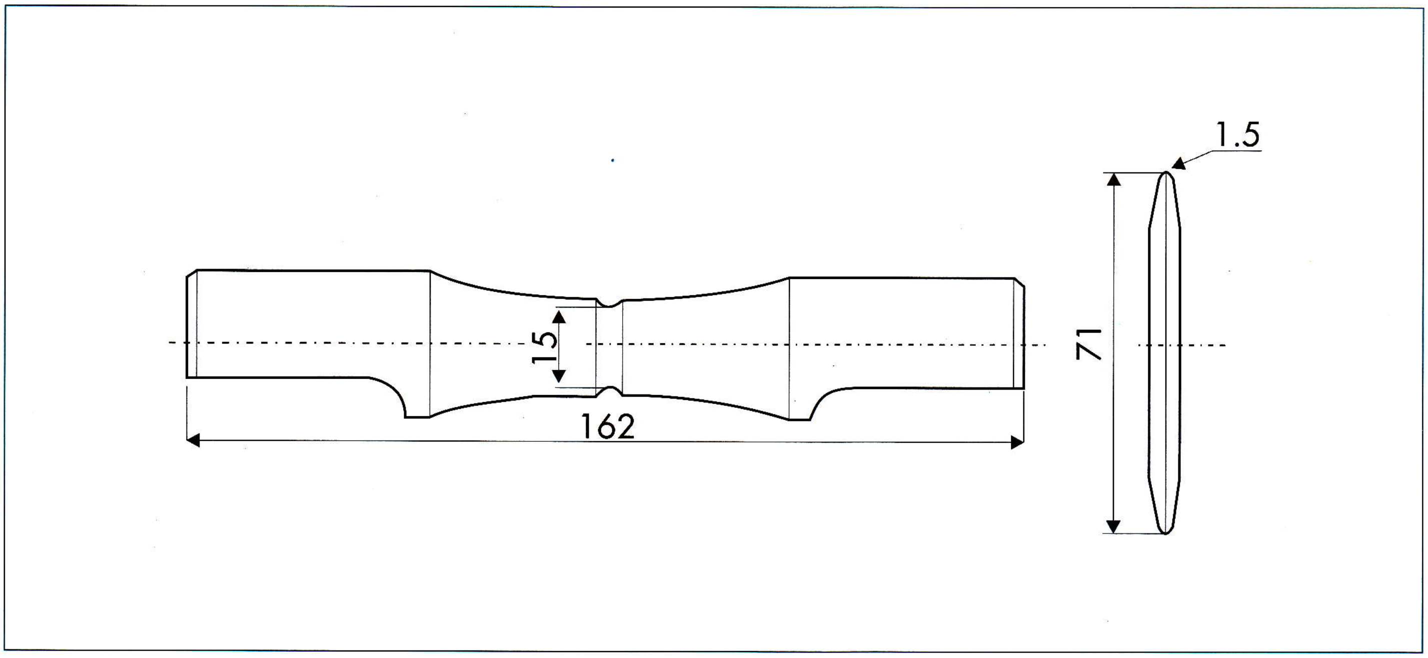

Figure 1: dimensions of the specimen and of the rolll

TABLE 1 - Mechanical characteristics

Material	σ_R [MPa]	$\sigma_{p0,2}$ [MPa]	E [MPa]	A [%]
40CrMo4	950	730	211,000	18

The residual stresses induced by rolling were measured at CRF by means of an X ray diffractometer; due to the shape of the notch it was only possible to measure the values along the circumferential σ_{rc}, and not along the longitudinal direction, σ_{rl}. The surface measured value is about equal to -500 MPa. The internal residual stress pattern was measured too by removing the external layer of material by using an electro-chemical machining device. Fig. 2 shows the circumferential residual stress pattern with respect to distance from the surface along the radial direction.

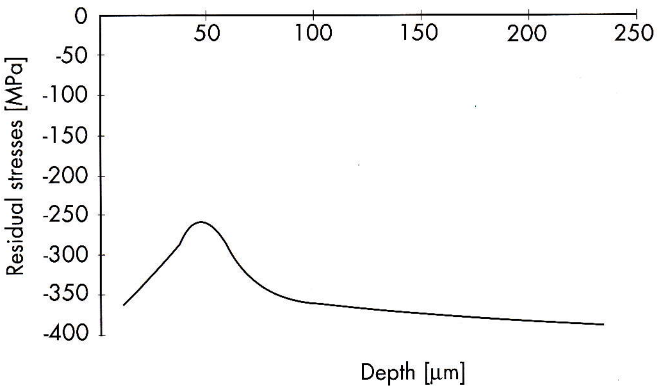

Figure 2: circumferential residual stress pattern

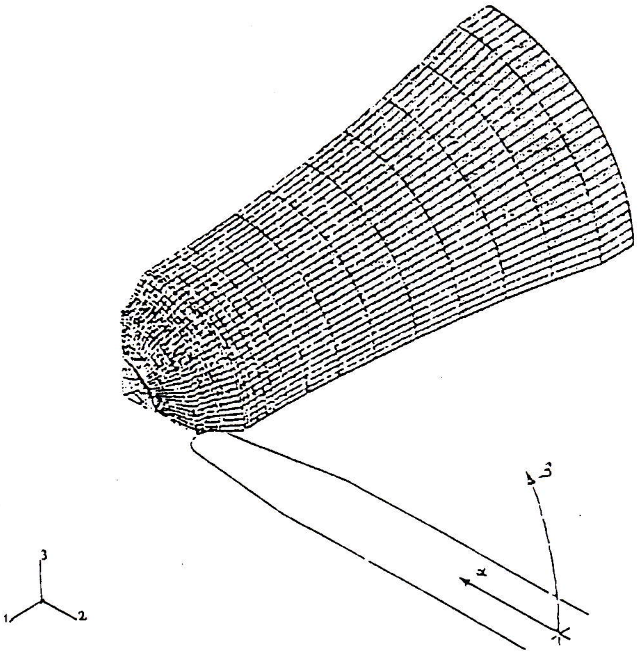

Figure 3: mesh of the specimen and of the roll

NUMERICAL MODELS

Finite element models involving contact problems are not easy to develop: in fact, the non-linear nature of these cases makes the computational solution very long and expensive. What is more, in order to validate the solution obtained, it is necessary to carry out accurate numerical tests and to make comparisons with the experimental data available.

In the case of deep rolling, these problems increase due to the fact that the rolled material is pressed with forces and contact pressure that are so high that material plasticization is caused. Furthermore, a correct simulation of the procedure must take into account not only the static pressure but also the rotation of the roll around the specimen. The problem is doubly non-linear, the computational difficulties increase and so likewise does the calculation time.

Deep rolling was simulated in three different phases: during the first, the roll is pushed onto the specimen with a load equal to the one imposed experimentally. The roll then rotates around the longitudinal axis of the specimen with the same contact load and, consequently with the same contact pressure. Finally the roll is removed from the surface of the specimen and it is now possible to evaluate the residual state of stress and strain of the specimen itself. Due to the results obtained in [9], only one load application was taken into account with a considerable saving of analysis time.

The contact between the two bodies was simulated by using special finite elements [12], [13], which permit a relative tangential displacement between the roll and the specimen and not only a static compression.

The specimen was modelled with solid elements having linear shape functions and the roll was modelled as a rigid body. Since the problem presents double geometrical symmetry only 1/4 of the specimen was modelled thus considerably cutting down on calculation time (see figure 3). The boundary conditions imposed are those of symmetry.

Initially, linear-elastic analyses were conducted, considering only the pushing of a roll with a small curvature radius. In this way the Hertz theory hypotheses are satisfied and it is possible to obtain a first validation of the model proposed by comparing the contact pressure and the stresses deriving from the contact. During this phase different models with an increasing grade of refinement were used to study the convergence of the results. When the differences between the theoretical and the numerical results did not vary significantly from one model to a finer one the refinement was stopped. The coarse mesh consists of 1018 elements and 1358 nodes while the finer one has 9533 elements and 10180 nodes.

The latter model was used for the elasto-plastic analyses that reproduced the deep rolling procedure, with the dimensions actually used. During the first step of the analysis the roll was compressed and moved away from the specimen and the actual resulting residual stress state was then analyzed.

The mechanical behaviour of the material was considered the material data shown in Table 1, as well as by considering the von Mises yielding criterium and the isotropic hardening rule. By then, assuming the same contact load, the roll was rotated around the axis of the specimen to simulate the actual rolling conditions. Because of the long calculation time only 10' of the specimen was rolled. However this rotation seems to be sufficient to correctly understand the role played by the plasticized material on the residual stress state of the treated part of the specimen. By comparing the results of the static pressing and of the rolling it is possible to determine whether the first type of analysis is sufficient to correctly simulate the deep rolling procedure in terms of residual stresses. The friction coefficient between the two contact bodies was not considered. However it is useful to remember that its influence on the residual stress state can be neglected [9]. Different analyses with different rolling loads were carried out to demonstrate the influence of the load on the residual stresses.

RESULTS

Linear elastic calculations

Two different linear elastic analyses were conducted in order to verify the numerical model. In the first, the specimen was loaded by a tensile load and the stress concentration factor was calculated and compared with the experimental value, obtained by means of a strain gauges test: agreement was good (the deviation is less than 3%). In the second one the Hertz contact problem was simulated. The contact pressure value deviation compared to the one obtained when using the Hertz formulas is 74% for the coarse model; this decreases to 11% when using the finer model. These differences tend to disappear when the stress component trend along the depth of the specimen is considered.

Elasto plastic calculations

Two different numerical analyses were conducted: the first simulates the roll that compresses the specimen and the second the roll that compresses and rotates on the specimen.

In order to simulate compression a radial load is applied on the roll; this has the same dimension of the roll used to perform the rolling; three different values of the radial load were considered: P=7,000 N, P=10,000 N, P=15,000 N, which is the actual rolling load.

In figure 4 the residual von Mises stress trend versus the radial thickness is shown: these values have been numerically calculated by imposing only the static roll compression (the roll is pushed and then removed from the specimen).

In the second type of numerical analysis rolling was simulated by means of rolling loads P equal to 7,000 N and 10,000 N; it was not possible to use the actual one (15,000 N) because its high value causes problems to achieve numerical convergence of the calculation.

In fig. 5 the deformation caused by the roll that moves on the specimen is shown: the trace of the roll can be seen.

After a 10° rotation the roll is moved away from the specimen and it is possible to obtain the values of the residual stresses. These values are those found in a radial plane far from the boundaries, in order not to feel their influence. In figure 6 it is possible to see the different values when the load changes from 7,000 N to 10,000 N. These values are larger than the mechanical strength of the material because only one component is shown, on the contrary if the von Mises equivalent stress the material mechanical behaviour is respected (figure 4).

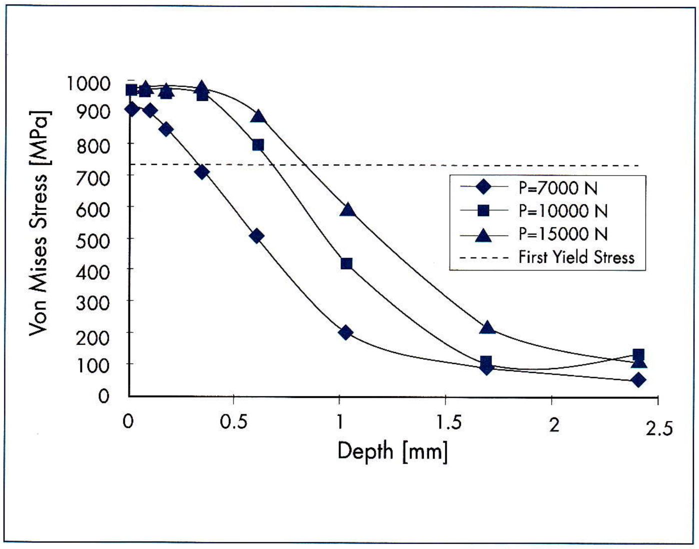

Figure 4: von Mises residual stress trend due to static compression of the roll

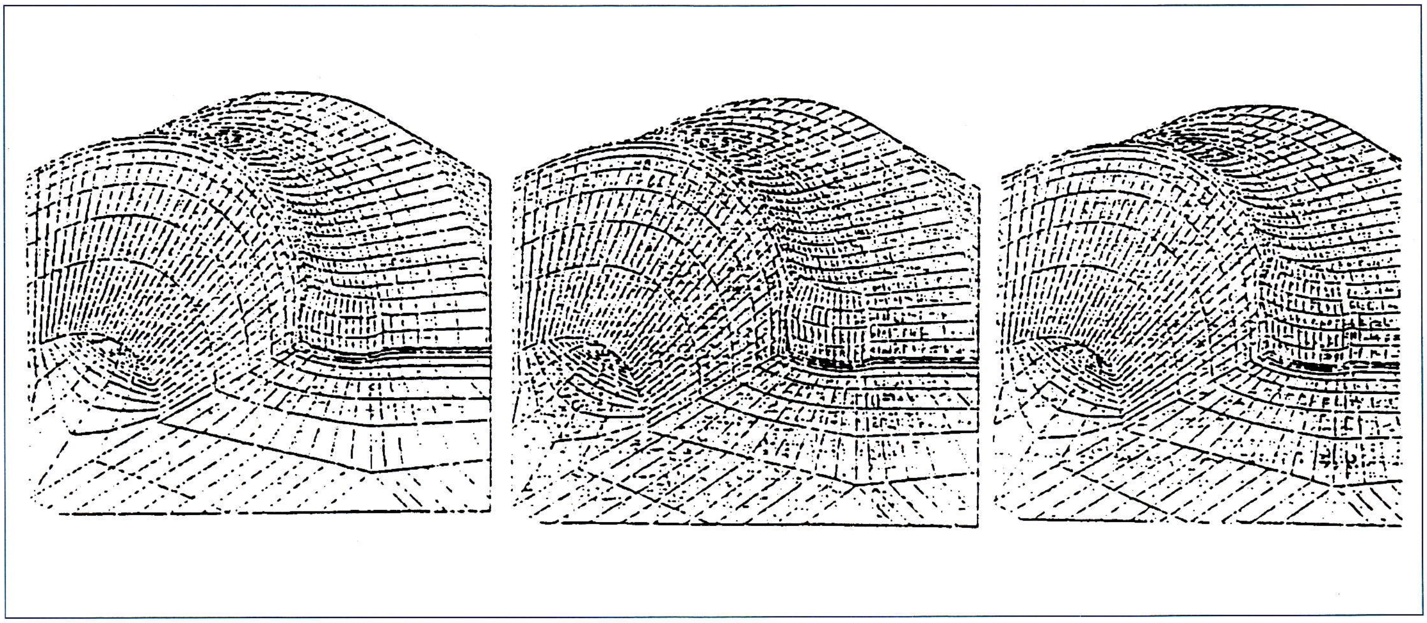

Figure 5: deformation (amplification factor equals 7) of the specimen, at different angular positions of the roll. The load is equal to 7000 N

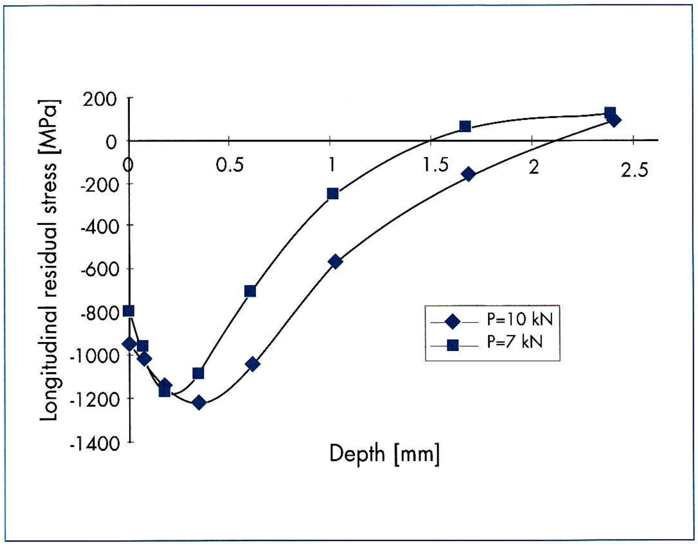

Figure 6: longitudinal residual stress pattern due to compression rolling with two different loads

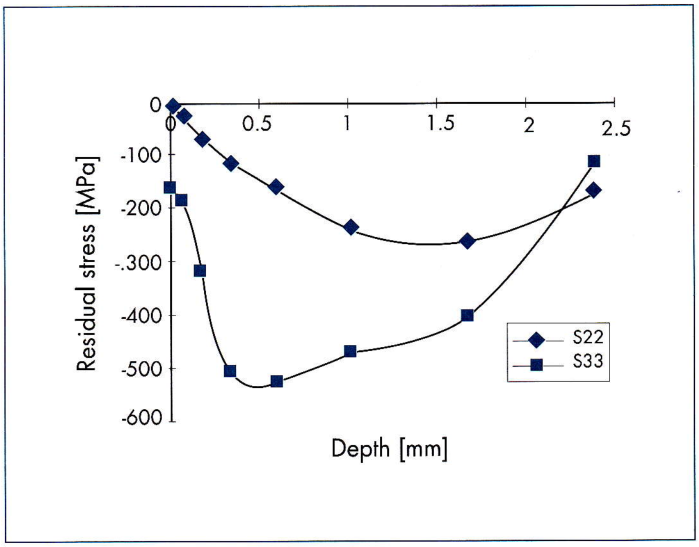

Figure 7: circumferential (S33) and radial (S22) residual stresses due to compression and rolling (P=10000 N)

If some values in this figure exceed the ultimate tensile stress it is due to the extrapolation of the results from the integration point to the external nodes.

In fig. 7 the radial and circumferential residual stress patterns are shown. It is difficult to compare the experimental results with the numerical ones because of the uncertainties of both the values and because of the different rolling load utilized due to the numerical problems encountered.

Only the circumferential values can be compared with the experimentally measured ones, in fact it was not possible to releave experimental measurements along the longitudinal direction. The surface numerical values are smaller than the experimental ones, this could be caused by the particular element type used to simulate the contact and to the boundary conditions imposed, which are an approximation of the actual situation. In fact the rolling is carried out by means of three rolls and it would be necessary to schematize one third of the specimen section. Besides the surface measurements are an average of the actual values on the layer of material interested by the X-ray beam. If the numerical value in correspondence of a depth of 0.2 mm (σ_{rc} about equal to -320 MPa) is considered, agreement can be found with the experimental trend of Fig. 2 (σ_{rc} about equal to -400 MPa).

In figure 8 the longitudinal residual stresses obtained by means of two different analyses (compression and compression with rolling) are compared. The trends are similar, both for the numerical values and the position of the maximum residual stress. The extension of the compressed zone is larger when the roll is only pushed on.

PREDICTION OF THE FATIGUE BEHAVIOUR

In order to predict the resulting fatigue behaviour the residual stress fields obtained by considering the different load values as well as the one due to a tensile load must be considered. An axial load was simulated because of the stress gradient caused by the notch. Bending and torsional loading were not considered because they require to model all the specimen with evident great increasing of the numerical dimensions of the calculation and difficulties in rolling all the surface of the specimen.

In the case of P=15,000 it was not possible to execute the compression and rolling analyses and, therefore, the results of the case with only compression has been considered. An axial load equal to 10,000 N has been considered and a finite element elastic linear calculation enables us to obtain the stress trend versus the depth measured along the radial direction. In figure 9 it is possible to note that this load induces on the surface a stress (called in figure 9 Applied Load) greater than the fatigue strength of the not rolled material.

In order to consider the actual fatigue behaviour of the specimen it is necessary to consider the longitudinal residual stresses and to superimpose them on the ones due to the applied load. In figure 9 it is possible to observe the actual trend of the stress (due to the applied load and due to the rolling) obtained for the three rolling loads considered.

From an analysis of these patterns it is possible to note that the largest rolling load is the most dangerous and would cause a fatigue crack in the subsurface layers of material. On the contrary, the residual stress field caused by the rolling load P=7,000 proves to be more favourable. In fact in this case the total stress pattern is lower than the fatigue strength of the material in the internal region of the specimen.

The residual stress relaxation was neglected bearing in mind the data reported in literature [6].

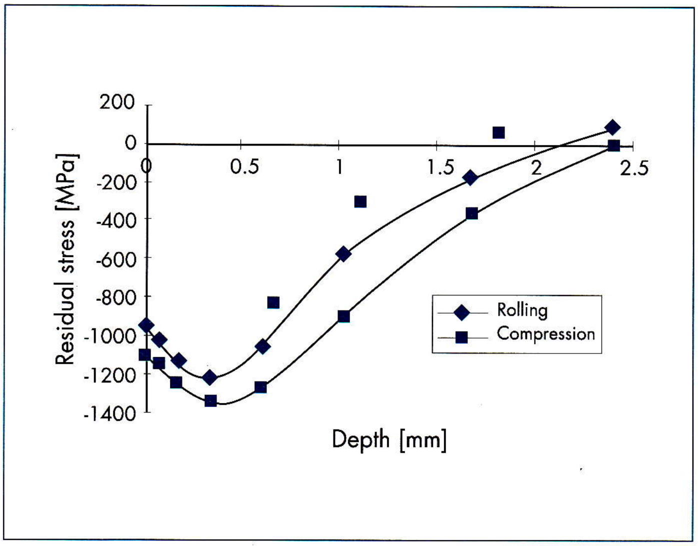

Figure 8: comparison between the longitudinal residual stresses obtained by means of the two different calculations

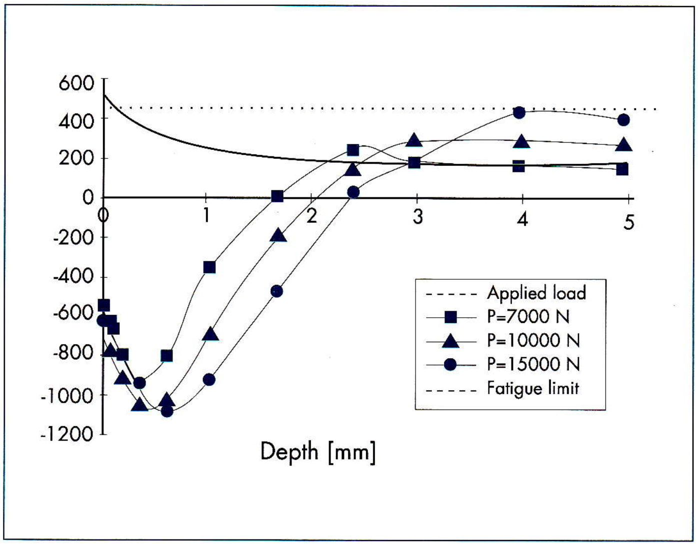

Figure 9: total longitudinal stresses (σ_{appl} + σ_{res}) versus depth, by varying the rolling load. The fatigue strenght of the material is shown (R=-1)

CONCLUSIONS

A numerical methodology to simulate deep rolling has been developed and applied to a notched specimen. The numerical results (particularly the residual stresses) have been compared with the experimental measurements. These are very difficult to carry out due to the shape of the notch: in this case the numerical calculations become very important with a view to predict the rolling effect.

Two different analyses were carried out: in the first only the static compression of the roll on to the specimen is considered while in the second the rotation of the roll around the specimen is also considered.

A comparison of these two methodologies shows that in the first case although the plasticization zone is larger the residual stress values are similar.

ACKNOWLEDGEMENTS

This research was supported by a M.U.R.S.T. grant and by ATA by means of its financial support to the thesis "Effetto della rullatura sulla resistenza a fatica di elementi intagliati" (A. Negri, C. Pulga).

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