EVALUATION OF THE RESIDUAL STRESSES ON CASE HARDENED STEEL BY X-RAY DIFFRACTION AND BLIND HOLE METHOD

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Abstract. *The aim is to evaluate the superficial residual stress condition resulting from the hard turning process of case hardened mechanical components made of DIN 21 NiCrMo 2 steel hardened with 58-62HRC. The component fatigue strength is fully associated to the residual stress condition, as many researchers have studied. The sample residual stress analysis has been experimentally conducted by two methods, the incremental blind hole technique and the X-ray diffraction method. The blind hole technique showed limitations in measuring very superficial stress values but is very useful to measure deeper stress values. The X-ray method is very accurate in superficial results but is not suitable to acquire deeper values. In order to understand their limitations and applicable fields, discussions about both results are conducted.*

Keywords*: residual stress, hard turning process, blind hole method, X-ray diffraction, case hardened steel*

1. INTRODUCTION

According to Griffiths (2001), the residual stress mechanisms generation can be represented by three models: thermal phase transformation, thermal/plastic deformation and plastic/mechanical deformation.

Residual stresses can be classified as macrostresses or microstresses, depending on the scale at which they are distributed. Their effects may be beneficial or detrimental to the component, depending on the sign, magnitude and stress distribution (Martins, 2004).

In the first model (thermal phase transformation), the residual stress is caused by a change in the structure volume. If the change causes a decrease in volume, the surface will collapse, but the core will resist. The result in this case is tensile residual stress. If the phase transformation causes an expansion, the result is compressive residual stress. In the second model (thermal/plastic deformation) the heating event causes surface expansion, and this expansion is relieved (as the heat is maintained) by the plastic flow, which is restricted to the superficial layer. In the third model (plastic/mechanical deformation), the compressive residual stress is due to the surface compression exerted by some form of mechanical action, there are no thermal effects. In cases in which only chemical events are dominant, residual stress is zero (Griffiths, 2001).

Conventional heat treatments produce residual compressive stress due to expansion in volume, which is an example of the first model. When a surface is shot peened, compressive residual stress is predominant due to the peening impacts; this is an example of the third model. Grinding produces variable residual stresses. In abusive operation condition, thermal events are dominant and tensile residual stress is the result. This is an example of the second model. In gentle unit events operation, cooling is improved and friction reduced, the unit event becomes mechanical and compressive residual stress is the result. In conventional conditions, residual stresses are as high as those obtained in abusive conditions, again due to the tendency of the predominantly thermal event (Field and Kahle, 1972). Because of the maximum residual stress similarity, the fatigue resistance limit is almost the same.

If a surface is produced by sequential operations, the final residual stress is different from the residual stress produced by a single operation. This is caused by the superposition of individual stress cases. For example, Fig. 1 shows the residual stress distribution along the sub-layer generated by hard turning followed by belt-grinding for bearing steel with 700 HV (60HRC). In Fig. 1, Grzesik et al (2006) present that the combination of two processes, belt-grinding with hard turning, created more compressive value modulus on the material surface than just the turning hard process. However, if the sequence process is reversed, the final residual stress will not be the same. This occurs because the material removal performed by hard turning will remove the belt-ground layer. The pattern and signal magnitude, as the process sequence will influence the final residual stress condition.

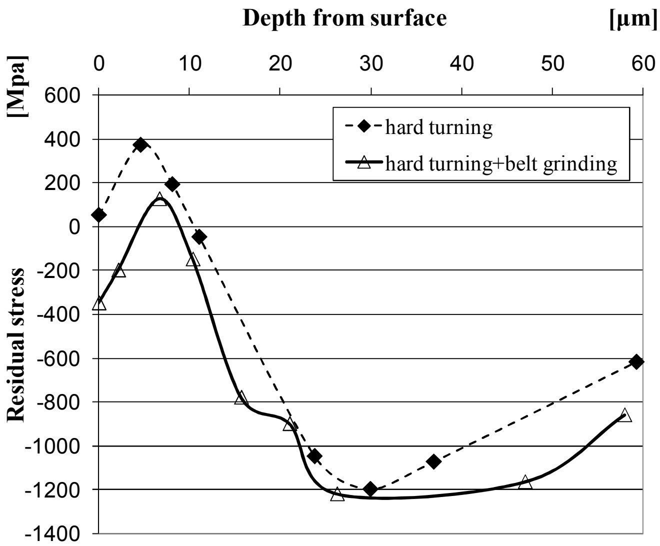


Figure 1. Residual stress profile distribution in sub-layers obtained by hard turning with cBN followed by belt grinding (Grzesik et al, 2006).

The residual stress magnitude and sign will have a significant effect on performance. For example, whereas resistance to fatigue has compressive stress, the component fatigue life will be greater than under tension stress. Metcut (1980) presented an inverse relationship between fatigue resistance and maximum residual stress in grinding processes, Fig.2.

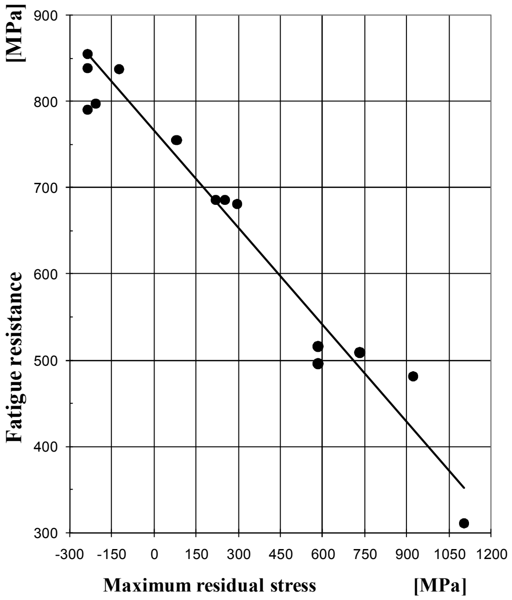


Figure 2. Residual stress and fatigue resistance (Metcut, 1980).

Matsumoto et al (1999), reported the effect of residual stresses in the performance of materials fatigue resistance subjected to grinding and turning processes in hardened material. In their study, it was demonstrated that the fatigue resistance of a part with higher compressive strain levels obtained in the hard turning process is superior compared to that of the grinding condition.

Several authors (Thiele and Melkote, 1999, Matsumoto et al, 1999, Delijaicov, 2004, Abraham, 2005, Hua et al, 2006, Javidi et al, 2008) concluded that the feed rate (f) has a strong influence on the compressive residual stress generation, being the main parameter associated condition. The depth of cut (a_p) and cutting speed (V_c) cause disagreement between the researchers, not showing a clear correlation in the residual stresses generation, not being stated as preponderant parameters. According to Matsumoto et al (1999) and Dahlman et al (2004) parameter a_p does not influence the final residual stress condition. Delijaicov, (2004) and Bordinassi (2006) indicated that the depth of cut variation (a_p) can influence the residual stress condition. Gunnberg et al (2006) mention that in one of their experiments, the V_c had a negative influence and generated tensile residual stresses. According to Rech and Moisan (2003), V_c strongly influences the final residual stress condition leading to a compressive state.

The tool tip acts against the workpiece during the machining, produces plastic deformation in the machined material, as well as friction between the tool and chip; chip friction against the piece generates thermal variations, causing alterations. According to Matsumoto et al (1999) and Guo and Wen (2004), the hard turning process has the ability to generate compressive residual stresses at greater depths when compared to the grinding process.

Thiele and Melkote (1999), Matsumoto et al (1999) and recently Hua et al (2006) and Javidi et al (2008) showed that the tool geometry edge exerts a great influence on residual stress generation. Generally rounded or chamfered edges are the most indicated. Hua et al (2006) emphasize that the preparation with more rounding radius, is the best tool condition for generating compressive residual stresses.

Compressive residual stresses can improve materials performance against external environment aggression and reduce the failure by fatigue. Yet in a manufacture line, residual stresses can lead to component distortions, making it necessary to introduce a finishing process stage, leading to expensive processes. Therefore, for desired part performance, it is important to predict and control the development of these subsurface residual stresses as a function of hard machining parameters (Umbrello et al, 2007). A typical subsurface residual stress profile is shown in Fig. 3. According to Umbrello et al (2008), Fig. 3 defines the main elements of the residual stress profile such as surface residual stress (a), maximum residual stress (b) and its distance from the surface (c) and, finally, the beneficial depth (d). This approach is very simple and useful for classifying surface residual stresses conditions produced by different parameters or manufacturing processes, and will be employed in this article.

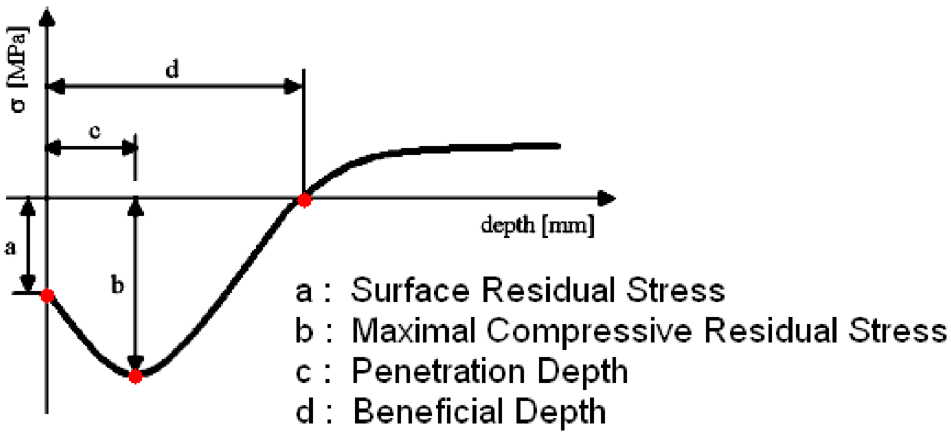


Figure 3. Main elements for a residual stress profile (Umbrello et al, 2008).

2. EXPERIMENTAL PROCEDURE

2.1. Hard turning experiments

Investigations on 6 samples made of case hardened steel DIN 21 NiCrMo 2 (ABNT 8620) were conducted, with hardness 700HV (58-62HRC) and 1.0 mm average case depth. Figure 4 presents the sample main dimensions.

The cBN insert was a TNGX110308S-WZ, low cBN content, tip radius 0.8mm, wiper geometry. Insert tool holding: CTJNL2525M11 with tool angles: position angle= 93º, cutting edge inclination angle = - 6 º, rake angle = - 6 º.

The machine was an universal CNC Turning INDEX MC400, 20kW, all the tests were conducted without cutting fluids. For each change in the pair V_c and f, the insert cutting edge was changed, so the tool wear was neglected for all tests.

Table 1 presents the cutting conditions for Cutting Speed V_c in m/min, Feed rate f in mm/rev and Constant depth of cut in millimeters.

Table 1: Cutting conditions.

	Vc [m/min]	feed [mm/rev]	Depth of cutting a_p[mm]
Condition 1	180	0.05	0.18
Condition 2	180	0.08	0.18
Condition 3	180	0.12	0.18
Condition 4	200	0.05	0.18
Condition 5	200	0.08	0.18
Condition 6	200	0.12	0.18

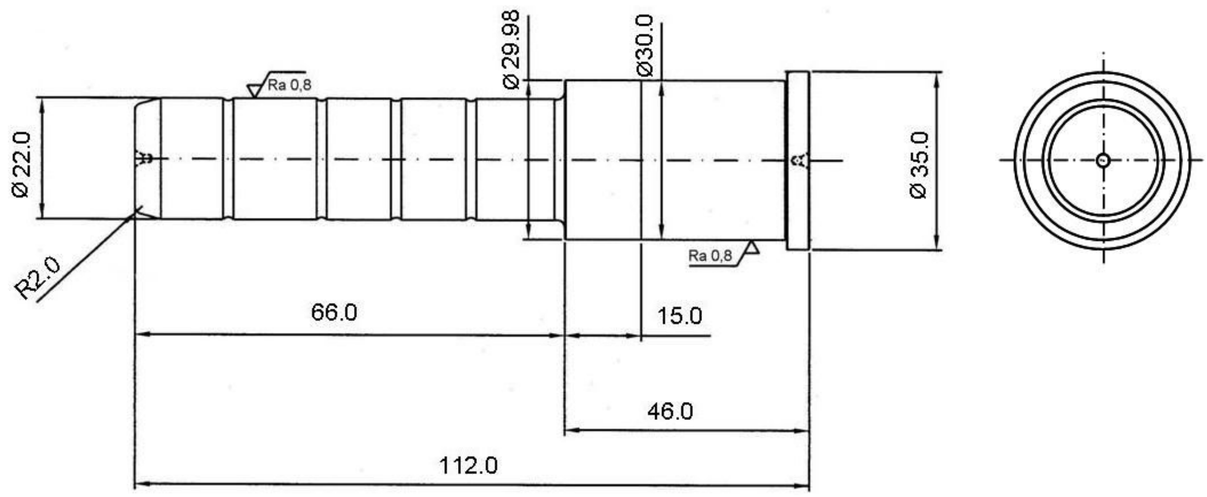


Figure 4. Sample simplified representation used in the hard turning experiment.

2.2. Residual stress with blind hole method

The experimental residual stresses have been raised in circumferential and axial direction by the blind hole incremental method using the RS-200 Milling Guide equipment from the Vishay Micro-Measurements Group, with incremental manual step for the acquisition of the deformation values at each step in the three directions known. The deformation values were processed and analyzed using the H-Drill software by integral method (Calle, 2004). Figure 5 shows the measuring equipment consisting of high speed pneumatic spindle and deformation collector Fig. 5(b), the strain gage fixed in the sample (a) and the sintered tungsten carbide drill Ø 1.8 mm.

(a) (b) (c)

Figure 5. Fixation system for the blind hole method (a) Details of the strain gage fixed in the sample (b) Equipment for residual stress measurement - high speed pneumatic spindle and deformation collector (c) Detail of sintered tungsten carbide drill Ø 1.8 mm.

The drill used has 1.85 mm diameter and the strain gage applied to the case was the 062RE manufactured by Vishay Micro-Measurements. Using the device micrometer and controlling the depth of cut, the drill is set close to the extensometer surface; at this point, all the P3 indicator channels are set to zero. The hole drilling is made carefully and slowly. At each 20 μm penetration approximately, the relief strain values shown in the indicator were recorded in a spreadsheet. The data are entered into the software H-Drill (Vishay) for analysis using the integral method. The material properties were considered uniform in all directions analyzed with constants E = 210 GPa and ν = 0.29.

2.3. Residual stress using X-ray diffraction

For X-ray diffraction measurements, a RIGAKU X-ray diffractometer was employed (DMAX Rint 2000). The sen²ψ methodology was applied with ψ starting at -60° to +60°, in steps of 10°, Cr tube, phase Fe-α and crystallographic planes (2 1 1). Material constants applied E = 210 GPa and ν = 0.29 (material properties were considered uniform in all directions analyzed). The residual stresses were measured in the circumferential direction, i.e., in tangential direction to the cutting force. Figure 6 shows the equipment.

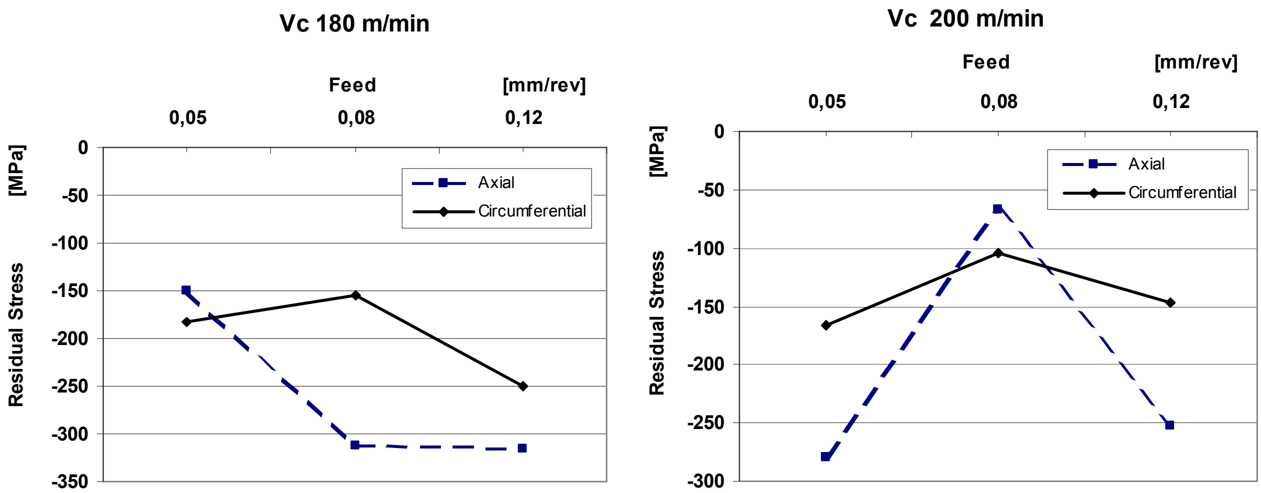
Figure 6. X-ray diffractometer, RIGAKU – DMAX Rint 2000.

For X-ray residual stresses analysis, one sample for each machine condition was used, thus six samples were machined and analyzed. In each sample, three measurements were made, and the average values were used intending to minimize readings errors.

3. RESULTS AND DISCUSSION

3.1. Residual stress with blind hole method

Figure 7 shows the surface residual stress as a function of feed rate for the two cutting speeds employed in the experiment; it is possible to note a great dispersion in the results, probably due to the measuring process. No clear correlations can be made for the cutting parameters used, due to the difficulty in setting up the blind hole device for initiating the measurement process. So as to start making the strain relieving hole, the drill has to be set up at the very sample surface. It is a difficult procedure, as it is not always possible to have the same position for all the samples with a micrometer in the device. Despite the starting imprecision of the process, the final results are in the compressive range.



(a) (b)

Figure 7. Surface residual stress (a) for V_c=180 m/min and (b) V_c=200m/min.

Figure 8 shows the maximum residual stress as a function of the feed rate for the two cutting speed employed in the experiment, the results shows that the feed rate may have some influence in the maximum residual stress value. For a feed rate of 0.05 mm/revolution, there is a great difference in the results but both are in the compressive stress values. The drill used in the blind hole device has almost the same hardness as the sample (about 10 points HRC greater), this causes the drill to wear during the hole making process, and can be a source of dispersion in the final results. Figure 8 shows that for both cutting speeds the results are in the compressive values range.

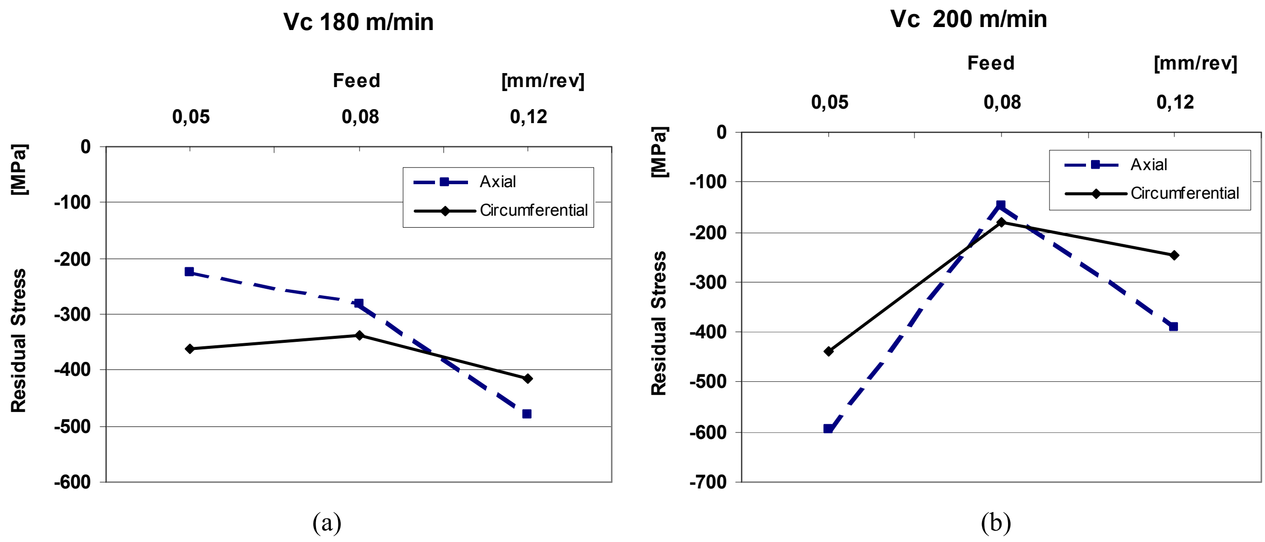


Figure 8. Maximum residual stress (a) for V_c=180 m/min and (b) V_c=200m/min.

Figure 9 shows that the maximum residual stress values were found at about 50 to 70 µm from the surface, the blind hole method is a relatively fast method for acquiring residual stress profiles that provide a better comprehension of the surface integrity and functionality. The beneficial depth is the maximum depth where it is still possible to have a compressive stress or a good residual stress condition, as presented in Fig. 10.

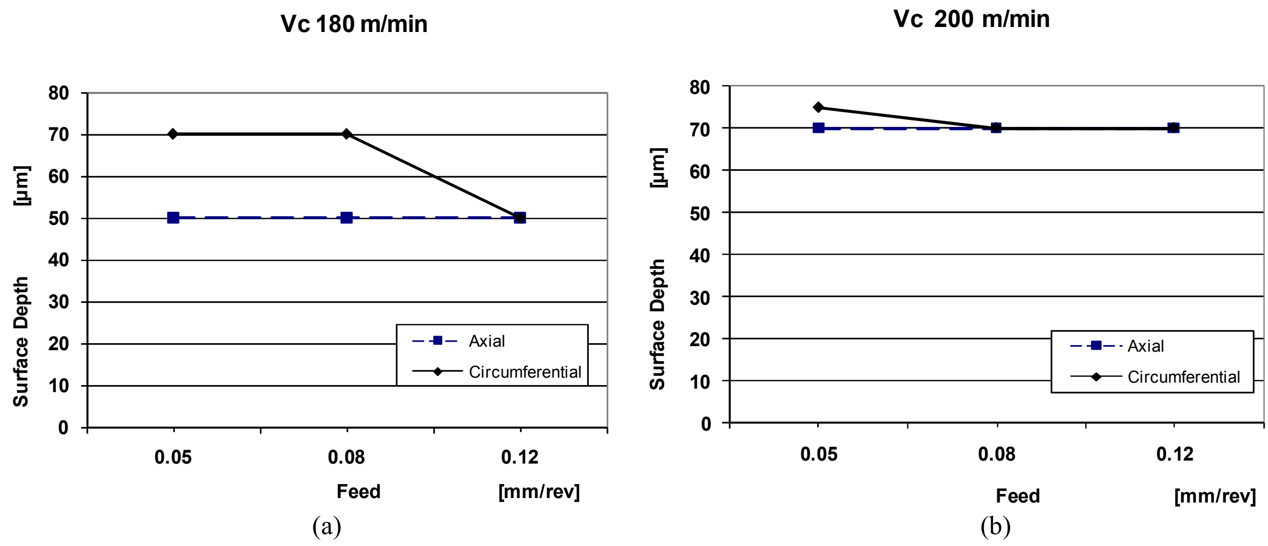
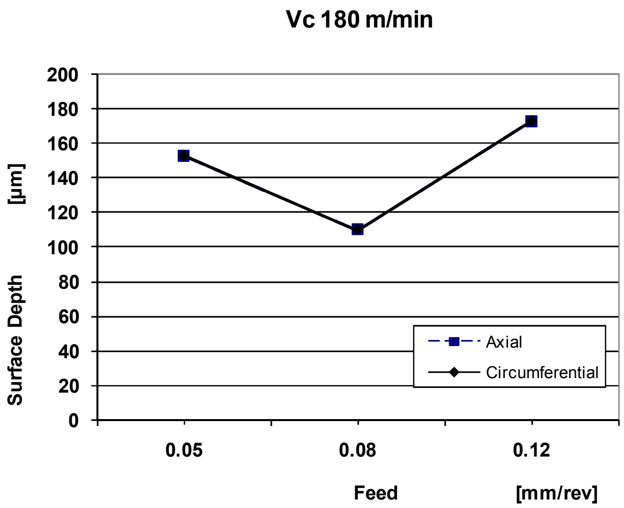
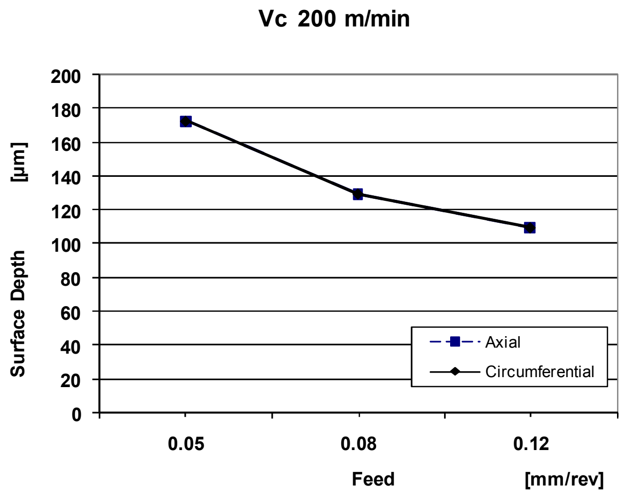


Figure 9. Penetration depth (a) for V_c=180 m/min and (b) V_c=200m/min.

For Fig. 10 results, both the axial and circumferential conditions have the same values due to an inherent condition of the method; the deep value is at the end of the drilled hole. The values for beneficial depth are in the range of 100 to 180 µm showing that the hard machining process can provide good conditions of compressive stress improving components fatigue life .



(a)



(b)

Figure 10. Beneficial depth (a) for V_c=180 m/min and (b) V_c=200m/min.

3.2. Residual stress with X-ray diffraction

Figure 11 shows the graphical analysis result of the circumferential surface residual stress, obtained according to the cutting conditions used in the experiment. For each cutting speed and feed rate, one sample was examined, and each analysis consisted in measuring in three distinct regions. Figure 11 shows the average results for each sample.

A wide dispersion in the results is presented by the bars in a confidence interval of 95%. The X-ray measurement is sensitive to the surface texture condition. The roughness can be a source of errors and dispersion observed in the results. Another fact to be noted is that the measurement was performed only in the circumferential direction, measuring the axial direction should have other values that could help to better understand the results. Despite the dispersion observed, all values are in the compressive residual stress range.

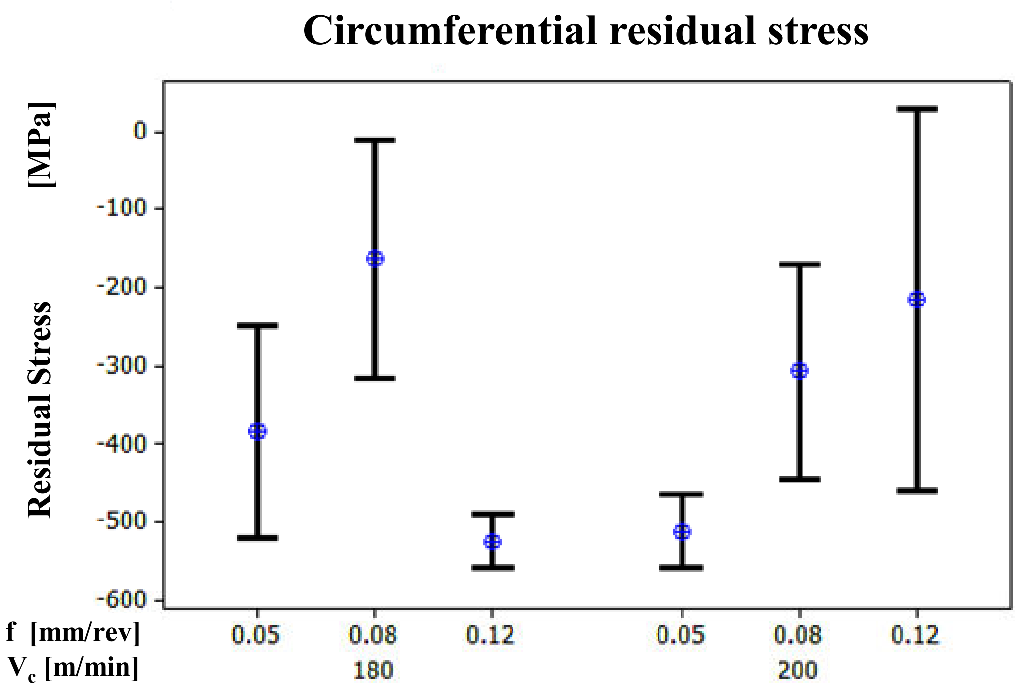


Figure 11. X-ray residual stress values for circumferential direction.

4. CONCLUSIONS

Residual stress measurements in the case of hardened components were made by the blind hole method and X-ray diffraction technique; both methods presented some dispersion in the resulting values but the compressive residual stress conditions were verified.

It is possible to verify that the X-ray method values are much more compressive than the blind hole method values, although the dispersion observed in the X-ray method. The X-ray method is a reliable method and is independent from operator's inability, as long as the part is correctly positioned and the machine is prepared (calibrated and programmed), all the measurement processes are automatically executed. The blind hole method used in this analysis is a fully manual device and therefore is operator dependent, it is thus important that all the measurements be made by the same operator who may know the process method.

For hardened parts, the correct drill hardness has to be observed, otherwise there will be problems in compensating the drill wear during the hole machining process.

The blind hole method is a practical way of having residual stress measurements made even in field applications, where is not possible to have a complex device such as an X-ray diffraction equipment. One disadvantage is that for some cases the small hole made by the blind hole method is not acceptable and the part has to be scrapped. Nevertheless, if a residual stress profile is necessary, even the X-ray technique could be a destructive method.

5. ACKNOWLEDGEMENTS

The authors would like to thank Polimold Ind. S/A for the samples supplied, the FEI University Center for the support in the residual stress measurements and laboratories use, the INPE for the X-ray measurements and Seco Tools-Brazil for the equipment and tools used in this experiment.

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