Residual stress development in hard machining - a review

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Abstract
Metal machining processes require primarily cutting tool materials with high hardness, high resistance to the abrasive wear and thermal stability. The development of cutting tool materials results in advanced tool materials such as primarily ceramics, cubic boron nitride and sintered carbides which are considered to have the ability to cut hard materials. As a finishing process, the machined surface of the final product needs to control the surface quality. The quality of machined surface can be determined by properties such as surface roughness, hardness variations, micro-structural changes, residual stresses, etc. These properties belong to the surface integrity of the work piece material. The surface integrity affects significantly the mechanical properties of the parts such as fatigue limit, stress-corrosion resistance, dimensional stability, etc. This paper presents an experimental study to analyze the evolution of residual stresses in relation to the different parameter of machining. For precision milling of hardened steel, parameters are cutting speed and feed rate with a constant depth of cut. Two different cutting tool materials were used in this study, ceramic and cubic boron nitride. The results show that residual stresses near the machined surface of hardened steel are suitable for compressive stress.

1. Introduction
Machining of hardened steel has become an important manufacturing process. Abrasive processes such as grinding have typically been required to machine hardened steels, but advances in machine tools and cutting materials have allowed precision hard milling to become a realistic substitution for many grinding applications. There are many advantages of hard machining, such as mostly increased stability, decreased cycle times, reductions in machine tool costs, and elimination of environmentally hazardous cutting fluids as discussed elsewhere [1,2,3,4].

The machining process requires cutting tool materials with higher hardness, thermal stability and also higher resistance to the abrasive wear. Advanced tool materials such as ceramics, cubic boron nitride (CBN) and some kinds of sintered carbide cutting tools are considered to have the ability to cut hardened steels. CBN tool materials show good performance during machining of hardened steel because of their hot hardness, low solubility in iron and good fracture toughness as discussed by Abrao, et al. [5].

As a finishing process, machined surfaces of the final product need to be controlled by the surface quality. The quality of machined surface can be determined by properties such as surface roughness, hardness variation, micro-structural changes, residual stresses, etc. These
properties are called the surface integrity of the machined material. The surface integrity affects significantly the mechanical properties of parts such as fatigue limit, dimensional stability, stress-corrosion resistance, etc. Figure 1, shows that properties of the machined surface have to be defined related with the cause of failure. The study of surface integrity of the machined surface in hard cutting has been the subject of research interest as discussed elsewhere [6 - 13]. Most research in machining of hardened steel has centered on hard turning especially in the areas of chip forming mechanisms and surface integrity issues of the hardened workpiece. El-Wardany, et.al. [10], investigated the effects of cutting parameters and tool wear on the chip formation mechanisms and the surface integrity during turning of hardened D2 tool steel. Tool wear has shown to have the most significant effect on the sub-surface distribution and variations of residual stress and micro-hardness. The residual stress of the machined surface strongly depends on various parameters including work hardness, phase transformation, tool wear, and cutting conditions as discussed by Liu [7].

Figure 1. The relationship between machining process and cause of failure.

Although not as extensively investigated as in turning, hard milling has received attention from the research community. Elbestawi, et al. [2] observed the effects of different process parameter on tool performances and the surface integrity of H13 tool steel. The milling forces, surface integrity, and tool wear vary with the cutting speed, type of tool inserts, and coating in the milling of H13 tool steel at 52 HRC. The high-speed milling of D2 steel in its hardened state showed that a sharp tool had a minor influence on the workpiece surface integrity as discussed by Boehner, et al. [14].

The influence of the hardness of the workpiece materials evaluated by Hua, et al. [15], found that the high workpiece hardness allows the generation of more compressive residual stresses. The statistical analysis performed by Coto, et al. [16] in turning of AISI 4340 steel states that the optimum (less tensile residual stresses) is obtained when using the lowest federate and highest cutting speed. In particular, the influence of the tool nose radius on the residual stresses during milling of Ti-6Al-4V workpiece material was recognized by Wyen, et al. [17]. Furthermore, Li, et al. [18] investigated that the compressive residual stresses in the milling of Ti-6Al-4V are higher when using higher cutting speed and feed rate.

This paper experimentally investigates the influence of cutting speeds and feed rates on the surface quality in milling of hardened steel (60 HRC). The parameter of the quality of a machined surface produced was the residual stress of the workpiece surface including surface layer.

2. Experimental Works

The objective of the present experiments was to identify the appropriate cutting condition when precision milling of hardened steel, primarily with ceramics and CBN tool materials
under different cutting conditions. Residual stresses of the prepared specimens were measured in the experimental works.

The workpiece material use in the experiments was AISI 52100 hardened steel (60HRC) with the nominal composition (wt. %): C – 0.98-1.10, Cr – 1.40, Fe – 97.50, Mn – 0.35, Si – 0.25, P < 0.25, and S < 0.25. For these tests, the workpiece materials supplied in block-sized of 110 mm x 7 mm x 6 mm. Tool inserts used in the experiments are all from SANDVIK Coromant, circle CBN – RCHT 12 04 MO CB50 and circle ceramics – RCKT 12 04 MO 6090 with the geometrical shape as iC = 12 mm and thickness 4.76 mm. Tool holders used for every single toothed cutter (fly mill) are Coromill 290, R290 –080Q27 – 12M (Dc = 80 mm) for circle CBN and ceramics. All cutting tests were performed on CNC milling machine FV25 with a programmable controller Heindenhain TNC310. All machining tests were conducted dry. The workpiece materials were machined with different cutting parameters. For ceramic cutting tools using depth of cut ap = 0.2 mm, feed-rate per tooth fz = 0.07 – 0.10 – 0.12 mm, cutting speed vc = 65 - 75 – 85 m/min. While CBN cutting tools using depth of cut ap = 0.2 mm, feed-rate per tooth fz = 0.07 – 0.10 – 0.12 mm, cutting speed vc = 115 – 140 – 160 m/min.

Residual stresses developed during hard milling were determined using beam deflection method. As a kind of mechanical method, the technique measures macro-stresses and determine residual stress profile. This measurement was done by the method of stress relieving which is based on the fact that removal of layers of material from the machined surface relieves a portion of residual stresses and disturbs the existing condition of equilibrium. This causes the remaining stresses to redistribute themselves and attain a new equilibrium by producing a change of the deflection of the workpiece. The layer removal of the workpiece is realized by electrolytic etching. Measurement of the changes in deflection using equipments in the Czech Technical University, Prague can then be used to compute residual stresses (figure 2).

![Figure 2](image_url)

**Figure 2.** Equipments used to measure residual stresses.

The electrolytic etching method is used to remove the surface layers because it allows removing layers with practically no additional stresses on the workpiece material. The method also removes a small amount of workpiece material. With removing layers of the workpiece surface, the stress equilibrium is changed and a deflection or displacement of the workpiece is produced. As the deflection is continuous, the same removal of material is also continuous. The residual stress is calculated using the layers of removed depth and deformation (figure 3). Or the individual increment of depth ΔH is calculated such a value of stress that will cause the
same deformation in case of loading by external forces. Therefore, by measuring the deflection changes, it is possible to compute the residual stresses.

![Equilibrium of residual stress profile across the beam.](image)

3. Results and discussion

Residual stresses resulting from machining operations have important aspects in assessing surface integrity. Even though such residual stresses are limited to a thin surface layer they have a direct influence on the performance of the machined component. In general, compressive residual stresses are to be preferred since they improve the fatigue life of parts and increase stress-corrosion cracking resistance, whereas tensile residual stresses are usually detrimental to these properties.

Residual stresses may be produced by inhomogenous plastic deformation induced by a mechanical and thermal load associated with the machining process. The thermal stress on the surface layer is capable to produce only tensile residual stress, but the applied mechanical load may produce both tensile and compressive residual stresses.

Results of residual stresses measured on and below the machined surface are presented in figure 4 and 5 for all testing points. It may be expected that residual stresses will be high at the surface (approximately 700 MPa, maximum) and decrease with an increase in depth below the surface. The residual stresses are generally negative (or compressive) for both ceramics and CBN tools. However, in machining with circle CBN tools [19] (figure 5), the surface layer is affected by low tensile stresses (approximately 100 MPa) for higher feed rates and cutting speed, feed rate 0.10 mm - cutting speed 160 m/min and feed rate 0.12 mm – cutting speed 140 m/min. The compressive residual stress produced in the machined surface of hardened steel was likely caused by a predominantly mechanical, rather than thermal influence.

Experimental data from figure 4 (c) and 5 (c) showed that for increasing feed rates and also increasing cutting speed caused the residual stresses to become smaller. The effect of cutting speed is usually related to the amount of heat generated during the machining process. The higher the cutting speed, the higher the cutting temperature generated. As the cutting speed increase, the residual stress will be tensile or compressive will depend on the extent of the depth of the permanent plastic deformation zone during machining. This zone depends on the stress generated by the mechanical and thermal loads in the process. If the stress does not reach the yield point of the material, compressive residual stresses will exist on the workpiece surface [7].
Figure 4. Residual stress distributions beneath the machined surface produced at a depth of cut 0.2 mm, feed rates (a) 0.7 mm, (b) 0.10 mm, and (c) 0.12 mm at different cutting speeds using ceramic cutting tool inserts.
Figure 5. Residual stress distributions beneath the machined surface produced at a depth of cut 0.2 mm, feed rates (a) 0.7 mm, (b) 0.10 mm, and (c) 0.12 mm at different cutting speeds using cubic boron nitride (CBN) cutting tool inserts.
4. Conclusions

Precision milling of the hardened steel (60 HRC) was conducted using ceramics and CBN cutting tools. The effects of feed rates and cutting speeds on the alterations of the machined surface and sub-surface were discussed. The following conclusions can be made.

- Compressive residual stresses are the most appearing on the machined surface. These stresses are high at the surface and decrease with the increase in depth beneath the surface.
- There is a tendency that increasing feed rates and cutting speed caused the residual stresses to decrease.
- Ceramics cutting tool is not so proper for intermittent cutting like face milling of the hardened steel.
- Some further works are necessary to justify this present investigation and gather with the study of surface metallurgical alteration to satisfy the quality of the machined surface.

5. References

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