Surface Integrity in Hard Machining of 300M Steel: Effect of Cutting-Edge Geometry on Machining Induced Residual Stresses

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Abstract

300M steel is widely used in the aerospace industry to manufacture landing gears due to its ultrahigh strength and high fracture toughness. Surface integrity in the hard turning process (one of the final manufacturing processes in making landing gears) can be influenced by tool geometries and cutting conditions. An experimental study is conducted on 300M steel to understand the role of cutting tool geometry and cutting conditions on surface integrity (surface roughness and residual stresses). Cutting tool geometries are varied along the nose edge region (chamfer, hone, and chamfer-hone). These varied geometries are tested at different cutting conditions to highlight the combinational complexity of cutting edges and cutting conditions in producing surface roughness and residual stresses. The results show the necessity of edge preparation in improving machining surface integrity in such a material.

Keywords: Hard machining; Surface integrity; Tool geometry

1. Introduction

It is well known that residual stresses are a natural consequence of manufacturing processes. These residual stresses, depending upon their nature, can significantly affect fatigue life, corrosion fatigue, and stress corrosion cracking with possible catastrophic consequences. Therefore, it is necessary to understand the mechanisms and the nature of the residual stresses induced during machining operations. This is especially true in the case where the safety of the component is of vital importance. In this paper, the effects of tool edge geometry on the residual stress induced by machining 300M steel (modified 4340 steel with higher silicon content) are discussed. 300M steel can exhibit both high toughness and ductility at elevated tensile strengths. The mentioned properties make this high strength steel ideal for applications like landing gears and slaps tracks in the aviation industry. However, given the role of finish machining as one of the final steps, it is important to understand how to control residual stresses in the machining process.

2. Background

During the finishing operation residual stresses are induced on the machined surface. It is well know that tensile residual stresses can reduce the fatigue life of a component [1,2] and even make some high strength steel susceptible to stress-cracking corrosion [3] that can result in catastrophic failures. On the other hand, induced compressive residual stresses can increase fatigue life and improve corrosion resistance resulting in an overall increase in safety [3]. Machining surface residual stresses have been a subject of extensive investigation by many researchers [4–8].

As early as 1950, it was well understood that residual stresses were the result of thermal and mechanical loads on the machined surface. Henriksen [9], in his extended research on the mechanisms of residual stress creation, concluded that mechanical forces are the main cause and the thermal stresses load is insignificant. Matsumoto et al. [10] while studying the effect of hardness on residual stresses carried out experiments machining 57 HRC
hardened steel with two different geometries. The first tool had a sharp edge and the second tool had a chamfer edge. A microstructure analysis showed that a thin white layer was present on the surface machined with the chamfer tool. However, the same was totally absent in the surface machined by a sharp edge. It was concluded that phase transformation was not responsible for the residual stress profile. On the other hand, the increase in hardness is correlated with an increase in the magnitude of the compressive residual stress. In a later study Matsumoto et al. [11], conducted further research to study the effect of tool edge geometry on residual stresses. Specimens of carburized case steel with hardness of 58 to 62 HRC were machined with cutting tools having four different edge geometries. The results revealed that when hardness and other cutting parameters remain constant, the plastic deformation near the cutting edge is a dominant factor in the creation of residual stresses profile. Thiele and Melkote [12] studied subsurface residual stresses on hardened AISI 52100 steel with hardness of 41 to 57 HRC. As expected, it was found that the material with a hardness of 57 HRC produce the highest residual stresses. The surface machined with the large hone yielded the most compressive residual stress profiles. This was true for all the different hardness tested. The authors concluded that, the increase in residual stress can be the result of increase in the stresses field induced by the tool. Plastic flow created by machining with large edge hone is the result of this increased residual stress profile along the cutting edge.

The previous research was focused on hone, sharp and chamfers tool edge geometries; in this paper the effect of a combination of chamfer and hone edges are studied. This paper presents a study of the effect of cutting-edge geometry on residual stresses induced by hard turning of 300M steel. The effects of other machining parameters such as feed rate and depth of cut are analyzed and their influence on the residual stress profile is presented here.

3. Experimental Setup

![Figure 1. Schematic of the experimental set up and cutting edge preparation details.](image)

The main focus of this paper is to determine the effects of cutting edge geometry on the surface integrity in hard turning of 300M steels. 300M steel workpieces were machined with three different edge geometries under constant cutting conditions in an attempt to explain the edge geometry effect on surface integrity. Ceramic inserts with chamfer, hone, and chamfer with hone geometries as shown in Figure 1 were used. The inserts were coated with a PVD TiN coating over an aluminum oxide and titanium carbonitride composite ceramic (Al2O3/TiCN). The inserts are rhomboid geometry corresponding to CNGA 432 ISO classification with a nose radius of 0.8 mm. The tool holder used to run the experiments was an ISO classification PCLNR 124 BHP with a rake angle -5° and an inclination angle -5°. The face turning (facing) tests were conducted on a HAAS® SL-20 turning center as shown in Figure 1. Round bars of 300M steel (127 mm in diameter and 50.8 mm in length) were machined without any coolant with the selected cutting tools. The experiments consisted of facing with a length of cut of 3 inches on the diameter. Two depths of cuts of 0.2 mm (low depth of cut) and 0.4 mm (high depth of cut) were used and the cutting speed was kept constant at 150 m/min for all tests. Two feed rates of 0.1 mm/rev (low feed) and 0.2 mm/rev (high feed) were used in combination with the two depths of cut and three different edge geometries. Before machining, the 300M steel bars were normalized to a temperature of 1700°F for 150 minutes in an inert atmosphere. Subsequently pieces were oil quenched followed by a double temper at a temperature of 300°F for five hours each time. Normalizing, quenching and double tempering heat treatment resulted in a hardness of 52 HRC. 300M Steel is essentially a modified AISI 4340 with a silicon content of 1.45% to 1.80%; the details of the composition are given in Table 1 [13]. 300M has very similar properties to 4340, but the addition of silicon adds more hardenability and prevents embrittlement when the steel is tempered at low temperatures.

<table>
<thead>
<tr>
<th>Alloy</th>
<th>C</th>
<th>Mn</th>
<th>Si</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>V</th>
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<tbody>
<tr>
<td>300M</td>
<td>0.40</td>
<td>0.65</td>
<td>1.45</td>
<td>0.70</td>
<td>1.65</td>
<td>0.30</td>
<td>0.05</td>
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<td></td>
<td>0.46</td>
<td>0.90</td>
<td>1.80</td>
<td>0.95</td>
<td>2.00</td>
<td>0.45</td>
<td>min</td>
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The hole-drilling method was used to measure the subsurface residual stresses in the machined work-pieces following the ASTM standard E837 [14]. The residual strains were precisely measured at the same radial distance from the center for all the machined work-pieces for consistency. The subsurface residual stresses were calculated from the measured residual strains using H-Drill® software. An optical surface profilometer
Zygo® NewView™ 5000 series along with the MetroPro™ metrology software was used to quantify the average surface roughness ($R_a$). An image zoom of 2x and 5x objective were used. A cutoff length (roughness sampling length) of 0.8 mm was used while estimating the average roughness profile as recommended [15]. $R_a$ measurements were taken at three different locations for each sample and the average of three measurements was used for this analysis. Scanning Electron Microscope (SEM) with 75x magnification was used to analyze the tool tribological aspects and their effects on the machining induced surface integrity.

4. Results and Discussion

After carefully conducting facing experiments on the HAAS® SL-20 turning center, subsurface residual stress profile and average surface roughness were measured as mentioned above. The maximum principal residual stress profile is generated for each case and used for the analysis as it is well known that the failure occurs along the maximum principal stress plane [16].

The measured machining induced subsurface residual stress profiles for the low depth of cut (0.2 mm) experiments are shown in Figure 2. The solid lines in the figure pertain to residual stresses induced by the lower feed rate (0.1 mm/rev) and the dotted lines show the residual stresses induced by higher feed rate (0.2 mm/rev). Figure 2 shows that the chamfer edge cutting tools produce higher surface residual stress compared to the hone only and chamfer-hone cutting tools. The chamfer-hone produced larger compressive residual stresses compared to hone only tools. The combination of chamfer edge and hone edge effectively produced better (compressive) residual stresses.

The residual stress formation due the edge preparation can be attributed to the ploughing action, and the thermal gradients due to the large local negative rake angles. The chamfer edge, hone edge, and chamfer-hone edge produces higher local negative rake angles, due to which higher cutting forces and temperatures are produced. These forces and temperatures primarily affect the machining induced residual stress formation. The mechanical loads tend to induce compressive residual stresses, while the thermal loads induce tensile residual stresses [17]. At lower feed rate, the thermal effects on the residual (higher) stress formation can be observed in Figure 2. At low feed rate (0.1 mm/rev) the tool movement is relatively slow, thereby allowing more time for the heat generated during the machining process to effect the subsurface. The effect can be seen in higher subsurface residual stress formation. Apparently, the chamfer edge and the hone edge produced tensile subsurface residual stresses at lower feed due to thermal dominance over the ploughing action along the cutting edge.

The chamfer tool produced a predominantly a tensile residual stress profile, with a peak residual stress of 202.5 MPa. The hone only edge produced a tensile surface residual stress (47 MPa) but the residual stress profile is predominantly compressive. The peak residual stress due the hone edge is compressive in nature (-138 MPa). The chamfer-hone on the other hand produced a higher compressive surface residual stress (-358.28 MPa) and peak residual stress (-358.28 MPa). In the chamfer-hone tools, the subsurface residual stresses tend to be compressive, possibly due to larger mechanical loading than the chamfer and hone edge tools. It is well established that a chamfer-hone edge produces higher cutting forces than chamfer and hone edge alone, the same was observed in the measured machining cutting forces. Also the chamfer-hone has higher local negative rake angles, thereby inducing more compressive residual stresses in hard machining [4].

Additionally, the location of the hone in the chamfer-hone and hone only tools is near the flank surface, thereby, more material is ploughed underneath the cutting edge into the just machined surface. It is reported in the literature that hone radius creates subsurface plastic flow, which in turn produces a compressive subsurface [12]. The hone edge ploughing effectively induces compressive loads into machined surface. Thus the hone only tool generated more compressive residual stresses than the chamfer (sharp edge near the flank face) only tool. This process also produces a material side flow as observed by Kishawy and Elbestawi at lower feed rates and higher rake angles [18]. Material side flow effect on the surface integrity is discussed in detail later in this paper.
At higher feed rate (0.2 mm/rev), the cutting tool moves relatively faster, thereby providing lesser time for the heat generated to affect the just machined subsurface; here a lower or more compressive residual stresses was generated. A similar trend is observed in hard machining of AISI 52100 steels by Dahlman et al. [4]. At higher feed rates, higher cutting forces are produced along with a larger plastic deformation thereby contributing to more compressive residual stresses [4]. The peak and surface residual stresses for all the three cutting tools were compressive with high feed rate (0.2 mm/rev) and low depth of cut (0.2 mm). The peak and surface residual stress for chamfer, hone and chamfer-hone tools are -412.7 MPa, -456.8 MPa and -703.5 MPa respectively. Even at higher feed rate, the chamfer-hone tool produced better subsurface residual stresses due to its high local negative rake angles.

Also, from the microscopical evidence (images from SEM at 75x magnification of the cutting edge as shown in Figure 3) the tool-chip contact is larger for higher feed rate as expected, and the complete chamfer land has been utilized. The complete utilization of the chamfer land increases the ploughing action which emphasizes the compressive mechanical effect. The result is seen in the subsurface residual stresses. The same effect is seen for the chamfer-hone cutting tools as well.

Maximum principal residual stresses induced by machining 300M steel at high depth of cut (0.4 mm) are plotted as shown in Figure 4. Machining 300M steel at high depth of cut with hone only tools resulted in chipped (broken) edges as shown in Figure 5. The exact instance of chipping is difficult to determine, hence the results from the hone only edges at higher depth of cut are not considered in the analysis. The hone only edges chipped for both the feed rates (0.1 mm/rev and 0.2 mm/rev) at higher depth of cut. Thereby the 0.4 mm depth cut is established as too high for machining 300M steel for the hone only edged ceramic tool. Figure 4 also shows the maximum principal stresses induced before machining the work-pieces. These residual stresses are induced pre-machining by the heat treatment process described in Section 3. All the machining experiments reduced the residual stresses from the pre-machined state, thus effectively improving the subsurface integrity.

Figure 4 shows that the chamfer-hone tools produces higher compressive residual stresses compared to chamfer tools. The surface residual stresses for chamfer-hone tools are -72.3 MPa and -717.9 MPa at 0.1 mm/rev and 0.2 mm/rev feed rates respectively. The surface residual stresses for chamfer only tools are -121.3 MPa and 136.4 MPa at 0.1 mm/rev and 0.2 mm/rev feed rates respectively. The scenario of chamfer tool producing better surface residual stresses than chamfer-hone is observed at low feed (0.1 mm/rev) and high depth of cut (0.2 mm/rev). This can be explained by the crater wear formed on the chamfer-hone edge as shown in Figure 5. The crater wear formation can be explained by the fact that chamfer-hone tools produce higher forces and higher temperatures along the tool chip contact area, thereby higher frictional load along the tool-chip contact area leading to wear. At low feed rate, the chip flow along the tool is assumed to have enough time for diffusion process along the tool-chip contact area. Also, 300M steel has high strength at elevated temperatures exerting higher pressure along the tool-chip contact area leading to crater wear. A detailed tool wear
study is planned for a later stage to understand the tool wear progression and is considered out of scope for the present paper. Thus with crater wear along the chamfer land, higher residual stresses were formed near the subsurface by chamfer-hone tools.

The feed rate effect remained same at higher depth of cut as well. The higher feed rate (0.2 mm/rev) produced more compressive residual stresses compared to lower feed rate (0.1 mm/rev). The same explanation given above (for low depth of cut) is attributed to residual stress formation for higher depth of cut. The fact that the depth of cut has minimal effect on residual stress formation [4] is established again, but at higher depth cut tool damage and tool wear was seen.

The machining induced surface residual stresses developed in 300M steel are compared in Figure 6 to summarize the effect of the cutting edge geometry. The chamfer-hone out performs the chamfer only and hone only cutting tools. Even with a crater wear at low feed and high depth as well, a compressive surface residual stress is induced by the chamfer-hone tool. Also, the hone only cutting edge produced better surface residual stresses than chamfer only cutting edge. The same trend is observed for all the experiments except for the broken hone edges at higher depth of cut. The residual stress formation is explained by the ploughing effect of the hone edge and the high local negative rake angles. The effect of the feed rate and depth of cut was also analyzed and followed the trend observed by the previous researchers.

The effects of tool edge geometry on machining generated average surface roughness ($R_a$) are shown in Figure 7. The chamfer edge cutting tool produced lower surface roughness values as compared to hone only cutting tool and chamfer-hone edge cutting tool. The theoretical machining surface roughness ($R_a$) was calculated using equation (1) given below.

$$R_a = \frac{f^2}{32R_e}$$

$f$ is the feed rate and $R_e$ is the nose radius. The theoretical surface roughness values are 0.39 μm for the feed rate of 0.1 mm/rev and 1.56 μm for the feed rate of 0.2 mm/rev. It was observed that the measured surface roughness were higher than theoretical surface roughness. Similar results have been observed by Thiele et al [12]. It was demonstrated that the edge hone tools create a significant subsurface plastic flow. Additionally, the same effect is not observed in cutting tools with chamfered tools without hones edges.

During the cutting operation, the increased interaction between the cutting edge and the material causes the material to be pushed to the side of the cutting edge. At higher negative rake angles and lower feed rates, the material underneath the cutting edge plastically deforms at higher temperature and behaves like a viscous liquid [18]. The plastically deformed material is squeezed out of the cutting edge region as material side flow [18]. This mechanism increases the height of the peaks of the cut profile resulting in an increase of surface roughness. It can be concluded that the effect of the hone radius has a bigger impact on side plastic flow than chamfer geometry. This same mechanism is not present in the case of the chamfered tool without hones. As a result the surface roughness of the chamfer tool follows more closely to the values of the theoretical roughness. The tool edge geometry play an important role in the surface roughness but still the feed is the dominant mechanism.

![Figure 6. Surface residual stresses (MPa) induced in 300M steel with coated ceramic tools.](image1)

![Figure 7. Average surface roughness (μm) generated by machining 300M steel with coated ceramic tools.](image2)
which is effect on the surface integrity. The chamfer-hone and that the edge preparation has profound and complex standard [19]. The performance of different cutting-edge roughness, residual stresses, etc. as per ANSI B211.1 geometry is very complex as for example, the chamfer -hone produces good subsurface residual stresses, but the edge geometries with each other. For example, the chamfer edge geometry produced better surface roughness compared to the other edge preparations, thus it is deemed as the ‘best’ then followed by hone edge, which is deemed ‘good’ and chamfer-hone is considered ‘bad’ with respect to other tools. From Table 2, we can see that the selection of appropriate cutting edge geometry is very complex as for example, the chamfer-hone produces good subsurface residual stresses, but the effect on surface roughness and tool life is not as good when compared to chamfer only cutting tool.

In conclusion, an experimental study to understand the effects of edge preparation on machining induced surface ingrity is conducted. Also, the effects of the feed rate and depth of cut are also studied. The results show that the edge preparation has profound and complex effect on the surface integrity. The chamfer-hone and hone tools (at low depth of cut) produced compressive natured residual stress profiles, but generated a higher surface roughness. The ploughing action of the cutting edge and subsequent material side flow induced compressive surface residual stresses but it increases the average surface roughness. At higher depth of cut (0.4 mm) the hone only tools chipped, while crater wear was observed on the chamfer-hone tools. The chamfer tools produced tensile residual stresses due to the thermal dominance and lower compressive ploughing effect. However, the chamfer only tools produced better surface finish and displayed better tool tribological performance.

This study has highlighted the intricate effect of feed rate on subsurface integrity, the higher feed rate induces more compressive residual stresses, but higher surface roughness. The depth of cut had minimal effect on the surface integrity, but it affected the tool wear and tool damage. Thus, the subsurface integrity generated by the different edge geometry has exposed the combinational complexity involved in selecting an appropriate cutting tool and cutting conditions for machining 300M steel.

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References


