CHAPTER 4

MACHINING OF HARDENED STEELS

4.1 Introduction

Turning of hardened steel is an economical method of generating a high quality machined surface. The high potential of hard machining is to increase productivity, to offset environmental concerns by using dry cutting as well as its competitiveness with grinding processes, have generated a significant industrial interest. Traditionally, grinding was the preferred method for finish machining of hardened steels. The advent of super hard tool materials has made it possible to avoid the traditional machining practice for hardened steels. Although a high surface quality has been achieved, industrial application of this technology is still rather limited. This is due to the uncertainties related to the integrity of the surface produced and the resulting part accuracy. Surface quality and integrity of hard machined parts are affected by many factors such as process variable, tool wear and so on.

In view of the growing engineering applications of these hardened steels, a need for detailed and systematic study of their machining characteristics and machinability is envisaged. By controlling the machining parameters, the intended surface finish, reduced tool wear and reduced cutting forces can be obtained. In the current chapter, experimental results obtained at various cutting conditions such as cutting speed, feed rate, depth of cut and cutting time are discussed. The responses considered are machining force, power required, tool wear and tool life, chip formation and surface roughness. Three types of cutting tools viz. multilayer CVD coated carbide, mixed ceramic and PVD coated ceramic tools were used for dry turning of hardened AISI4340 steel (48HRc) and AISI H13 steel (54HRc).
4.2 Effect of Cutting Parameters on Cutting Forces

Force measurement in metal cutting is an essential requirement as it is related to machine part design, tool design, power consumption, vibration, part accuracy and other influential factors. Measuring the cutting force tends for understand the cutting mechanism such as the effects of cutting variables on the cutting force, the machinability of the work piece, the process of chip formation, tool wear, quality of machined surface and accuracy. In the present study, influence of cutting parameters on machining forces during dry turning of hardened AISI 4340 and AISI H13 steels with different cutting tools are studied. The three types of machining forces namely cutting force \( (F_c) \), thrust force \( (F_t) \) and feed force \( (F_f) \) were measured.

4.2.1 Effect of Cutting Speed

Fig. 4.1(a), (b) and (c) shows the results of cutting forces at different cutting speeds when turning of hardened AISI 4340 and AISI H13 steels with different tools at constant feed rate of 0.14 mm/rev and depth of cut 0.6 mm respectively. Fig. 4.1(a) reveals the variation of cutting forces against cutting speed for the turning of both the steels with multilayer coated carbide tool at constant cutting time of 4min. It can be observed that the cutting forces decreases with increasing cutting speed in turning of hardened AISI 4340 and H13 steels. It perhaps due to increase in temperature at the shear plane region leads to the plastic softening of shear plane and hence reduces shear strength of the material (Lima et al., 2005).

It is observed that the cutting force \( (F_c) \) is highest among all the components of cutting forces measured during hard turning of both the steels. As shown in Fig. 4.1(a), the trend observed shows that the cutting force \( (F_c) \) has decreased with increase in cutting speed of 80 m/min to 260m/min. The thrust force \( (F_t) \) was found to
be decreased with increase in cutting speed till 200 m/min. However, relatively less
decrease in thrust force was observed with further increase in cutting speed. Similarly
feed force ($F_f$) decreased until the cutting speed of 200 m/min, further increase in
cutting speed results in approximately steady state of feed force ($F_f$). Thus depicts the
critical limit of cutting speed within considered range of machining conditions for
studied materials. Cutting speed between 200 m/min to 260 m/min increases the
interface tool-chip temperature, which softens materials to be cut. Consequently,
limits the shearing forces in shear zone, hence tool-chip contact was reduced (Lima et
al., 2005). The reduced tool-chip interaction caused the steady state of thrust force ($F_t$)
and feed force ($F_f$).

Figure 4.1 (a) Variation of cutting forces with cutting speed for the turning of
hardened AISI 4340 and H13 steels with multilayer coated carbide tool at
constant cutting time of 4 min., (Symbols: M1: AISI 4340 steel; M2: AISI
H13 steel, $F_c$: cutting force, $F_t$: thrust force and $F_f$: feed force)
Figure 4.1 (b) Variation of cutting forces with cutting speed for the turning of hardened AISI 4340 and AISI H13 steels with mixed ceramic tool and (c) coated ceramic tool at constant cutting time of 4 min. (Symbols: M1: AISI 4340 steel; M2: AISI H13 steel, $F_f$: cutting force, $F_t$: thrust force and $F_c$: feed force)
It is observed that during machining of both the steels, the increase in cutting speed from 80 m/min to 260 m/min resulted in the decrease of cutting forces in the range of 25% to 34%. The results show that the cutting forces of hardened H13 steel (54HRc) are slightly higher than of hardened AISI 4340 steel (48HRc). The results showed that, at low cutting speed of 80 m/min cutting forces of H13 steel is slightly higher (about 12-15%) than AISI 4340 steel, but at higher cutting speed of 260m/min, the cutting forces of H13 steel is about 8-11% higher than AISI 4340 steel. The H13 steel possesses higher strength and hardness of the material and also more brittleness compared to AISI 4340 steel. Hence cutting forces were observed higher during turning of H13 than AISI 4340 steel. Similar results were observed in mixed ceramic and coated ceramic tool (Fig. 4.1(b) and Fig. 4.1(c)).

It is also observed in Fig.4.1(a), the multilayer coated carbide tool exhibit slightly higher cutting forces than the mixed ceramic tool (approximately 10% to 18% as in Fig.4.1(b)) and coated ceramic tools (around 20-28% as in Fig.4.1(c)). It indicates that the coated ceramic tool exhibits higher wear resistance and lower heat generation than the multilayer coated carbide tool and mixed ceramic tool. It defeats that there is significant influence of hardness of the cutting tools and coating materials.

From the above results, it is evident that while hard turning of different steels, the cutting forces have high influences on the process. The cutting forces were higher at low cutting speeds and reduced as the cutting speed increased. At low cutting speeds, higher cutting forces were encountered due to low cutting temperature and built up edge (BUE) formation. High cutting speed results in high temperature in turn reduces the forces due to thermal softening of work piece materials.
4.2.2 Effect of Feed Rate

Fig. 4.2 (a), (b) and (c) shows the variations of cutting forces with different feed rates when machining AISI 4340 and H13 steels at a constant cutting speed of 140 m/min and depth of cut of 0.6 mm. Fig. 4.2(a) show the results of cutting forces against feed rate for multilayer coated carbide tool. It can be observed that the cutting forces significantly increases with increasing feed rate in turning of both the steels. As the feed rate is increased, the region of sheared chip increases, since resistance to material rupture is higher, hence requires larger efforts for chip removal (Yallese et al., 2009; Lima et al., 2007).

Figure 4.2 (a) Variation of cutting forces with feed rate for the turning of hardened AISI 4340 and H13 steel with multilayer coated carbide at constant cutting time of 4min. (Symbols: M1: AISI 4340 and M2: AISI H13 steel)
Figure 4.2 (b) Variation of cutting forces with feed rate for the turning of hardened AISI 4340 and AISI H13 steel with mixed ceramic and (c) coated ceramic tool at constant cutting time of 4 min. (Symbols: M1: AISI 4340 steel; M2: AISI H13 steel)
The results show that the increase in the feed rate from 0.06 to 0.26 mm/rev, the cutting forces increases around 76 to 84\% in multilayer coated carbide tool, 60 to 68\% in mixed ceramic tool and 52 to 62\% in coated ceramic tool respectively for both the steels. It perhaps due to the increase of feed rate induces a larger volume of the material to cut in a same unit of time, besides establishing a dynamic effect on the cutting forces. It also leads to corresponding increase in the normal contact stress at the tool chip interface and in the tool chip contact area. Hence cutting forces were found to be increased with the increase in feed rate. Similar results were observed in mixed ceramic tool and coated ceramic tool (Fig. 4.2(b) and Fig. 4.2(c)).

The machining results also show that the cutting forces of hardened H13 steel are slightly higher (around 15 to 25\% in Fig. 4.2(a)) than the AISI 4340 steel with multilayer carbide tool. Similarly, for mixed ceramic tool (around 11 to 18\% in Fig. 4.2(b)), and coated ceramic tool (around 10 to 14\% in Fig. 4.2(c)) respectively. It may be due to the influence of tool material composition and thermal properties of the tool. From the above results, it indicates that increase in feed rate causes the increase the cutting force ($F_c$) and thrust force ($F_t$). However, the feed force ($F_f$) does not significantly influence during turning of both the steels at constant cutting speed 140 m/min and depth of cut 0.6 mm.

4.2.3 Effect of Depth of Cut

Fig. 4.3(a), (b) and (c) shows the variation of cutting forces at different depth of cut when turning of hardened AISI 4340 and H13 steels at constant cutting speed of 140 m/min, feed rate of 0.14 mm/rev and cutting time of 4 min respectively. It is observed that the cutting forces increases linearly with increase in depth of cut. It may be due to the fact that, increase in depth of cut results in increased tool work contact
length. Subsequently, chip thickness becomes significant that causes the growth of the volume of deformed metal and that requires greater cutting forces to cut the chip.

The results shows that the increase in the depth of cut from of 0.3 to 1.2 mm, the cutting forces increases around 75% to 90% in multilayer coated carbide tool, 64% to 78% in mixed ceramic tool and 48% to 62% in coated ceramic tool respectively for both the steels. The results show a trend that the cutting forces of H13 steel is higher than the AISI 430 steel with multilayer coated carbide, mixed ceramic and coated ceramic tools. As shown in Fig. 4.3(a) at the small depth of cut of 0.3mm, the cutting forces of hardened H13 steel is about 5.0% to 12.0% higher than that of AISI 4340 steel, but the cutting force of H13 steel is about 15% to 28% higher than AISI 4340 steel at the large depth of 0.26mm. It is also observed that the increase in depth of cut causes the increases cutting forces. Especially cutting force \( (F_c) \) and thrust force \( (F_t) \) are dominant followed by the feed force \( (F_f) \). It is indicated that the difference between cutting force values of the H13 steel and AISI 4340 steel is greatest when using larger depth of cut and high hardness of the work piece.

![Figure 4.3(a)](image)

**Figure 4.3(a)** Variation of cutting forces with depth of cut for the turning of AISI 4340 and AISI H13 steel with multilayer coated carbide at constant cutting time of 4min., (Symbols: M1: AISI 4340 steel; M2: AISI H13 steel)
Figure 4.3 (b) Variation of cutting forces with depth of cut for the turning of hardened AISI 4340 and AISI H13 steel with mixed ceramic tool and (c) coated ceramic tool at constant cutting time of 4 min. (Symbols: M1: AISI 4340 steel; M2: AISI H13 steel)
4.2.4 Effect of Cutting Time

Fig. 4.4(a), (b) and (c) shows the variation of cutting forces with cutting time for turning of hardened AISI 4340 and H13 steels with multilayer coated carbide, mixed ceramic and coated ceramic tools at a constant cutting speed of 140 m/min, feed rate of 0.14 mm/rev, depth of cut of 0.6 mm. It is observed that the cutting forces increase with increasing cutting time for both the steels at given cutting conditions. It can be seen that the multilayer coated carbide tool exhibits higher cutting forces than the ceramic tools in turning of both the steels. In addition, the trends of cutting forces of H13 steel are higher than the AISI 4340 steel. This is due to the progressive wear caused by higher friction force generated between tool and work piece.

Figure 4.4(a) Effect of cutting time on cutting forces in turning of AISI 4340 and AISI H13 steel with multilayer coated carbide at constant cutting at \( V_c = 140 \text{m/min}, f = 0.14 \text{mm/rev} \) and \( d = 0.6 \text{mm} \)
Figure 4.4 (b) Effect of cutting time on cutting forces in turning of AISI 4340 and AISI H13 steel with mixed ceramic and (c) coated ceramic tool at constant cutting at \( V_c = 140 \text{m/min} \), \( f = 0.14 \text{mm/rev} \) and \( d = 0.6 \text{mm} \)
As shown in the Fig.4.4 (a), (b) and (c), there is a tendency for cutting force (around 11% to 15%) and thrust force (around 25% to 33%) increases with the increase in cutting time. The reason for these results obtained with constant cutting parameters, it is important to note that a progressive degradation of the tool corresponds to the rise in the cutting forces. The tool material composition and properties are crucial to the behavior of machining forces, which in turn affect tool life (Huang and Liang, 2003). Therefore, performance of cutting tools is directly affected by process parameters.

It can be concluded that the cutting force is important in machining because they provide distinctive signature of the mechanics of machining. It plays an important role in determining the energy consumed and machining power requirements of process, tool and work piece deflections. In hard turning, because of the high hardness of the work piece, it results in higher cutting forces than usual and this reduces the performance of the cutting tool.

4.3 Effect of Cutting Parameters on Machining Power

Fig. 4.5 (a), (b) and (c) shows the variation of machining power with different cutting parameters for the machining of hardened AISI 4340 and AISI H13 steels using different cutting tools at constant cutting time of 4min. Fig. 4.5 (a) shows the results of machining power with different cutting speeds for AISI 4340 steel and H13 steel at constant feed rate of 0.14mm/rev and depth of cut of 0.6mm. The results indicate that the increase in the cutting speed from 80m/min to 260m/min, the machining power increases for both the steels with different cutting tools.
Figure 4.5(a) Effect of cutting speed and (b) Effect of feed rate on machining power in turning of hardened AISI 4340 and AISI H13 steel at constant cutting time of 4 min., (KCP05: Coated Carbide; KY1615: Mixed Ceramic tool; KY 4400: Coated Ceramic; M1: AISI 4340 Steel; M2: AISI H13 Steel)
Fig. 4.5(b) shows the results of machining power with different feed rates for AISI 4340 steel and H13 steel at constant cutting speed of 140m/min and depth of cut of 0.6mm. It can be observed that the feed rate increases from 0.06mm/rev to 0.26mm/rev, the machining power increases in multilayer coated carbide tool. Similar results were observed in mixed ceramic and coated ceramic tools. At the lower feed rate, abrasive marks are observed on the rake face and flank wear land. It indicated that at lower feed rate, abrasive wear was the dominant wear mechanism in multilayer coated carbide tool.

Fig. 4.5(c) shows the results of machining power with different depth of cuts for AISI 4340 steel and H13 steel at constant cutting speed of 140m/min and feed rate of 0.14mm/rev. The results show that the increase in the depth of cut from 0.3mm to 1.2mm, the machining power increases for both the steels with different cutting tools. It indicates that at lower cutting parameters, there is a small resistance to cutting tool,
and while at the higher cutting parameters, the work material offers more resistance to cutting tool thus increasing the friction. Hence, the cutting force increases due to increase in friction, which in turn increases the machining power. When the feed rate or depth of cut are increased with the increase of cutting velocities, high power were required to deform the material within short period of time. From the above discussion, it is clear that the machining power can be minimized by employing lower values of cutting speed, feed rate and depth of cut. Similar discussion can be found elsewhere (Gaitonde et al., 2009).

4.3.1 Effect of Cutting time on Machining power

Fig. 4.6 shows the variation of machining power with cutting time for turning of hardened AISI 4340 and H13 steels with different cutting tools at a constant cutting speed of 140 m/min, feed rate of 0.14 mm/rev, depth of cut of 0.6 mm. The results showed that the machining power increase slightly with increasing cutting time for both the steels at given cutting conditions. It is observed that the multilayer coated carbide tool exhibits higher machining power than the ceramic tools in turning of both the steels. This is due that the energy required during cutting increasing proportionally with the increase of hardness.

![Graph showing effect of cutting time on machining power](image)

**Figure 4.6** Effect of cutting time on machining power in turning of AISI 4340 and AISI H13 steel at constant $V_c = 140$m/min, $f = 0.14$mm/rev and $d = 0.6$mm
4.4 Effect of Cutting Parameters on Tool Wear

In general, cutting tools used for hard turning require extreme hardness, high compressive strength, high resistance to abrasive wear, thermal resistance and chemical stability even at elevated temperatures. For continuous/interrupted cuts, tool materials with high toughness are more frequently required to prevent chipping and edge failure. The cost of downtime for tool changing affects the economic advantage of the process (More et al., 2006; Dureja et al., 2010). Coated carbide, ceramic and cubic boron nitride (CBN), polycrystalline diamond (PCD) tools are only choices available that can meet the demands of machining of hard materials. Coated carbide, ceramic and CBN have higher fracture toughness, higher thermal conductivity and low thermal expansion coefficient, favorable in continuous/interrupted cutting operations (Sahin and Motorcu, 2005; Dureja et al., 2010).

In most practical cases, two important criteria related to tool life are simultaneously used to evaluate the finishing performance of a hard turning process. They are attainable surface quality and tool wear, which are directly influenced by the cutting tool material and geometry. Therefore, in order to prolong tool life and prevent edge failure, selection of the optimal tool material for each particular application is important. Flank wear should be controlled within a limit value, defined as the tool life criterion (e.g. \( VB_{\text{max}} = 0.2\text{mm} \)), as it causes degradation of surface finish and thermal damage on the machined surface due to tool-work friction. In addition, crater wear, which can occur near the cutting edge and weakens it, is also a significant failure mode in hard turning. Dry conditions are usually recommended for hard turning because coolant use may cause greater thermal shock in hard tool materials and induce chipping (Matsumoto, 1996).
This section discusses the results of dry turning of hardened AISI 4340 and H13 steels using multilayer CVD(TiN/MT-TiCN/Al₂O₃) coated carbide, mixed ceramic (Al₂O₃+TiC) and PVD(TiN) coated ceramic tool materials.

4.4.1 Effect of Cutting Speed

Fig. 4.7 (a), (b) and (c) shows the effect of cutting speed on tool wear in dry turning of hardened AISI 4340 and H13 steels with different tools at a constant cutting time of 4min, feed rate of 0.14 mm/rev and depth of cut of 0.6mm. The results show that the tool wear significantly increases with increase in cutting speed for the dry turning of both the steels with all the cutting tools. The figure also shows that the coated ceramic tool exhibits lowest flank wear than mixed ceramic and multilayer coated carbide tool under similar cutting conditions. This may be due to their ability to retain hardness at elevated temperatures (Luo et al., 1999).

As shown in Fig. 4.7(a), the speed increases from 80 to 260 m/min, the tool flank wear of the multilayer coated carbide tool varies from 0.065 to 0.170mm while machining AISI H13 steel. However during machining of AISI 4340 steel the flank wear varies only 0.05 to 0.145mm. It can be seen that all cutting tools exhibits better performance at lower cutting speeds during turning of both the steels. With the increase in cutting speed, the rubbing action between tool and work piece is faster and high cutting temperature generated even though less contact time exits. Hence, higher cutting temperature and stress generated at the rake and flank sides softens the tool edge and more wear occurred (Lee and Mathew, (2007)).

It is observed that the maximum flank wear of around 0.185mm at higher cutting speed during turning of hardened H13 steel (54HRc) with multilayer coated carbide tool. This may be due to the high hardness of the work material which causes
high cutting forces and high cutting temperature. The higher cutting speed caused inhomogeneous shear strain and translation from continuous chip to saw tooth chip occurred. The friction force was found to increase due to very irregular chip–tool contact. This intern removed the coated layer of the tool. In addition, serious diffusion was encountered. The reason is that the binder of the tool is abraded by hard carbide particles of the work piece material, which leads substrate tool material (cemented carbide grains) to be detached from the bond. The tool fracture was evident from the SEM image shown in Fig. 4.8. It indicates that there should an optimum cutting speed for multilayer coated carbide tool to machine high hardness alloy steel.

![Multilayer Coated Carbide Tool](image)

**Figure 4.7 (a)** Variation of tool wear with cutting speed for AISI 4340 steel and H13 steel at a constant feed rate of 0.14mm/rev, depth of cut of 0.6mm and cutting time of 4 min with multilayer coated carbide
Figure 4.7 (b) Variation of tool wear with cutting speed for AISI 4340 steel and H13 steel at a constant feed rate of 0.14mm/rev, depth of cut of 0.6mm and cutting time of 4 min with mixed ceramic tool and (c) coated ceramic tool.
Similarly in Fig. 4.7(b), the mixed ceramic tool exhibits tool flank wear of 0.05 to 0.12mm for H13 steel and 0.046 to 0.105mm for AISI 4340 steel. The coated ceramic tool flank wear varies from 0.042 to 0.086mm for H13 steel and 0.036 to 0.07mm for AISI 4340 steel as in Fig. 4.7(c). The results showed that ceramic tools have exhibits higher wear resistance, lower heat generation and lower cutting forces when compared to carbide tools. The reason for this may be that at lower cutting speed, the amount of the adhered layer (work material) increases and acts as a protective film to reduce tool wear, which leads to an increase of the tool life. At higher cutting speed the cutting temperature is very high that results thermal softening of the tool face. Under such conditions, it can be easily abraded by the hard particles of the work material, and tool wear is accelerated. Thereafter, the life of ceramic tools would rapidly be reduced. From above it can be deduced that adhesion and abrasion are the main factors for the tool wear in ceramic tools. Initially, it is adhesion at the lower cutting speeds and as speed goes up, abrasion sets in.
and flank faces close to the nose area probably caused the yield strength of the tool to reduce (Lee and Mathew, 2007).

As in Fig. 4.9 (b) and (c) coated ceramic and mixed ceramic tools showed slightly lower values of tool wear than multi layer coated carbide tool at all cutting conditions for both the steels. The maximum flank wear during turning of H13 steel with mixed ceramic and coated ceramic tools are observed of around 0.115mm and 0.09mm respectively. This can be attributed to the increase in temperature at high feed rates which causes softening of tool material (Astakhov, 2004). From the above it can be deduced that the feed rate is increased causes increase in material removal rate, but feed rate has detrimental effect on tool life.

![Figure 4.9 (a)](image)

**Figure 4.9 (a)** Variation of tool wear with feed rate for AISI 4340 steel and H13 steel at a constant cutting time of 4min, cutting speed of 140m/min and depth of cut of 0.6mm with multilayer coated carbide tool
Figure 4.9 (b) Variation of tool wear with feed rate for AISI 4340 steel and H13 steel at a constant cutting time of 4 min, cutting speed of 140 m/min and depth of cut of 0.6 mm with mixed ceramic and (c) coated ceramic tools.
While comparing the tool wear of ceramics and coated carbide tools when machining of hardened steels, results showed that cutting speed is predominant factor for tool wear and followed by the tool hardness. Coated ceramic tools show better performance than coated carbides. When comparing performance of ceramics and carbide tools while turning hardened steels, experiments showed that coated carbides performed better at speed up to 200m/min. while ceramics are superior at higher cutting speeds (up to 260m/min).

**4.4.2 Effect of Feed Rate**

Fig. 4.9 (a), (b) and (c) shows the variation of tool wear with feed rate for various cutting tools and materials at a constant cutting time of 4min, cutting speed of 140m/min and depth of cut of 0.6mm. It is observed that the tool flank wear increases with increase in feed rate increases of 0.06mm/rev to 0.26mm/rev.

Fig. 4.9 (a) shows the effect of feed rate on tool flank wear with multilayer coated carbide tool at constant depth of cut of 0.6mm and cutting speed of 140m/min. The flank wear rate increases relatively with increasing feed rate from 0.06 to 0.10mm/rev, while it increases rapidly with further increase in feed rate of 0.14 to 0.26mm/rev. The results showed that the maximum flank wear observed at higher feed rate of 0.26mm/rev is around 0.12mm and 0.145mm during turning of AISI 4340 and H13 steels respectively. It is observed that at higher feed rate of 0.26 mm/rev, contact between cutting tool and work piece increases. Hence, it leads the multilayer coated carbide tool to suffer rapid wear, chipping, or fracture. The tool wear pattern was evident from the SEM image shown in Fig. 4.10. The reason might be that at higher values of feed rate, higher cutting temperature and stress generated on the rake
**Figure 4.10** SEM Image showing the tool wear pattern on multilayer carbide tool while cutting AISI 4340 steel at feed rate of 0.26 mm/rev

### 4.4.3 Effect of Depth of Cut

Fig. 4.11 (a), (b) and (c) represents the variation of tool wear with depth of cut for turning of AISI 4340 steel and H13 steel at constant cutting time of 4min, cutting speed of 140m/min and feed rate of 0.14 mm/rev using different cutting tools. Fig. 4.11(a) shows effect of depth of cut on tool flank wear with multilayer coated carbide tool at constant feed rate of 0.14mm/rev and cutting speed of 140m/min. The flanks wear increases (around 0.07 to 0.13mm) relatively with increasing depth of cut from 0.3 to 1.2 mm for both the steels. Similarly, as in Fig. 4.11(b) and (c) coated ceramic and mixed ceramic tools showed slightly lower values of tool wear than multi layer coated carbide tool at all cutting conditions. It is observed that at lower depth of cut all the cutting tools performed well and exhibits lower tool wear rate during turning of both the steels.
It is observed that the lower depth of cut does not show much influence on the tool wear in turning of both the steels. Although, the tool flank wear slightly increases with increase in depth of cut for all the cutting tools. The increase in tool flank wear is probably due to abrasion at the rake and flank face of the cutting tool as the cutting time progress. When the depth of cut increases, the specific contact stress at the tool-chip interfaces and average contact temperature remain unchanged (Astakhov, 2004). In addition, a high temperature in cutting can be reach due to the smaller thermal conductivity of coated carbide and ceramic tools. Hence, the adhesive force in the chip-tool contact would be larger. This causes the deposited layer on the cutting edges to form more easily. The protective layer would reduce the abrasive wear of the tool; hence its flank and nose wear are smaller.

![Graph](image)

**Figure 4.11 (a)** Variation of tool wear with depth of cut for AISI 4340 steel and H13 steel at a constant cutting time of 4 min cutting speed of 140m/min and feed rate of 0.14mm/rev with multilayer coated carbide tool
Figure 4.11 (b) Variation of tool wear with depth of cut for AISI 4340 steel and H13 steel at a constant cutting speed of 140m/min and feed rate of 0.14mm/rev with mixed ceramic and (c) coated ceramic tools.
4.4.4 Effect of Cutting Time

The measurement of progressive tool wear is important in order to determine the life of the tool. The continuous use of tool after its useful life leads to damages on the work piece resulting in poor surface finish and increased cutting force. During hard turning process with ceramics and coated carbide tools exhibit abrasion, adhesion and diffusion types of wear. At lower cutting conditions abrasion was the predominant wear phenomenon observed in multilayer coated carbide tool. During hard machining with ceramic tool at lower/moderate cutting conditions a protective layer was formed at the tool tip interface, acting as diffusion barrier and resulted in prolong tool life. While at higher cutting conditions cutting temperature become the dominant factor instead of cutting force for both ceramic and carbide tools (Lin et al., 2008).

To study the progressive tool wear on the flank surface, a series of turning tests with refined hardened AISI 4340 and H13 steels were performed at the cutting time of 2, 4, 6 and 8 min, where each test was starting from a fresh insert corner. Figure 4.12 (a), (b) and (c) shows the variation of tool wear with cutting time for AISI 4340 and H13 steels materials at a constant cutting speed of 140 m/min, feed rate of 0.14 mm/rev, depth of cut of 0.6 mm using different tools. As the cutting time increases, the rake face and flank face wear increases for all cutting conditions. It is observed that the AISI 4340 steel shows less flank wear compared to H13 steel for all the cutting conditions. This wear behavior may be due to the hardness difference of the work piece materials.
Figure 4.12(a) Variation of tool wear with cutting time at constant cutting speed of 140 m/min, feed rate of 0.14 mm/rev and depth of cut of 0.6 mm with multilayer coated carbide and (b) mixed Ceramic tool
Figure 4.12 (c) Variation of tool wear with cutting time for various cutting tools and materials for a constant cutting speed of 140 m/min, feed rate of 0.14 mm/rev and depth of cut of 0.6 mm with coated ceramic tool.

As in Fig.4.12 (a), it is observed that the tool wear after 2 min of cutting time is around 0.04 to 0.06 mm for multilayer coated carbide tool for both the steels. The flanks wear increases of around 0.12 to 0.15 mm relatively with increasing cutting time of 8 min. It can be seen that during the initial stages of cutting, wear at flank face and nose was uniform. Further cutting caused the wear width at the nose to increase faster than that at the flank face. Higher cutting temperature expedites the oxidation of binder, exposing few carbide particles on the flank wear land. Nose and flank face were severely gouged by the hard particles of work piece material exhibiting abrasive wear phenomenon. It is responsible for enhanced tool wear.

Fig.4.12 (b) shows the wear behavior of mixed ceramic tool at different time intervals during turning of both the steels. It can be observed that the mixed ceramic
tool (around 0.095 to 0.115mm after 8min) showed better performance than the coated carbide tool. The reduced progressive flank wear in the case of ceramic tools is due to the reduction in cutting temperature at the cutting edge. During machining, ceramic tools have higher wear resistance, lower heat generation and lower cutting forces when compared to coated carbide tools (Sales et al., 2008).

As in Fig. 4.12(c), the flank wear in case of coated ceramic tool (around 0.065 to 0.080mm after 8min) is lower when comparing to coated carbide and coated ceramic tool. It was found that the TiN coating layers reduced tool/chip adhesion and that its main wear mechanism was abrasion and also due to its higher hardness and temperature resistance capability. More detail about these wear mechanisms will be discussed at section 4.5

4.5 Tool Wear Mechanism

Tool wear is a phenomenon caused due to mechanical and chemical process which changes the tool from its original shape during cutting resulting from gradual loss of tool material. The wear mechanism responsible for a particular tool failure mode can be different depending on the cutting parameters (cutting speed, feed rate and depth of cut), material types, and geometry of tool used. The four main wear mechanisms which occur during metal cutting are abrasion (abrasive), attrition (adhesion), diffusion and oxidation wear (Trent et al., 2000).

Abrasion wear prevails at low cutting speeds and at low chip tool interface temperature when sliding conditions prevail. It is caused by hard particles or asperities at the tool work piece interface during the relative motion between the tool surface and the work piece surface (Huang and Liang, 2004). This mechanical wear the causes the wear on the flank, rake face, and at depth of cut notch. Abrasive wear
increases with the increase in cutting speed (Lim et al., 1999). Adhesion wear occurs when tool material is removed from the tool surface when the adhesive junction in the tool material or coating breaks. The tool rake surface can deteriorate fast during adhesive wear. If the cutting speed is further increased, the adhesion wear effect can be reduced. Chemical wear occurs at a high temperature which causes diffusion of material from tool surface to chip and vice versa. The contact conditions can change fast because of chemical diffusion that can lead to tool failure (Yang et al., 2001). At very high cutting speed, the presence of air and high temperature produce oxidation wear. Chemical reaction can take place between tool and work piece hence weakened the tool.

In this study, dry machining of hardened AISI 4340 steel and H13 steel with multilayer CVD coated carbide, mixed ceramic (Al2O3 + TiC) and PVD coated ceramic tools were conducted at different cutting conditions. The coated carbide inserts, have a multilayer coating (TiN/MT TiCN/Al2O3) on cemented carbide substrate. The coating consisted of a thick moderate temperature chemical vapor deposition (MT CVD) of TiN for heat resistance and with low coefficient of friction, TiCN for wear resistance and thermally stable and Al2O3 for heat and crater wear resistance. The combined top coating and gradient substrate provide extremely good behavior during dry machining (Olortegui et al., 2010). The coated ceramic inserts have PVD coating (TiN) on alumina and titanium carbide (Al2O3 (70%) + TiC (30%)) substrate. To study the wear mechanism on the flank, nose (corner) and rake surface, a series of turning tests were performed at different time intervals, where each test was starting from a fresh insert corner. The type of wear will be analyzed using optical microscopy images and SEM analysis.
4.5.1 Wear mechanism for coated carbide tool

Fig. 4.13 illustrate the worn surfaces of multilayer coated tool in the machining of hardened H13 steel for cutting time of 2min and 8min. The micrographic examination showed that the coating material has been removed on the flank, nose (corner) and rake surfaces of the cutting tool. It can be seen that the smooth and clean abrasive grooves of the worn area indicates that tool were uniformly abraded. These grooves are oriented along the cutting speed direction. The latter seems to be the results of high abrasive wear. Grooves usually appear at the beginning of the machining and never disappear. It indicated that abrasion was the main mechanism of wear which results in the formation of abrasive marks on the tool. Similar phenomenon was also observed by Luo et al., (1999) and Poulachon et al., (2001).

From the above discussion it is clear that the wear mechanism occurs initially, delay in wear is due to the superior wear resistance of the outer alumina (Al₂O₃) coating at studied conditions. Between 1min and 2min, flank wear took place mostly on the Al₂O₃ coating, which is shown in the micrographic images (4.13(a)), and then titanium carbonitride (TiCN) coating was exposed at first 4min and finally TiN coating exposed between 6 to 8min. It is observed that the wear effects on flank face of the tool occur after first 8min of cutting duration as in Fig. 4.13(b). It indicates that TiCN did not wear at such high rates between 4min and 8min due to its high hot hardness. Once the carbide substrate was exposed, the steel adhesion can take place due to the excellent affinity between steel and carbide. The adhered steel pulled the carbide grains out when the steel detached from the carbide substrate. At this condition tool wear is accelerated resulting in reduction of tool life. In general, the flank wear ($VB_{max}$) rate is expected, after rapid initial wear, to reach a steady state and finally an accelerated wear rate regime (Stephenson et al., 2006). This may be because
the wear front will attack mostly the softer and more adherent carbide substrate without extending the flank wear land, once the carbide is exposed. The tool wear pattern was evident from the SEM image shown in Fig. 4.14(a).

![SEM views of wear effect observed on multilayer coated carbide tool at (a) \( V_c = 140 \text{ m/min, } f=0.14 \text{mm/rev, } d=0.6 \text{mm and } t=8 \text{min.} \) (b) \( V_c = 260 \text{ m/min, } f=0.1 \text{mm/rev, } d=0.6 \text{mm and } t=8 \text{min.} \)](image)

**Figure 4.13** Micrographic images of worn cutting edges of coated carbide tool during turning of H13 steel at \( V_c = 140 \text{ m/min, } f=0.14 \text{mm/rev, } d=0.6 \text{mm and } t=2 \text{min and } t=8 \text{min.} \)

**Figure 4.14** SEM views of wear effect observed on multilayer coated carbide tool at (a) \( V_c = 140 \text{ m/min, } f=0.14 \text{mm/rev, } d=0.6 \text{mm and } t=8 \text{min.} \) (b) \( V_c = 260 \text{ m/min, } f=0.1 \text{mm/rev, } d=0.6 \text{mm and } t=8 \text{min.} \)
Fig. 4.14 (b) shows the SEM view of multilayer coated carbide during turning of hardened H13 steel at the cutting condition of $V_c=260$ m/min, $f=0.1$ mm/rev $d=0.6$ mm and $t=8$ min. It is observed that extensive crater wear occurs at rake face of the tool. It may be due to loss of both coating and tool materials on rake face of the tool. The crater wear increase proportionally with increasing speed and increasing cutting time by resulting edge chipping at rake face. In addition, abrasion action causes the wear on rake face to be attributed by sliding of the saw tooth chips on rake face. In order to confirm through EDAX pattern of the worn-out insert test showing the presence of oxygen element, the built-up layer consists of Fe element, which is the constituents of work material as in Fig. 4.15. EDAX pattern also reveals the presence of elements like Ti and Al, which are present in the binder phase of the multilayer coated carbide tool. Moreover, Luo et al., (1999) affirm that the origin of grooves is attributed to the tool binder damage caused by hard carbide particles of the work piece leading to carbide tool grains falling out when machining hardened steel with a coated carbide tool. Fig. 4.16 shows some example of worn surfaces on the multilayer coated carbides during turning of hardened AISI 4340 steel and AISI H13 steel at different cutting condition.

It can be depicted that at lower cutting conditions, abrasion was the dominant wear mechanism during turning of hardened steel with multilayer coated carbide tool. At higher cutting conditions, combination of both abrasion and diffusion were main active wear mechanisms on tool wear. It was also observed during experiments that the tool wear is concentrated typically on the nose region because of higher stresses and thermal softening of tool material due to higher temperature at this region.

From the above results, it can be deduced that the multilayer (TiN/MT TiCN/Al₂O₃) coated carbide tool appeared to have the best wear resistance under the
lower conditions used. The combination of chemically stable Al₂O₃ with low thermal conductivity, TiCN with high abrasive resistance and the TiN with heat resistance coating improved the overall wear resistance of the cutting tool.

<table>
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</table>

**Figure 4.15** EDAX pattern of the worn-out coated carbide tool (magnification 500x and 20.0 kV) at \( V_r = 260 \) m/min, \( f = 0.10 \) mm/rev and \( d = 0.6 \) mm

**Figure 4.16** Examples of tool worn appearance on the multilayer coated carbides during (a) turning of H13 steel at \( V_r = 260 \) m/min, \( f = 0.1 \) mm/rev, \( d = 0.6 \) mm and \( t = 4 \) min, (b) magnification of site A in (a), (c) turning of AISI 4340 steel at \( V_r = 260 \) m/min, \( f = 0.26 \) mm/rev, \( d = 0.6 \) mm and \( t = 8 \) min, (d) magnification of site A in (c).
4.5.2 Wear mechanism for ceramic tools

Fig. 4.17(a) illustrate the worn surfaces of the mixed ceramic tool during turning of hardened AISI H13 steel (54HRC) at cutting speed of 140m/min, feed rate of 0.14mm/rev and depth of cut of 0.6mm after 8min. It is observed that there are some abrasive traces and a layer adhered to the cutting edges. It indicates that wear behavior is typical abrasion and adhesion. Abrasive wear is mainly caused by hard particles or impurities within the work piece such as carbide and oxide compounds. The hard particles may be on the underside of the chip which passes the tool face and remove some of the tool material. The adhesive layer deposited on the tool face as detected using EDAX analysis is mainly Fe element of the work material (Fig. 4.18). These layers cover some abrasive grooves. This layer can reduce the deterioration of some grooves during cutting, hence it has a protective action, which reduces the wear and improves the tool life. However, when the layer is removed by severe abrasion action the tool wear increases.

Fig. 4.17(b) micrographic views of worn surfaces of the ceramic tool during turning of H13 steel at cutting speed of 260 m/min, feed rate of 0.14mm/rev, depth of cut of 0.6mm and cutting time of 8min. It can be seen that the extensive crater wear occurred on the rake face of the tool. Moreover, worn zone is extended below the cutting edge causing the creation of a characteristic deep triangular groove adjacent to the corner, named as notch groove wear. It is considered that the crater size increases due to the abrasive mechanism that occurs with the increased cutting speed. The high temperature that occurs on the cutting area causes the tool hot hardness to decrease. This speeds up the material loss from the tool surface. It indicates that the ceramic tools are highly brittle, high cutting forces at low cutting speeds possibly led to more
chipping on the flank face compared to that led by low cutting forces at high cutting speeds.

(a) At $V_c = 140 \text{ m/min}$, $f = 0.14 \text{ mm/rev}$, $d = 0.6 \text{ mm}$ and $t = 8 \text{ min}$

(b) At $V_c = 260 \text{ m/min}$, $f = 0.14 \text{ mm/rev}$, $d = 0.6 \text{ mm}$ and $t = 8 \text{ min}$

Figure 4.17 Micrographic images of worn cutting edges of mixed ceramic tool during turning of hardened AISI H13 steel at different cutting conditions.

<table>
<thead>
<tr>
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</tr>
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<td>Total</td>
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</tr>
</tbody>
</table>

Figure 4.18 EDAX pattern of the worn-out tool (magnification 500x and 20.0 kV) at $V_c = 140 \text{ m/min}$, $f = 0.14 \text{ mm/rev}$ and $d = 0.6 \text{ mm}$
Fig. 4.19 illustrates the micrographic images of worn cutting edges of mixed ceramic tool. It exhibits deep abrasive grooves formed on the rake and flank surfaces of the ceramic tool during turning of AISI 4340 steel at cutting speed of 260m/min, feed rate of 0.26mm/rev, depth of cut of 0.6mm and time of 8min. It indicates that due to abrasion action causes the wear on flank and rake faces to be attributed by higher cutting conditions and sliding of the chip on rake face. From the above it reveals that the ceramic tool exhibits abrasion and adhesion were dominant and wear mechanisms, although notch grooves and chipping on the rake and flank faces were observed in high speed and low feed rate combinations of cutting conditions.

4.5.3 Wear mechanism for coated ceramic tool

Fig.4.20 (a) and (b) shows the images of the nose, flank and rake faces of the PVD (TiN) coated ceramic tool during turning of hardened H13 steel at the cutting time of 2min and 8min. It can be seen that there are some abrasion marks on the cutting edges. It indicates that wear behavior is purely abrasive type of wear mechanism. However, it can be observed in Fig. 4.20(b) that the crater formation (after 8min) was very low when compared to mixed ceramic and coated carbide tools. In addition, no chipping is observed on the cutting tool edge that is subjected to the cutting process under the same conditions. This is because of the coating applied on
the ceramic tool provides toughness for the cutting tool. Therefore, a coated cutting tool is not affected by the vibrations and possible shock loads. It indicts that the TiN coating on ceramic tool is good for heat resistance and with low coefficient of friction. Besides TiN coating made the ceramic tool gain a certain degree of toughness. This toughness caused a decrease in chipping type damage in the cutting tool.

Fig. 4.20(c) show the micrographic images of coated ceramic tool during turning of AISI 4340 steel at cutting speed of 260m/min, feed rate of 0.26mm/rev, depth of cut of 0.6mm and cutting time of 8min. It is observed that the increase in tool wear at higher cutting conditions is probably due to the abrasion at the rake and flank faces as the machining time progresses. However, when the cutting temperature is very high due to the increase of cutting speed and feed rate, the coated layer on the tool face becomes soft. Under such conditions, it can be easily abraded by the hard particles of the work material, and tool wear is accelerated. Therefore, the life of coated ceramic tools would gradually be reduced.

While comparing the performance of the coated carbide and ceramic tools, the results showed that cutting speed and feed rate are predominated factors for tool life and followed by the tool hardness. Coated ceramic tool provides better tool life than mixed ceramic and coated carbide tool. The experimental results conclude that abrasion and adhesion wear are the main wear mechanisms for the multilayer coated carbide tool. Similarly, for the mixed ceramic and coated ceramic tools, abrasion and adhesion wear are the dominant wear mechanism during turning of hardened AIS 4340 and H13 steels.
(a) AISI H13 steel at $V_c=140 \text{ m/min}$, $f=0.14\text{ mm/rev}$, $d=0.6\text{ mm}$ and $t=2\text{ min}$

(b) AISI H13 steel at $V_c=140 \text{ m/min}$, $f=0.14\text{ mm/rev}$, $d=0.6\text{ mm}$ and $t=8\text{ min}$

(c) AISI 4340 steel at $V_c=260\text{ m/min}$, $f=0.26\text{ mm/rev}$, $d=0.6\text{ mm}$ and $t=8\text{ min}$

**Figure 4.20** Micrographic images of worn cutting edges of coated ceramic tool during turning of AISI 4340 steel and H13 steel at different cutting conditions.

### 4.5 Chip Formation in Hardened Steel Machining

Variety of chips is normally formed during machining. The nature of the chip formation process is extremely complicated. The exact mechanism of or combination of mechanisms for chip formation depends upon the metallurgical aspects of the tool work piece system and the cutting process parameters. Chips produced in machining most metals and alloys can be generally classified into four distinct categories based
on their geometric shapes: flow, wavy, saw-toothed/segmented, and discontinuous (Komanduri and Brown, 1981).

Flow type chip arises in machining of ductile materials and is classified by its uniform cross-section. Wavy chips occur when the shear angle oscillates widely causing fluctuations in cutting forces and chip thickness (Shaw and Vyas, 1993, Manson et al., 2007). Both the flow and wavy chips are considered continuous as there is no gross fracturing but only signs of uneven strains in the chip. When there are cracks or fracture in the chip formation, the chip may be discontinuous or saw-toothed/segmented. Discontinuous chip formation is common in machining brittle materials at low cutting speeds (Tonshoff et al., 2000), and these chips are classified by their nearly identical and discontinuous segments that are entirely separated by their broken segments.

Saw-toothed chips, a common name for segmented chips, are semi continuous and have zones of low shear strain (continuous portion) and high shear strain (discontinuous portion). Saw toothed chips are normally formed and represented an essential feature of hard turning process. This type of chip is defined as a continuous chip with periodic variation in thickness. This type is desirable from the viewpoint of chip disposal but it is source of cutting force fluctuations that represent a high dynamic load on the cutting tool (Poulachon et al., 2001, Morehead et al., 2007).

The study of chip formation is important since it affects the thermal and mechanical loads that alter the surface integrity of the machined surface. It is also useful for cutting force prediction, and tool wear studies (Morehead et al., 2007). In this section the chips obtained from each cutting conditions that has been collected was being analyzed. The psychical appearance or chip form of the chips collected
during the machining test performed during different cutting conditions was observed using digital camera and optical microscope and also chips thickness were measured by using a pointed micrometer.

4.5.1 Chip formation in AISI 4340 Steel

In general, at lower cutting conditions short broken irregular shaped chips were obtained. The probable reason is may be at low cutting conditions rubbing and abrasive actions are more predominant than the actual machining and hence irregular shaped chips are produced. With increased feed rate loose arc chips, with increased speed continuous chips and with increased depth of cut long continuous chips were observed. The chip breaking was also seen at higher cutting speeds. On the other hand, curled chips were seen at high cutting speed with lower feed rate and depth of cut.

Fig.4.21 represents some aspects of chips obtained in the present investigation under various cutting conditions during turning of hardened AISI 4340 steel (48 HRc). At cutting conditions of \( V_c=140 \text{m/min} \), \( f=0.10 \text{ mm/rev} \) and \( d=0.6\text{mm} \), long loose arc type thin chips were observed (Fig.4.21 (a)), but minor crack initiation on the outer surface of the chip was observed. This may be due to the chip formed during cutting for lower hardness work material \(<50\text{HRc}\) is mainly produced by plastic deformation (Luo et al., 1999, Huang and Liang, 2003). On the other hand, long tubular structured coiled type saw toothed chips were seen at \( V_c= 200\text{m/min} \), \( f=0.18\text{mm/rev} \) and \( d=0.8\text{mm} \) (Fig.4.21 (b)). This type chips at above conditions are probably due to effective machining because of shearing of work piece leading to plastic deformation.
At higher cutting conditions of $V_c=260\,\text{m/min}$, $f=0.18\,\text{mm/rev}$ and $d=1.2\,\text{mm}$ short saw toothed/segmented loose arc thick chips were observed as in Fig. 4.21 (c). And also the chip burning and cracking due to very high temperature were observed at higher cutting conditions. This may be due to the fact that increases of shear angle when the cutting speed and feed rate increases (Lee and Mathew, (2006)).

**4.5.2 Chip formation in AISI H13 steel**

Fig. 4.22 shows the chips formation at various cutting conditions during turning of hardened H13 steels (54 HRc). It is observed that the saw tooth chip formation occurs at all the cutting conditions. Fig. 4.22(a) shows that the continuous ribbon type of chip with minor crack initiation on the outer surface of the chip was observed during turning of H13 steel at lower cutting conditions of $V_c=140\,\text{m/min}$, $f=0.1\,\text{mm/rev}$ and $d=0.6\,\text{mm}$. This may be due to the reduction of chip thickness with the increase of work hardness results from the increase of shear angle. This phenomenon has also been reported by Komanduri et al., (1981).

As in Fig. 4.22(b)–(c), it is observed that the chip produced becomes thinner and its shape changes from flow type to coiled type saw-tooth chips at higher cutting conditions. The reason for this may be the chips are subjected to severe deformation and the heat generated during cutting flows mostly into the chip. The high temperature would concentrate on the local shear band of the chip. Hence, a saw tooth chip is formed. Moreover, when the hardness of the work material turned becomes larger (>50HRc), the material is more brittle, which in turn causes the fracture energy required during cutting to be smaller. This leads to the chip more readily developing a saw-tooth appearance. The chip breaking was also seen higher cutting conditions.
(a) At $V_c=140\text{m/min}$, $f=0.10 \text{mm/rev}$ and $d=0.8\text{mm}$

(b) At $V_c=200\text{m/min}$, $f=0.14 \text{mm/rev}$ and $d=0.8\text{mm}$

(c) At $V_c=260\text{m/min}$, $f=0.18 \text{mm/rev}$ and $d=1.2\text{mm}$

**Figure 4.21** Chip formation during hard turning of AISI 4340 steel at different cutting conditions
Figure 4.22 Chip formation during hard turning of AISI H13 steel at different cutting conditions

(a) At $V_c=140$ m/min, $f=0.1$ mm/rev and $d=0.6$ mm

(b) At $V_c=200$ m/min, $f=0.14$ mm/rev and $d=1.0$ mm

(b) At $V_c=260$ m/min, $f=0.18$ mm/rev and $d=0.6$ mm
Fig. 4.23 shows the comparison of chip formation at the cutting conditions of cutting speed of 140m/min, feed rate of 0.26mm/rev and depth of cut of 0.6mm during turning of AISI 4340 and H13 steels. It can be seen that the AISI H13 steel chip thickness is less compared to the AISI 4340 steel and uniform saw tooth formation is observed. It is also observed that the white layer formation (white and dark layer) in back side of chips during turning of hardened H13 steel, but it was not observed in AISI 4340 steel. It may be due the fact that at high feed rate and hardness of the material tends to be formation of white layer on the surface of the chip. Ng et al., (1999) suggested that the white layer was severely strained and subjected to high temperature followed by rapid cooling.

(a) Turning of AISI 4340 steel at Vc=140m/min, f=0.26mm/rev, d=0.6mm and t=4min

(b) Turning of H13 steel at Vc=140m/min, f=0.26mm/rev, d=0.6mm and t=4min

Figure 4.23 Photomicrographs showing chip formation and deformation zone depending on the conditions for hardened steels (30x)
4.5.3 Effect of Cutting Parameters on Chip Thickness

The method of measuring chip thickness is given in the chapter 3. The average chip thickness was considered for comparison all the cutting tools. Fig. 4.24 shows the variations produced in chip thickness during turning of hardened AISI 4340 steel and AISI H13 steel at different cutting conditions with various cutting tools. It can be seen that the chip thickness decreases with increased with increased cutting speeds while the chip thickness increases with increasing feed rates when machining both the materials. It is also observed that the chip thickness slightly decreases with increase in depth of cut for all the cutting conditions.

![Figure 4.24 (a) Effect of cutting speed on chip thickness variations produced during turning of hardened AISI 4340 and H13 steels (KCP05: Multilayer Coated Carbide; KY1615: Mixed Ceramic tool; KY 4400: Coated Ceramic; M1: AISI 4340 Steel; M2: AISI H13 Steel)]
Figure 4.24 (b) Effect of feed rate and (c) depth of cut on chip thickness variations produced during turning of hardened AISI 4340 and H13 steels (KCP05: Multilayer Coated Carbide; KY1615: Mixed Ceramic tool; KY 4400: Coated Ceramic; M1: AISI 4340 Steel; M2: AISI H13 Steel)
Fig. 4.24 (a) shows the variation of measured chip thickness with cutting speed ranging between 80 to 260 m/min when machining of AISI 4340 and H13 steels at feed rate of 0.14 mm/rev, depth of cut of 0.6 mm and cutting time of 4 min. It is observed that chip thickness decreases (around 20 to 30%) with increased cutting speeds. As in Fig. 4.24 (b), it is observed that the chip thickness increases (around 10 to 15%) with an increase in feed rate of 0.06 to 0.26 mm/rev for both the materials. In addition, it can be seen that the chip thickness of AISI 4340 steel is larger than (around 3 to 8%) the AISI H13 steel. Fig. 4.24(c) shows that the chip thickness depends on the depth of cut while machining AISI 4340 and H13 steel. It shows that the chip thickness for depth of cuts 0.3 to 1.2 mm slightly decreases. It indicates that the determination of chip thickness depends significantly on cutting speed, feed rate and hardness and chemical compositions of the materials being machined.