

Tool Damage and Adhesion Effects in Turning and Drilling of Hardened Steels

Chris M. Taylor, Ian Cook, Raul Alegre, Pedro Arrazola, Phil Spiers

Abstract—Noteworthy results have been obtained in the turning and drilling of hardened high-strength steels using tungsten carbide based cutting tools. In a finish turning process, it was seen that surface roughness and tool flank wear followed very different trends against cutting time. The suggested explanation for this behaviour is that the profile cut into the workpiece surface is determined by the tool's cutting edge profile. It is shown that the profile appearing on the cut surface changes rapidly over time, so the profile of the tool cutting edge should also be changing rapidly. Workpiece material adhered onto the cutting tool, which is also known as a built-up edge, is a phenomenon which could explain the observations made. In terms of tool damage modes, workpiece material adhesion is believed to have contributed to tool wear in examples provided from finish turning, thread turning and drilling. Additionally, evidence of tool fracture and tool abrasion were recorded.

Keywords—Turning, drilling, adhesion, wear, hard steels.

I. INTRODUCTION

HIGH strength steels are used where in-service requirements are greater than those offered by common steels, which justifies the additional cost of forming and subsequent manufacturing processes. Examples of high-strength steel applications can be found in the aerospace, oil and gas, and nuclear industries.

Hardening of high-strength steels is achieved via heat treatment procedures [1]. Precipitation hardenable stainless steels ("PH stainless") undergo precipitation or age hardening, where they are held at an aging temperature for some hours before liquid quenching (cooling). Precipitates (or fine particles) come out of solution during aging of the steel, impeding dislocations and increasing overall strength and hardness. In the solution treated state PH stainless steels are relatively machinable and during hardening, little distortion occurs in comparison to other types of stainless steel. For other high strength steels, hardening may be achieved by through-heating then quenching in oil or water, which reduces the mean grain size.

Numerous researchers of machining behavior, with examples being Paro et al. [2] and Korkut et al. [3] have categorised high strength stainless and non-corrosion-resistant

steels as hard-to-cut materials. This categorization has been justified by various tendencies: relatively high levels of workpiece material adhesion to the cutting edge, also known as built-up edges (BUEs), over a wide range of cutting parameters; abrasive particle content; high fracture toughness and strength; work hardening effects during the machining process; and high tool tip temperatures due to low thermal conductivity.

Studies and models of turning process parameters [4]-[6] have found that the feed rate is the primary factor affecting surface finish in turning. Due to the geometry of cusps also known as kinematic feed marks, higher feed rates lead to a higher surface roughness. Data presented in [7], [8] show that in general, surface roughness reduces with increasing surface speed. Korkut et al. [3] also observed reducing roughness as the surface speed increased, the authors drew a link between this observation and the reducing size of BUEs as the surface speed increases. An insightful description of the nature and origin of BUEs in general is provided by Heginbotham and Gogia [9].

Childs et al. [10] analysed existing data and created new data related to the edge geometry and roughness of turning inserts, to see the effect on surface finish in turning. These researchers concluded that the tool corner radius plays a dominant role at higher feed rates whilst the tool edge radius (sharpness) plays a dominant role at low feed rates. The materials studied were aluminium alloys, and cutting durations which would induce tool wear were avoided. Pavel et al. [11] studied the turning of steels at hardness 48 and 62 HRC with PCBN inserts. The authors found that surface roughness increased uniformly over time in the case of continuous turning, but that the surface roughness reduced over time in the case of interrupted turning. They observed that in continuous turning the tool edge wore to form a sharp profile, hence the cut surface became more jagged over time, i.e. a roughness increase. In intermittent turning the tool wore to form a blunt profile which led to an increasingly flat, smooth surface.

In terms of drilling high-strength steels, the drill flutes transport cut material up and out of the hole being drilled, as such it is important that drills feature effective chip breakers and smooth, low-friction flutes [12]. Through-tool coolant supply holes deliver coolant flow into the bottom of the drilled hole, reducing the temperature near the cutting edges and helping to transport metal cuttings into and up the flutes. This reduces the chances of swarf jamming, and is particularly important when drilling deeper holes. A common coating for tungsten carbide drills working on high strength steels is

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titanium aluminium nitride (TiAlN), which helps to reduce the “welding” effect- in other words, workpiece adhesion.

Nomani et al. [13] studied the drilling of stainless steels. They used cemented tungsten carbide drills, with a TiAlN coating. Adhesion dominated the causes of wear, with lesser abrasion effects also observed. Built-up material was found adhering to the cutting edge of drills, growing in size during cutting then breaking away and in doing so, plucking carbide material from the tool flank. Fracturing of the chisel edge and fatigue fracture of the flutes also occurred. The authors found that duplex stainless steel was less machinable than 316L austenitic stainless steel, due to greater workpiece material build-up. They suggested that less adhesion occurred for the case of 316L due to the presence in the steel of solid lubricant elements sulphur and phosphorus.

Venkatesh and Xue [14] ran drilling tests involving tool inserts with different cutting edge designs. The authors used a quick-stop cutting device to gather chip roots, then measured the size of the BUEs. They found that a large BUE correlated to a long tool life but a poor surface finish, whilst a small BUE correlated to short tool life and a better surface finish.

Three case studies are described in the following sections, related to novel machining trials conducted on hardened steels using coated tungsten carbide based cutting tools. The aims in this paper are: (1) to investigate the link between tool wear, adhesion and surface roughness in finish turning; and (2) to examine the dominant tool damage mechanisms in finish turning, thread turning and drilling, these being operations which mostly involve continuous cutting contact between the tool and workpiece.

II. TOOL WEAR AND SURFACE ROUGHNESS IN FINISH TURNING

A. Trials Information

Finish turning trials were carried out on a vacuum arc remelted low-alloy steel which in the hardened and tempered state has a hardness of 55 HRC and ultimate tensile strength of 2000 MPa. The hardening process for this alloy involves through-heating then oil quenching, followed by tempering and air cooling. The finish turning process was carried out on the outer diameter (i.e. the curved surface) of a cylindrical bar, on a MAG Hawk 300 CNC-controlled lathe. Hard turning by definition is applied to materials which have a hardness of over 45 HRC, so these can be described as hard turning trials. The tool design used was a coated tungsten carbide-cobalt rhombic turning insert with a nose (corner) radius of 1.6mm. The radial depth of cut, feed rate and surface speed were fixed at 0.25 mm, 0.088 mm/rev and 195 m/min, respectively. The cutting fluid was a water-based emulsion supplied at 6-8% concentration. This fluid was supplied with flood delivery, at approximately 15 litres per minute flowrate.

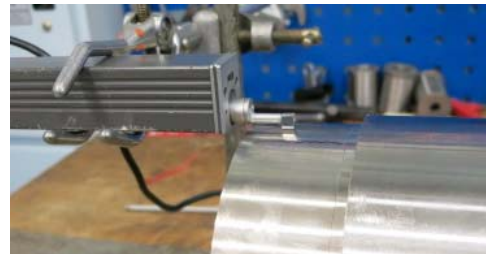


Fig. 1 Measuring roughness on turned bar surface

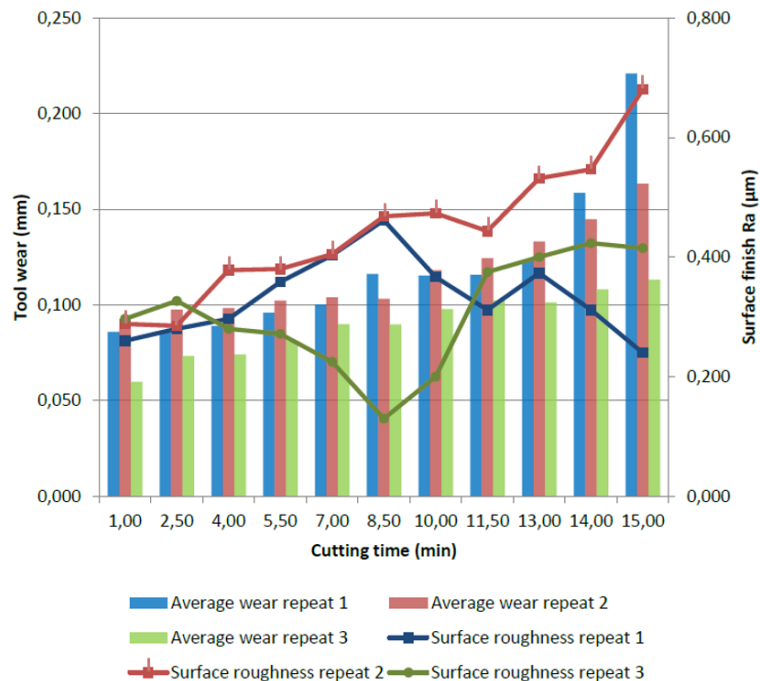


Fig. 2 Tool flank wear and surface roughness progression against time for repeat finish turning cuts. Surface finish in micrometres

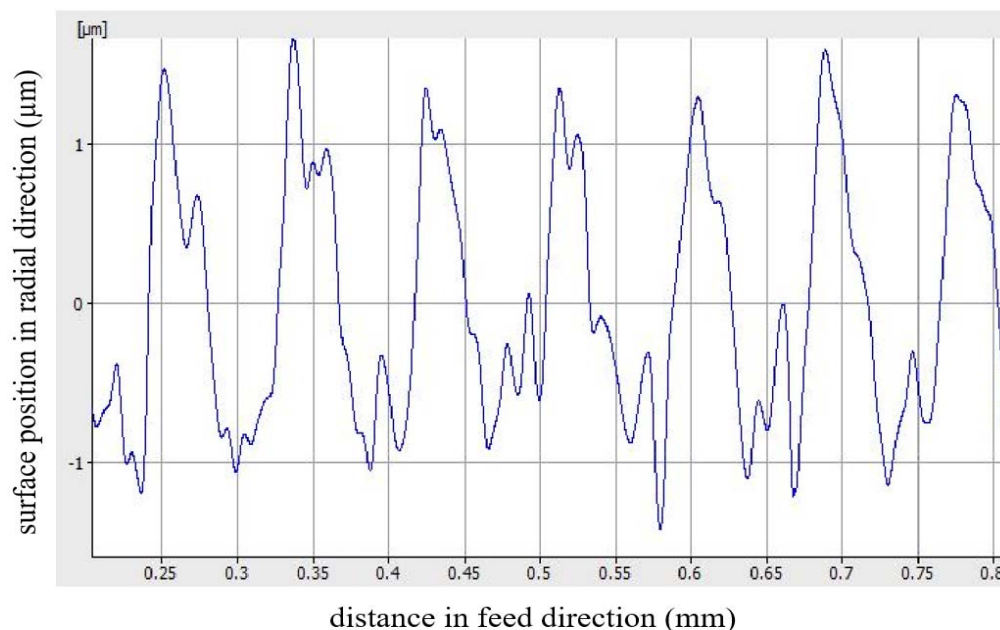


Fig. 3 Turned surface profile, in plane perpendicular to cutting speed direction

A standard toolmaker's microscope was used to gather images of the rake and flank faces of each tool for wear measurement and analysis. A Mitutoyo SJ-301 device was used to measure surface roughness in the direction of the bar's axis, applying a fixed cutoff wavelength of 0.8 mm (refer to Fig. 1 for a picture of the roughness measurement arrangement). InfiniteFocus G4 and SL devices from Alicona were used to create high resolution 3D scans of the turned surface and of damaged cutting tools.



Fig. 4 High resolution 3D scans of tools after 15 minutes' turning

B. Results and Discussion

For the results which are relevant to the following discussion see Figs. 2-4. Referring to Fig. 2 first, turning tool wear tests were run in an identical fashion three times over. Each repeat test began with a brand new cutting edge: the edge progressively wore during the cutting process. The measured average surface roughness (R_a) is seen to increase and decrease over time. In repeat 2, there is an almost-monotonic upward trend in surface roughness from 0 to 15 minutes of insert cutting time, in repeat 3 there is an overall upward trend in roughness over time with large fluctuation, whilst in repeat 1 the roughness returns to very near the starting value after 15 minutes of cutting. However, over the same time period, the

measured average tool flank wear increases monotonically in all three cases.

The hypothesis to explain this behaviour is that the geometrical effect of adhered workpiece material superimposed onto wear on the cutting edge is what is creating the variable profile cut into the bar's surface and causing the variation in surface roughness. This is borne out by the way in which surface roughness fluctuates independently of the size of the wear scar (Fig. 2), and by the cross-sectional profile measured on the turned surface (Fig. 3). Adhesion causes short-term fluctuations in the surface roughness, whilst tool wear leads to a long-term upward trend in surface roughness (only seen in 2 out of 3 repeat tests). From examination of the turned surface data in Fig. 3, the cross-sectional profile of the surface in the direction of tool feed can be observed to have a cyclic wave-type pattern with a wavelength of 0.088 mm. Note that the tool feed and workpiece rotation combine to create a helical cutting pattern. 0.088mm is the feed per revolution of the turning operation, equivalent to the pitch of the cut helix. However, the exact appearance of each wave profile varies noticeably at each revolution of the bar. Fig. 3 is a scan of the surface created at the end of repeat wear test number 2, where the highest surface roughness was measured. The cut wave profile corresponds to the true profile (shape) of the cutting edge, similar to the case of a serrated knife moving through butter. The nominal shape of the cutting edge is a circle arc, as the tool insert was created with a 1.6 mm radius nose, but the true profile cut into the workpiece surface is far from a circle arc. The profile of the cutting edge has been modified by the joint effects of adhesion and wear. Each revolution of the bar occurs in less than one second, the tool wear occurring in this time period is minimal so the rapid change of profile observable from wave to wave in Fig. 3

cannot be explained by tool wear. The proposal is that adhesion or BUE on the tool cutting edge has a large effect on the instantaneous surface finish of the turned bar.

Fig. 4 displays high-resolution scans of the three turning inserts used in these trials. Moving clockwise from the top left, the inserts are from repeat trials 1, 2, and 3 as discussed. The rake face coating is black in colour; the insert flank coating is lighter in colour. The thin edges between the black surfaces and lighter-coloured surfaces are the cutting edges. The reflective silvery material visible in damaged areas along the cutting edges is adhered workpiece material. The uncoated tungsten carbide and cobalt substrate would appear as matt grey, but any areas where the coating has been removed are now covered in adhered material. Many thin “track” or “groove” damage features can be seen on the tool flanks, particularly visible for insert 3. These are orientated perpendicular to the cutting edges, and are the result of abrasive flank wear. Additionally, crater wear can be seen on the rake face in the case of inserts 1 and 2, this is due to the motion and heat resulting from cut chips (swarf) flowing over the rake face.

The findings from the case studied here are notably different from the findings of Pavel et al. [11] reported in Section I, in terms of the trend in surface roughness evolution against cutting time. However, Pavel et al. [11] used PCBN inserts, which are said to be less susceptible to the effects of workpiece material build-up.

III. FAILURE MODES IN DRILLING AND THREAD TURNING

A. Trials Information

Drilling and thread turning trials were carried out on a newly-developed precipitation-hardening corrosion-resistant high strength steel, which in the aged state develops 53 HRC hardness and 1900 MPa ultimate tensile strength. It is aged at around 500 °C for 10 hours before quenching in oil.

Drilling trials took place on a Starrag ZT1000 5-axis machining centre, which was chosen for its structurally-rigid machining head and a spindle speed of up to 24000 revolutions per minute. Blind holes were drilled to a depth of 50 mm with 4.5 mm diameter coated solid carbide 2-fluted drills. The hole depth is therefore 11 times the diameter. Fig. 5 shows an image of the drilled test holes. A shrink fit tool holder was used for all 4.5 mm drilling as shown in Fig. 6 (a). This holder provided a high grip force and low tool runout (or eccentricity), being less than 10 micrometres in all cases. The cutting fluid was a water-based emulsion supplied at 6-8% concentration. All 4.5 mm drills featured through-tool coolant holes, coolant was supplied through the machine spindle to the tool with 70 bar supply pressure.

In the thread turning process, ISO standard threads were created with a 60-degree form and a pitch of 1.5 mm, equal to the programmed feed per revolution (refer to Fig. 7 for a picture of a finished thread). A shank tool was used to hold coated tungsten carbide based threading inserts as shown in Fig. 6 (b). The Hawk CNC lathe was used for thread turning, the same machine as described in Section II. Threads were

created using multiple deepening passes of the same threading insert, via a G34 thread cutting NC cycle.

Other test hardware (microscope and Alicona devices) used for the drilling and thread turning trials were as described in Section II.



Fig. 5 Array of blind drilled holes in test piece surface

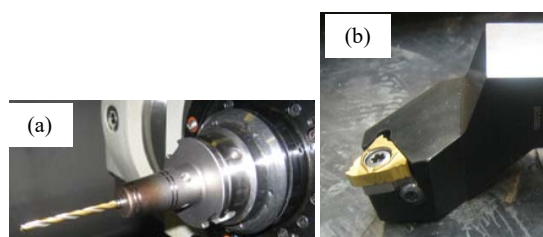


Fig. 6 Tool holding arrangements for (a) drilling and (b) thread turning

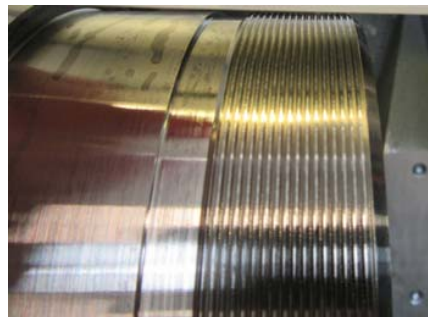


Fig. 7 Turned thread on cylindrical test piece

B. Results and Discussion

The most common failure mode for drills was as shown in Fig. 8, involving loss of the corner region. This was the failure mode in around 70% of cases. In the remaining 30% of cases, fractures at the chisel edge (drill point) or fractures of the flutes (i.e. the drill broke into two or more large pieces) occurred. In threading, from 12 tests on various insert designs the worn-out cutting edges looked similar to Fig. 9 in every case.

Examining the drill images first: the appearance of the damage in Fig. 8 (a) suggests a “chip” or fracture on the drill corner, but from inspection of Fig. 8 (b), there is a great deal of adhesion around the area of missing tool material. There is no evidence of abrasion in this case. Three possible explanations are that: the drill corner fractured due to excessive cutting stresses imparted into the substrate; or that

adhesion wear plucked away the drill corners as observed by Nomani et al. [13]; or that the flow of cut material (swarf) has caused damage in the corner region, by jamming or abrasion. Both flutes had suffered the same type of damage simultaneously. An argument against stress-related fracture is made in a separate paragraph below. It is worth noting that the effective cutting speed on the end of the drill increases with distance from the centre point. At the centre point (also known as the chisel edge), fractures can occur due to high thrust and near-zero surface speed. The corner of each flute is a weak point structurally, meanwhile the surface speed is at its maximum value at the corner and periphery of the drill, which makes thermally-driven wear mechanisms more likely.

When examining the threading insert (Fig. 9), adhered or “welded” material is present covering the entire damaged area of the cutting edge, which was also the case for the finish turning and drilling examples in this paper. A combination of adhesion and abrasion is the probable dominant cause of damage to the tool tip. Thread turning is a process where productivity is likely to be constrained by tool wear, because machining of the correct thread form requires a thin, sharp

insert geometry. The tip radius of the thread turning inserts used was 0.13 mm, which is required to create the correct thread root radius. The corner radius on the drills was around 0.2 mm, which may make the corner susceptible to damage. A blunter reinforced drill corner may survive better, if this is acceptable in terms of the hole geometrical requirements.

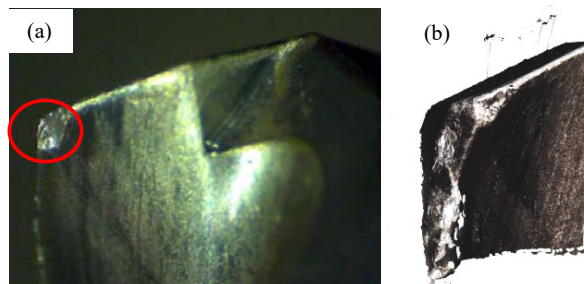


Fig. 8 Drilling failure images (a) microscope image of the end of flute 1; and (b) high-resolution 3D scan of failed drill corner, flute 2

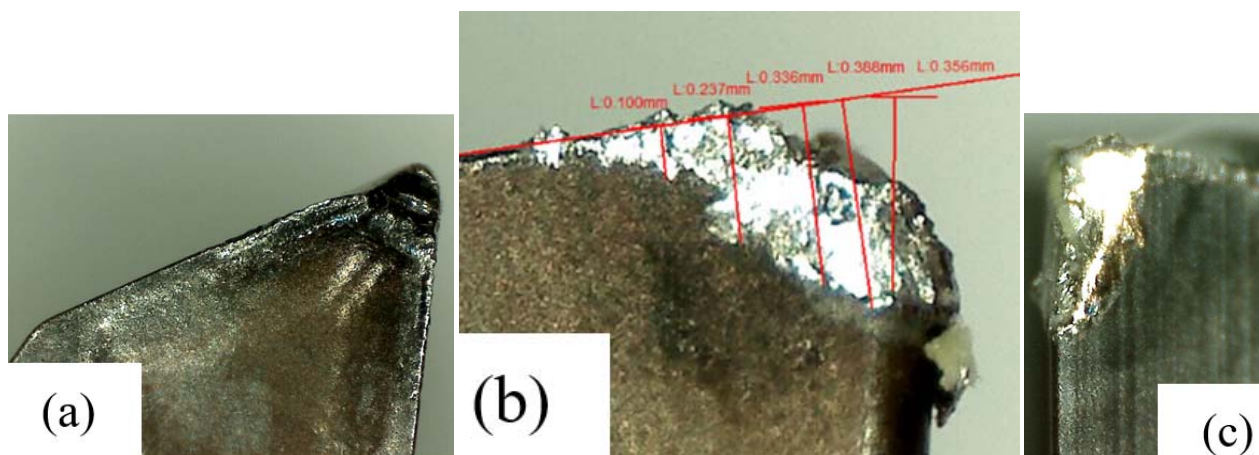


Fig. 9 Microscope images of failed thread turning inserts: (a) rake face view; (b) flank view 1; (c) flank view 2

As well as the hardened condition, these steels have undergone selective testing in the normalized and solution treated heat treatment conditions. An interesting observation is that cutting forces measured in various machining processes were very similar for the three heat treatment conditions. When drilling the steel in the solution treated state with all the other test conditions as discussed above, no damage such as seen in Fig. 8 occurred at the corner of the drill. The cutting forces measured were very similar, which makes a case against the corner being damaged by fracture due to imparted stress.

When the steel machined in Section III is age hardened, its strength and hardness are approximately doubled. Why the cutting forces do not change significantly between the various heat treatment conditions, and the role played by the machining temperature in this case, are interesting questions to consider.

IV. CONCLUSIONS

Three case studies have been presented, from the machining of hardened high-strength steels using coated tools with a tungsten carbide based substrate.

In finish turning of a low-alloy steel it was seen that the measured surface roughness increased and decreased against cutting time, whereas tool wear increased monotonically against time. It is proposed that for this particular machining configuration the variation in the turned surface roughness is dictated by two factors, these being the worn shape of the tool cutting edge, and workpiece material adhered onto the cutting edge. The two factors combine to create the effective profile of the cutting edge, which in turn creates the profile cut into the surface of the workpiece.

In finish turning, thread turning and drilling on low-alloy and stainless steels, the main observations made in relation to tool wear were of adhered material which can pluck away

pieces of the tool surface, also evidence of abrasion was seen on tool flanks. There were some instances of fractures in drilling, and rake face crater wear in turning. These are the mechanisms of tool damage, which limit the productivity of the machining processes.

Two areas for potential further study are investigating the effect of heat treatment on cutting forces in metal machining, and further study of the tool damage mechanisms observed, to gather more evidence and better understand the phenomena observed.

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