Design of inclusion engineered steel for high speed machining

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Merchant’s model for flow chip morphology is based on the tribological conditions of sliding at the tool-chip interface. This condition is realized only at low cutting speeds, when the work of friction due to asperity contact occurs. At higher cutting speeds however, the asperities are squeezed to make atomic contact at the tool-chip contact, causing the tribological conditions at the tool-chip contact to change from sliding to seizure. In consequence, the work of shear in the secondary shear zone of the chip occurs, the bulk of which converts to heat. Major microstructural softening events like dynamic recrystallisation or phase transformation follow, which cause shear localisation. High diffusivity paths in shear localised region coupled with high temperature, cause chemical wear on the rake face of the tool by dissolution of the tool into the chip by diffusion mechanism. In most industrial alloys, shear localisation in the primary shear zone is coupled to shear localisation in the secondary shear zone, which localizes the chemical wear at the cutting edge of the tool, impairing the surface finish.

Tool life can be significantly improved by in-situ lubrication at the tool-chip contact by work-piece engineering. The concept of inclusion engineering of steel is based on modification of existing oxide inclusions to be glassy by deoxidation control in steel-making. During metal cutting, the glassy oxide inclusions are designed to soften to form in-situ a viscous layer of adequate thickness that lubricates the tool-chip interface, restoring the sliding tribological condition. Thus, inclusion engineering of the steel (work-piece) allows the control of chip morphology, suppresses chemical tool wear by preventing shear localisation in the chip, and improves the precision of the machined surface due to protection of the cutting edge of the tool at higher cutting speeds. Results from trial heats of inclusion engineered steel produced under industrial steel making conditions will be presented, which show enhanced tool life at higher cutting speeds.

Introduction:

Merchant’s model [1] on force diagram for metal cutting is based on sliding tribological condition involving asperity contact at the tool-chip interface. Trent and his coworkers [2, 3] deduced from metallographic evidence that the tool-chip contact involved atomic contact at higher cutting speeds. Gekonde et al. [4] proposed that tribological conditions of seizure occur at the tool-chip interface, when the normal stress exceeds the flow stress of the asperities. Under these conditions, the asperities are squeezed to make atomic contact. Once the atomic contact is established at the tool-chip interface, the work of shear in the secondary shear zone of the chip is involved rather than friction in the sliding of asperities. Oxley incorporated this concept in his comprehensive model for flow chip morphology [5]. Oxley’s model for predicting equilibrium shear angle turns out to be the most comprehensive approach that incorporates both the mechanics of metal cutting and dynamic behaviour of metal during metal cutting. Oxley’s prediction of equilibrium shear angle for flow chip morphology is validated in metal cutting at low cutting speeds. However, the domain of flow chip is limited by major microstructural softening events that occur at high cutting speeds particularly if the matrix is hardened by heat treatment or there is a large volume fraction of second phase particles. Microstructural softening causes shear localisation. Shear localisation provides high diffusivity paths through increased dislocation density and increased grain boundary surface through ultra-fine grains formed by dynamic recrystallisation. The objective of this research is to prevent accelerated chemical wear.
due to shear localisation by inclusion engineering of steel.

**Background:**

Metal cutting is a large strain, high strain-rate deformation process in which shear instability condition is attained in the primary shear zone. At large strain characteristic of primary shear zone, shear instability occurs when the flow stress decrement due to thermal softening overtakes the increment in flow stress due to strain and strain-rate hardening. Zener and Hollomon [6] were the first to analyse the physics of large strain, high strain-rate deformation behaviour of metals. They proposed that when the decrement in flow stress due to thermal softening overtakes the increment in stress due to strain hardening, plastic deformation becomes unstable and the homogeneous deformation gives way to a localised band-like deformation to form adiabatic shear bands. However, Meyers [7] has pointed out that shear instability is a necessary but not an adequate condition for shear localisation. He has postulated that a major microstructural softening event is essential for shear localisation to occur. Meyers has demonstrated that dynamic recrystallisation is a major microstructural softening event that is effective in promoting shear localisation. Though most of the metal cutting is carried out under conditions of shear instability, shear localisation in chips is observed only under certain conditions, which are found to be dependent upon both material as well as metal cutting parameters. In the present work, it is shown that microstructural softening events cause shear localisation in metal cutting. Three competing microstructural softening events are identified, which cause shear localisation in metal cutting, see Figure-1. Dynamic recrystallisation and phase transformation are the two important microstructural softening events that occur in the matrix; Geometric softening is the third microstructural softening event that occurs due to incompatibility of deformation between matrix and second phase particles, leading to plastic strain instability and fracture. The flow localisation caused by the strain instability in the presence of voids is referred to as geometric softening. The large compressive stress occurring in the secondary shear zone at the tool-chip interface tends to suppress geometric softening in the secondary shear zone. However geometric softening is promoted by the state of stress in the primary shear zone, leading to fracture with or without the aid of shear localisation in the secondary shear zone[8].

![Microstructural softening events in metal cutting.](image)

**Objective:**

The overall objective is to enhance tool life at high cutting speeds by inclusion engineering the steel. The objective is to design oxide inclusions that soften at the temperature and pressure occurring at the tool-chip interface to the required viscosity to lubricate the tool-chip interface at higher cutting speeds.

**Studies on Shear localisation:**

Detailed metallographic characterisation of chips generated at higher cutting speeds in a range of model iron alloys with and without second phase particles both in the hardened and unhardened condition by heat treatment showed evidence of microstructural softening events due to phase transformation and dynamic recrystallisation. The weakening of mechanical properties of a polycrystal while it is undergoing phase transformation causes shear localisation in the case of phase transformation [9].

These microstructural softening events ought to occur within exceedingly short deformation time, which is typically $10^{-3}$-$10^{-5}$ s. Meyers [10] has clarified that subgrain rotation is the underpinning mechanism of dynamic recrystallisation causing shear localisation during large strain, high strain rate deformation. The typical recrystallised grain size obtained by the rotation mechanism is very small in the range of 0.1-0.3 micrometer, which is comparable to what is
observed in the secondary shear zone in metal cutting. According to this model, the typical temperature at which the rotational mechanism of dynamic recrystallisation operates is about \((0.45-0.5)T_{\text{melting-point}}\), which, in the case of steel is 550-630°C. Since the phase transformation temperature is higher than the temperature of dynamic recrystallisation in steel, it is surmised that the dynamic recrystallisation will precede phase transformation to cause shear localisation in the secondary shear zone in the case of steel chips. Figure-2 shows a TEM picture of the secondary shear zone in the chip from machining of AISI/SAE 1045 steel using a cemented tungsten carbide tool (K-11) at a cutting speed of 240m/min, exhibiting ultra-fine grains of about 0.25 \(\mu\)m [13]. Electron diffraction studies confirmed the presence of twinned martensitic structure, and this serves as evidence for austenitisation of steel in the secondary shear zone.

Modeling of dissolution tool wear by diffusion mechanism:

Ingle [15] has quantified the amount of chemical wear occurring in cemented carbide tool during machining AISI 1045 steel as a function of cutting speed. He demonstrated that at higher cutting speeds, dissolution of the tool into the chip occurs by diffusion mechanism. He determined the amount of tungsten that is atomically dissolved in the chips, which is taken as a direct quantitative measure of chemical wear. He analyzed the data using quantitative modeling of diffusional wear. He concluded that high diffusivity paths are involved, which he attributed to grain boundary diffusion. In order to reconcile the prediction with the experimental data, grain size of the order of 15 nm was required at a cutting speed of 240m/min, whereas the observed grain size at the tool-chip interface was about 0.25 \(\mu\)m diameter. Ramanujachar [16] determined chemical wear by the same technique in machining low carbon free cutting steel of AISI 1215 grade with cemented carbide tool. The experimentally measured wear was more than what could be accounted for by his FEM model. He attributed the enhanced diffusion to high diffusivity paths associated with dislocation pipes. The phenomenological studies in model alloys show that enhanced diffusional crater wear correlates with shear localisation in the secondary shear zone, caused by microstructural softening due to either dynamic recrystallisation or phase transformation. This is attributed to high diffusivity paths associated with shear localisation in the secondary shear zone. More importantly, localised chemical wear at the cutting edge of the tool is related to onset of shear localisation in the primary shear zone. Dynamically recrystallised ultra-fine grains of about 20 nm size are observed in transformation shear bands occurring in the primary shear zone of the chip in machining hardened Fe-28%Ni-0.1% C model alloy and the corresponding phenomenon is attributed to high diffusivity paths associated with shear localisation.

Accelerated chemical wear due to shear localisation in secondary and primary shear zones:

Shear localisation in the secondary shear zone caused by dynamic recrystallisation or phase transformation provides high diffusivity paths through ultra-fine grains, which accelerate the chemical dissolution of the tool into the chip by diffusion mechanism. This causes crater wear to occur on rake face of the tool at tool-chip interface. But a more important effect of shear localisation in the secondary shear zone is to promote shear localisation in the primary shear zone in a coupled manner. Once shear localisation occurs in the primary shear zone due to dynamic recrystallisation or phase transformation, enhanced diffusional wear is localised at the cutting edge of the tool, where the primary shear zone contacts the tool. Figure 3(a) shows shear localised chip morphology caused by the reverse martensite to austenite phase transformation occurring at 400°C in machining Fe-28.9%Ni-0.1% C alloy at a cutting speed of 456m/min and Figure 3(b) the consequent chemical wear localised at the cutting edge of the tool. Figure-3(c) is a dark field image from TEM diffraction of shear localised region in the primary shear zone shown in Figure-3 (a), exhibiting ultra-fine recrystallised grains of about 20 nanometer diameter[14].
tool chemical wear is localised at the cutting edge of the tool, see Figure-3. High dislocation density and increased grain boundary surface associated with ultra-fine grain size observed in shear localised regions are the principal sources of high diffusivity paths that cause enhanced diffusional wear upon shear localisation.

Concept of workpiece engineering to prevent chemical wear:

Since chemical wear is caused by high diffusivity paths due to ultra-fine grains associated with shear localisation, the best strategy to prevent chemical wear is to suppress shear localisation. Since the tribological conditions of seizure at the tool-chip interface cause shear localisation in the secondary shear zone, it is possible to suppress shear localisation in the secondary shear zone by lubricating the tool-chip interface. The effect of in-situ lubrication at the tool-chip interface using glassy oxide inclusions dispersed in the workpiece is to minimise the energy expended in the secondary shear zone. The smaller the energy consumed in the secondary shear zone, the larger the equilibrium shear angle. In consequence, the strain and the temperature in shear plane will be low, which, in turn, will suppress shear localisation in the primary shear zone. In consequence, chemical wear at the cutting edge of tool can be prevented.
Design of inclusion engineered steel

“In the macroscopic case of liquid lubrication, the shearing is taking place within the bulk liquid (that is at a liquid–liquid interface) which usually offers less resistance to shearing (friction) than does a solid-liquid interface” [18]. This principle underlies the concept of inclusion engineering of steels for in-situ lubrication of the tool-chip interface. The steel is designed to be self lubricating by modifying the rheologies of existing oxide inclusions normally present in steel after deoxidation. Glassy inclusions are designed to soften at the tool-chip interface temperature and form in-situ a viscous layer of adequate thickness so that the shear is accommodated within the viscous layer [19]. Thus, the viscous layer of glass (super-cooled liquid) formed in-situ lubricates the tool-chip interface, thereby preventing the occurrence of tribological phenomenon of seizure. The base chemistry of the melt and deoxidation process are controlled so that both exogenous (formed directly in the melt by deoxidation) and indigenous inclusions (formed during solidification of the melt) are glassy in inclusion engineered steel [17]. It should be emphasized that the volume fraction of inclusions required to lubricate the tool-chip interface is very small, being of the order of \(10^{-4}\). The efficacy of the viscous layer in suppressing the tribological phenomenon of seizure was investigated in free cutting steels. Glassy oxide inclusions engineered into AISI 1215 was demonstrated to be more effective than HfN coating in suppressing dissolution crater wear [16], see Figure 4.

Diffusional profiles of tungsten and cobalt in the chips were characterised as a function of cutting speed using SIMS (Secondary Ion Mass Spectro-metry) technique in order to confirm the diffusional wear mechanism. The amount of tungsten that is atomically dissolved into the chip is quantified using instrumental neutron activation analysis by a method originally developed by Ingle [13] and this is used as a quantitative measure of chemical wear. Inductively coupled plasma-mass spectrometric (ICP-MS) analysis was also used to determine the minute concentration of tungsten and titanium in the chip in stead of neutron activation analysis.

By preventing the tribological phenomenon of seizure through inclusion engineering, it is demonstrated that it is possible to prevent chemical wear of the tool by suppressing shear localisation in the secondary and hence primary shear zones.

Steel-making aspects of inclusion engineering:

The thermodynamic modeling is a very powerful tool for through process modeling of design and control of the LMF slag composition so as to control deoxidation of the melt through slag-melt equilibration in LMF. Since the control of the target slag composition in LMF is dependent upon upstream process control involving minimal carry over furnace slag and reproducible recovery of deoxidants during primary deoxidation, a clean steel practice is a precursor for slag-metal equilibration. Slag-metal equilibration is used to control the residual concentration of reactive elements and soluble oxygen in the melt. Calcium treatment is used for the control of exogenous inclusions directly from deoxidation of the melt. The compositional control of the melt chemistry allows the prediction of indigenous inclusions. Fig.5 a-c show the three important steps in inclusion engineering of steel for producing glassy oxide inclusions. Step-1 is the slag-melt equilibration to control the residual aluminum and residual oxygen contents of the melt in LMF (Fig.5a). Step-2 is the calcium treatment to produce the target glassy exogenous oxide inclusions by deoxidation control and modifying existing oxide inclusions in LMF (Fig.5 b). Step-3 is the solidification of steel to form target indigenous glassy oxide inclusions by control of the melt chemistry (Fig.5 c). Thermodynamic modeling is applied in the design and the control of base chemistry, deoxidation and slag-metal equilibration, as well as calcium treatment for inclusion engineering of steel to form the target glassy oxide inclusions [20].

**Figure 4:** Comparison of tool wear in machining of leaded (AISI 12L14), non-leaded AISI 1215 and inclusion engineered AISI 1215 free cutting steels with uncoated cemented carbide (K1) tool and with HfN coated cemented carbide tool (AISI1215) at a cutting speed of 160 m/min.

**Improvement in tool life due to inclusion engineering at higher cutting speeds:**
The inclusion engineering technology is based through process modeling of steel making operation. The goal is to design and target glassy oxide inclusions of required viscosity for in-situ lubrication of the tool-chip interface at high cutting speeds. The glassy oxide inclusions are designed to soften at the tool-chip interface temperature and form a viscous layer of adequate thickness so that the shear is accommodated within the viscous layer. Thus the inclusions are designed to restore sliding tribology at the tool-chip interface in the required range of cutting speeds. This concept was applied on a commercial steel grade 11SMN37 produced by von Moos Stahl AG. This steel is resulphured so that the MnS inclusions aid chip fracture. Figure-6 shows the tool wear results of this non-leaded free-cutting steel compared to conventional leaded steels. The inclusion engineered steel was produced using on-line deoxidation control. The machinability assessment was carried out at 100, 200, 300 and 400m/min cutting speed. Figure-6 shows the flank wear results of inclusion engineered (I.E.) steels in comparison with leaded steel grades with and without Ca treatment as a function of higher cutting speeds. The inclusion engineered steel offers a distinct advantage over leaded steel at higher cutting speeds. The flank wear rate of inclusion engineered steel is considerably less than that of non-inclusion engineered conventional leaded grade steel at speeds of 200 m/min and above whereas it is comparable to leaded steel at a low cutting speed of 100 m/min. The significant reduction in flank wear at higher cutting speeds is attributed to the efficacy of glassy oxide inclusions in lubricating the tool chip interface, which restores the sliding tribological conditions.

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