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Tribological wear analysis

Fagersta, August 2015 – This is the fourth in a series of articles relating to the application of metal cutting tools and the loads generated in machining processes. The first article focused on basic metalcutting concepts and on the relationship between tool geometry, feed rates and mechanical loads in turning operations. The next two articles analysed mechanical and thermal loads in milling. This article explains interactions between the cut chip and the tool via the theories of tribology, a relatively new area of metalcutting load analysis. Tribology studies how surfaces in contact with each other interact at certain temperatures and pressures.

Toolwear theories
In a metal cutting operation, a tool deforms the workpiece material and causes it to shear away in the form of chips. The deformation process generates heat and pressure, loads that eventually cause the tool to wear out or fail. Traditional wear theory says the failures result from friction between the chip and tool, which are in contact but not attached to one another.

Recent research into cutting tool failure mechanisms, however, has determined that the pressures and temperatures in metalcutting, especially those generated when machining high-performance workpiece materials, are such that traditional wear theory does not fully describe what occurs at the chip/tool interface.

Tribological research has determined that the cutting process does not simply involve a single shearing event and subsequent disconnection of chip and tool. In fact, secondary and tertiary connections and disconnections also occur. The chip shears away, adheres to the rake face and then shears away again before finally sliding off the tool. The main wear mechanism is repeated shearing, not friction.

Figures 1 and 2 illustrate the metalcutting process as described via tribology. Figure 1 shows preliminary deformation of the workpiece material in Zone 5. Zone 3 is the separation zone, also called the stagnation point, because the relative movement of the workpiece material and tool at that area is essentially zero. Initial shearing takes place in Primary Shearing Zone 1, where the material shears off and the chip forms. Then, in Secondary Shearing Zone 2, the chip is in contact with the rake face. The high pressures cause the chip to adhere to the rake face of the tool.
Figure 2 provides a closer look at the action in Zone 2. In Zone A, the workpiece material presses against the cutting edge with extreme force and begins to stick to the tool. In Zone B, the material adheres to the rake face. In Zone C, the chip shears away from the rake face and slides across it, ending contact between it and the tool.

Figure 1 also shows secondary shearing on the tool flank in Zone 4. The same shearing and adhering sequence that occurs in Zone 2 on the rake face also happens on the flank. The events in Zone 4 produce flank wear, which is more predictable than the rake face wear in Zone 2 and is relatively harmless. In some workpiece materials, however, shearing on the flank face results in surface hardening or work hardening that has a detrimental effect on the cutting tool and workpiece.

**Built-up edge**

Adhering of workpiece material to the tool rake face begins in thin layers and builds as further layers accumulate. This process can lead to a negative phenomenon known as built-up edge. If a significant amount of material accumulates on the tool, it can change the profile of the cutting edge. The built-up material can also break off and damage the edge. In perhaps the worst case, the edge buildup may be deposited on to the workpiece. In any or all of these situations, edge buildup makes the cutting process unpredictable and uncontrollable. The main focus of tribology is learning what causes built-up edge and what can be done to minimise the problem.

Two aspects of the cutting process contribute to attachment of the chip to the rake face. One factor is the very high pressures and temperatures that exist in the cutting zone. The other factor is the relatively slow speed of the chip across the tool rake face, beginning with zero motion at the stagnation point.
When two materials are in contact with each other under high pressure and temperature, and move slowly, the conditions are prime for them to adhere to one another and for built-up edge to form.

Minimising adherence and the chances for forming built-up edge involves reducing the contact time between the chip and the rake face. The most straightforward solution is to increase the cutting speed and apply a sharper tool. Faster cutting speeds reduce the time the tool and workpiece material are in contact with each other. The resulting higher process temperatures can also reduce the strength of any edge buildup or eliminate it entirely. The sharper tool has a higher approach angle that forces the chip to travel a longer distance over a set period of time, i.e. move more quickly.

Material tendencies
Tribology has gained attention recently because the possibility of built-up edge formation is much greater in workpiece materials that were not commonly machined 20 years ago. For example, the phenomenon of built-up edge occurs but has not been a critical problem in familiar materials such as higher-carbon steels. Application of correct machining parameters generally eliminates adhesion and prevents built-up edge. Further, there is no issue in extremely short-chipping materials such as cast iron. Long-chipping materials, on the other hand, automatically produce longer contact time between the chip and tool, creating more risk for adherence between them. When machining materials such as low carbon steels and aluminium, the possibility of built-up edge is greater.

Built-up edge is most prevalent when machining materials with high ductility, high adhesion tendencies and abrasiveness. A prime example is the family of aerospace and energy industry materials encompassing titaniums, nickel-based alloys and heat-resistant metals. Additional factors promoting edge buildup are the high pressure and temperatures that are generated when machining these tough alloys that have poor thermal conductivity. And in general, cutting speeds for these materials are usually slower than average.

In addition to maximising cutting speeds and tool sharpness, there are approaches to controlling built-up edge that focus on the surface condition of the tool. Somewhat surprisingly, there are two essentially opposing schools of thought on the subject. One approach says that if the surface of the tool is smoother, there will be less energy generated as the chip glides over the tool face. Lower temperatures and less contact reduce tendencies for built-up edge. Contrary to that theory is the concept that a rougher tool surface, formed with ridges or features on the scale of microns, will result in less contact between the chip and rake face and thereby reduce the chance for adhesion. Neither approach is fully proven, and in some circumstances either can be effective.
Conclusion: progress via tribology
The research and theories of tribology, and the process and tool technologies developed to deal with issues such as built-up edge (see sidebar), focus on the goal of producing machined surface quality that meets customer requirements. Next to dimensional and shape requirements, surface roughness is very often how part quality is defined. Especially in aerospace and nuclear applications, surface finish is a top priority because machining imperfections can represent the origin of cracks in critical aircraft and power generation components.

Built-up edge will result in poor surface finishes and a need to change tools frequently. With efforts including tribological research, progress has been made in limiting the occurrence and effects of built-up edge. The progress can be quantified in terms of cost to performance: specifically, how much it costs to generate one square millimeter of correctly machined workpiece surface. Over the last five years, the cost-to-performance ratio for finishing titanium has improved by close to 20 times. Advances in both cutting tool materials and tool geometries have contributed to the success, but most important are carefully developed combinations of the two. Knowledge of the tribological mechanisms involved in tool application can enable machinists to control phenomena such as built-up edge and produce desired surface finishes at lower costs, thereby maximising productivity and profitability.

Sidebar: Application of tribological findings
Tooling engineers apply the findings of tribological research in the development of tools and machining processes. On the process side, application of higher cutting speeds and sharp cutting edge geometries is effective in controlling formation of built-up edge in many circumstances. Other tool geometry choices, such as use of positive rake tools, can help direct cut material away from the workpiece.

Tool coatings are a proven way to reduce adhesion of workpiece material to the cutting tool. Lubricious coatings such as TiN have traditionally been used to ease chip flow in steel machining, as have diamond coatings in aluminium machining applications.

Recent development efforts put strong emphasis on a coating’s role in minimising edge buildup. For example, the newest generation of Seco’s CVD aluminium-oxide Duratomic® coating is based on tribological principles. Development engineers manipulated coating components in response to expanded knowledge of the interactions between the chips and the cutting tool.

Another example of Seco coatings aimed at controlling built-up edge is the new silver PVD uni-coating developed for MS2050 milling inserts. The coating has high heat resistance capabilities and also practically eliminates the occurrence of built-up edge when cutting sticky materials such as titanium. With the absence of built-up edge, the inserts last about 50 percent longer and run at much higher cutting parameters as compared with existing tools.

At the leading edge of tribological research are efforts to make phenomena such as edge buildup positive contributors to machining productivity. In some cases, a thin layer of workpiece material on the surface of the cutting tool can slow the progress of wear. The challenge is to limit this tool protection layer to a thickness that does not affect tool geometry and also does not separate from the tool surface.
Continual introduction of new high-performance alloys that pose increasingly tougher machining challenges make tribological research a dynamic field. Developers of cutting tools and machining processes are using the new perspective provided by tribology to respond to and solve the challenges in innovative ways.

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Headquartered in Fagersta, Sweden and present in more than 50 countries, Seco Tools is a leading global provider of metal cutting solutions for milling, turning, holemaking and toolholding. For more than 80 years, the company has provided the technologies, processes and support that manufacturers depend on for maximum productivity and profitability. For more information on how Seco’s innovative products and expert services bring success to manufacturers across all industry segments, please visit www.secotools.com