Improved Ion Bond Recoating for the Gear Manufacturing Industry

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This article summarizes the development of an improved titanium nitride (TiN) recoating process, which has, when compared to conventional recoat methods, demonstrated tool life increases of up to three times in performance testing of hobs and shaper cutters. This new coating process, called Super TiN™, surpasses the performance of standard TiN recoating for machining gear components. Super TiN incorporates stripping, surface preparation, smooth coating techniques and polishing before and after recoating. The combination of these improvements to the recoating process is the key to its performance.

A primary objective of the development program was to improve the surface finish of recoated hobs and shaper cutters. To this end, research was conducted to study the effect of stripping prior to recoating, to quantify the effect of coating parameters on surface defect formation and to characterize the effect of polishing processes on recoated tool surface finish and edge condition. In addition, both laboratory and field testing were carried out over a period of two years to determine recoating performance on hobs and shaper cutters.

Introduction

The TiN coating studied was deposited by Multi-Arc's ION BOND® Physical Vapor Deposition (PVD) process. In this process, arc evaporation is used to create a highly ionized plasma that allows for deposition of adherent coating at temperatures as low as 400°C (752°F). In a standard coating cycle, tools to be recoated are first fixtured in a vacuum chamber. Following evacuation of the chamber, the tools are heated via one of several methods, dependent on the application. These include ion bombardment, glow discharge or radiant heating. After the tools reach temperature, an arc is struck on multiple titanium cathodes positioned inside the chamber. The arc flash evaporates and ionizes the titanium, which is attracted to the negatively biased components. Nitrogen or another reactive gas is then introduced to a small partial pressure and reacts with the metal to form a coating.

The advantages of the cathodic arc PVD process have been widely reported in the technical literature (Refs. 1–5). The cathodic arc process generates a high level of metal vapor ionization and high ion energy. These lead to exceptional coating adhesion even at low deposition temperatures. The multiple arc sources also provide coating uniformity and allow the deposition of alloy coatings such as TiAlN (Ref. 6). The low deposition temperature allows the coating of tool steels, powder metal alloys, cermets and cemented carbides without affecting their mechanical properties.

The one disadvantage of cathodic arc PVD is the emission of unreacted titanium droplets from the cathodes (Refs. 7–8). These droplets, often referred to as "macro-particles," can lead to growth defects and rough coatings (Ref. 8). Rough coatings, in turn, can lead to a high coefficient of friction, metal pickup and reduced tool performance. The negative effects of rough coating are particularly troublesome when tools are

Newer coatings with TiAlN and TiCN, as well as TiN are now being used for gear cutting tools.

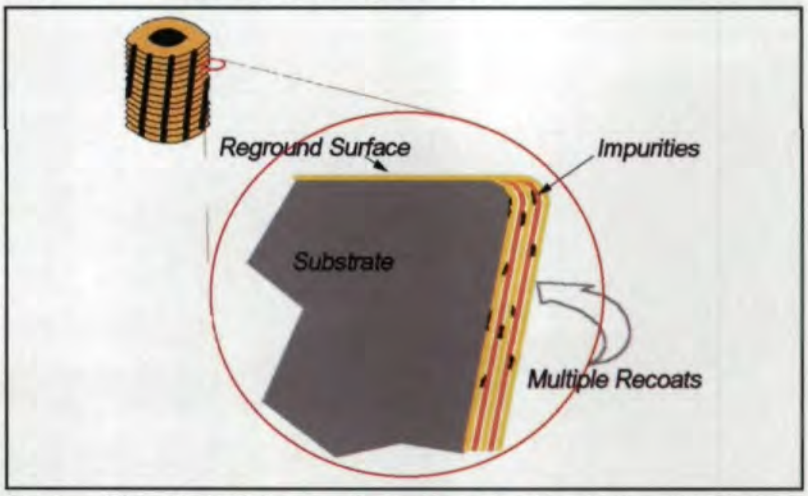

Fig. 1 — Contaminants between coating layers can compromise the adhesion of the coating.

recoated multiple times, as in the case of gear cutting tools. Hobs and shapers are often reground and recoated as many as 20 times. This can lead to excessive roughening on the flanks of hob teeth.

Recoating

PVD TiN coating has become widely used on metal cutting tools since its introduction in the early 1980s. Numerous technical papers have been written confirming the advantages of TiN coating and recoating (Refs. 9–12). In the early 1980s, when recoating was a new concept, users of expensive TiN coated tools, such as hobs, broaches and shaper cutters, noticed that tool performance decreased after sharpening. Sharpened tools cut fewer parts than the original coated tool. Furthermore speeds and feeds often had to be reduced.

Recoating was developed as a program to restore the performance of a sharpened tool to that of the original coated tool. Recoating replaces the TiN coating on the cutting face of a tool each time it is sharpened. The renewed coating allows tools to run at their optimum performance levels. Recoating is a proven process that can cut tooling and production costs by as much as 20–40% (Ref. 10).

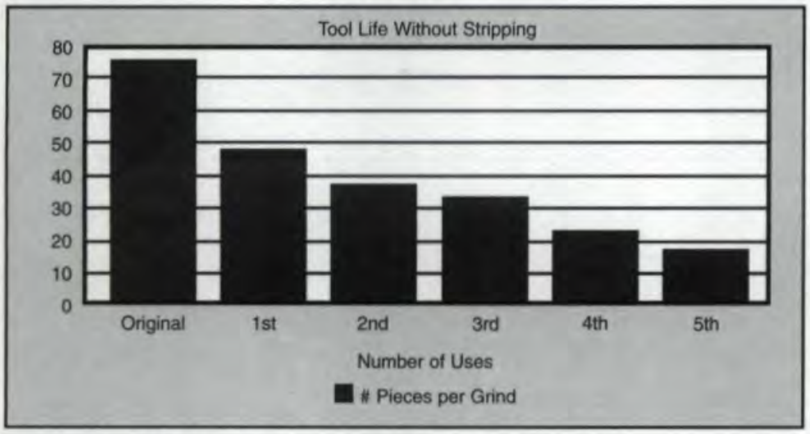

Fig. 2 — Number of pieces produced with recoated TiN shaper cutters.

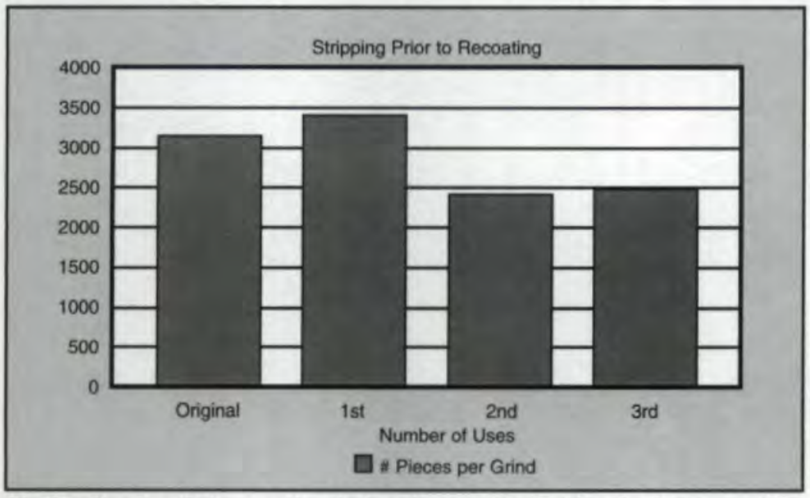

Fig. 3 — Number of pieces produced when shaper cutter is stripped prior to recoating.

In 1993 Multi-Arc initiated a development program to further improve recoated tool performance. As mentioned above, the scope of this program included

- Study of the effect of stripping prior to recoating,
- Study of the effect of coating parameters on defect formation and growth,
- Characterization of the effect of the polishing processes on tool surface finish and edge condition,
- Determination of the performance of Super TiN recoated hobs and shaper cutters.

Stripping

Stripping prior to recoating was investigated to determine if it could reduce or eliminate peel-back on the tooth flank on recoated hobs. Peel-back occurs when the TiN coating delaminates from the surface of the tool or between coating layers. With a recoated hob, as shown in Fig. 1, the adhesion between the successive layers of coating can be compromised by contaminants such as glass bead particles, metal build-up and flakes of old coating. Poor adhesion adjacent to contaminants, in turn, provides an initiation site for coating delamination under the loads experienced during cutting.

The stripping technique studied involved immersing the coated hobs in a hydrogen peroxide based solution at room temperature. The solution chemically reacts with titanium nitride, removing it and leaving a thin oxide on the hob.

The effect of coating build-up on tool performance is illustrated in Fig. 2. Shaper cutters were used to machine 4140 steel gears at a manufacturer of automotive transmissions. After each sharpening the cutters were liquid honed, cleaned and recoated with 2–3 microns of TiN. Fig. 2 shows the number of pieces produced with these cutters during six successive uses of the tool, which represents the average life span. Each point is the average of the results produced by 10 tools. The results show that the number of pieces machined decreased to less than half the original coated tool performance after six recoatings. The drop in performance is attributed in part to changes in tool geometry and clearance angles and in part to coating build-up.

Most of the tool wear was isolated to one or two teeth on the cutter. The majority of the teeth had only .005" (0.13 mm) of wear, but some had peeled back on the tip. Once the coating wore through to the substrate, the deterioration rapidly progressed to a peel-back state. The first teeth to wear through the coating often progressed to peel-back before the machine cycle was finished, resulting in wear as high as .095" (2.4 mm).

When shaper cutters are stripped prior to recoating with TiN, the number of pieces produced decreases, but much less dramatically.

Data from Land Rover, which is illustrated in Fig. 3, shows that an ASP 23 shaper cutter, when stripped prior to every recoating, had a decrease of only around 20% after sharpening and recoating 3 times. These cutters were 5" (127 mm) in diameter and 1.5" (38 mm) high operating at 35 sfm and a .012" (0.3 mm)/stroke.

The results show that the number of pieces machined actually increased to an average of 3,659 pieces following the first recoating when compared to the original TiN coated hob, which machined an average of 3,363 pieces. After subsequent sharpening, stripping and recoating cycles, the life dropped into the range of 2,700-2,800 pieces/grind.

Based on results like these, stripping of old TiN coating prior to recoating has become a standard Super TiN practice.

Defect Formation and Growth

It is well known that hard compound coatings produced using cathodic arc deposition exhibit higher roughness when compared with sputtered and E-beam deposited coatings. Many researchers have connected this problem to the droplet emission during arcing on the target. The protruding features from the coating surface are often called "macros," "macro-particles" or "droplets." Based on Multi-Arc's research, the term "growth defect" would be more appropriate. This conclusion is based on the observation that macro-particles deposited during the conditioning phase of a coating cycle can either grow as the cycle proceeds or be covered over as coating material is deposited. Both growth and macro-particle generation are dependent on process conditions.

Coating process conditions, in particular bias voltage and bias voltage waveform, were studied to determine their effect on defect formation and growth. In order to determine the effect of waveform on defect growth and propagation, several different power supplies were used to deposit TiN coatings on high speed steel coupons in a commercial ION BOND® PVD system. The coating process protocol is listed in Table 1.

Test coupons were fixtured in a rotating fixture facing the cathodes during the conditioning and coating cycles. The typical SEM micrographs of the TiN coating deposited with the best and worst power supplies are shown in Fig. 4. It is obvious from these pictures that the size and

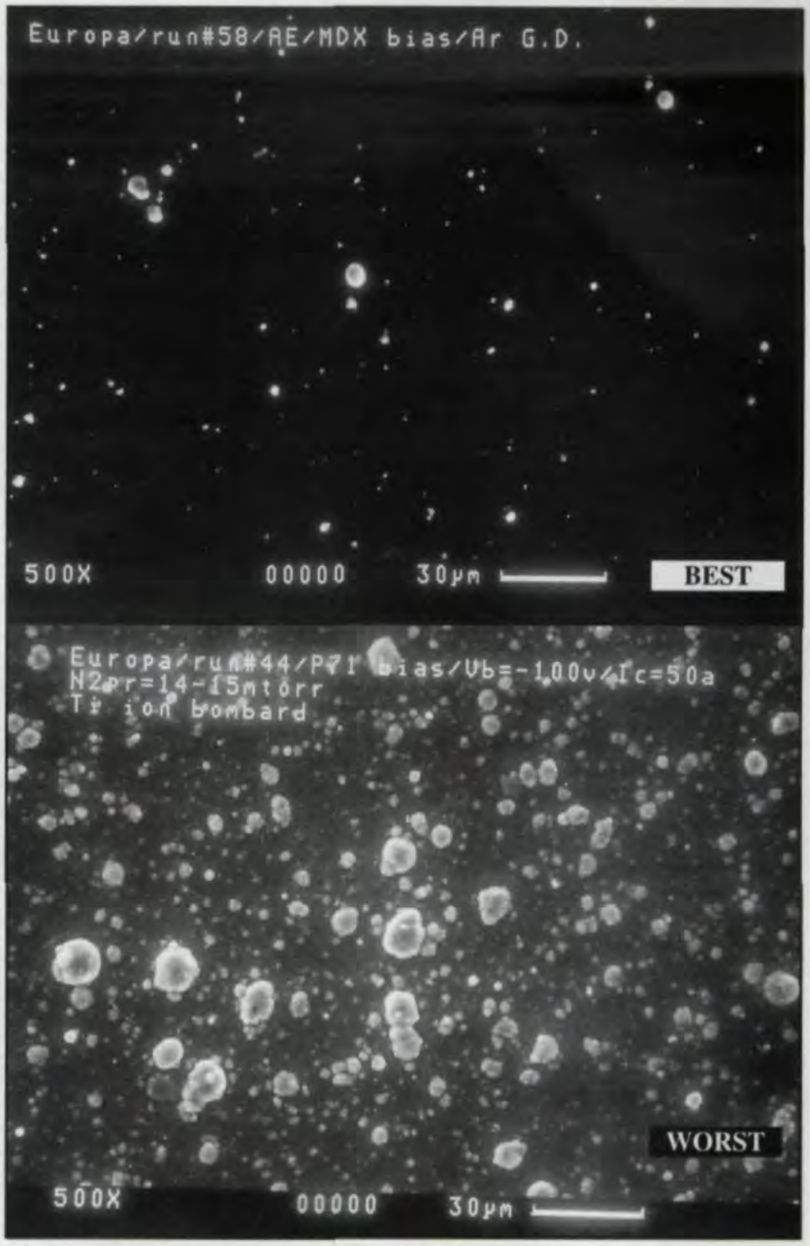

Fig. 4 — SEM photomicrographs of TiN surface for the different bias power supplies.

Table 1 — ION BOND® Coating Protocol	
Conditioning Cycle	**5 minutes Ti ion bombardment in vacuum**
Number of Evaporators	4
Bias Voltage	-1000V
Coating Cycle	**45 minutes w/15m Torr N_2 pressure**
Number of Evaporators	4
Bias Voltage	-100V
Deposition Temperature	900–1000°F
Coating Thickness	~7 microns

Table 2 — Surface Properties of Deposited TiN

Bias Power Supply	Ra, Angstrom	Defect Density (mm^{-2})	Area Covered by Defects (%)
Best	3,000	10,000	3
Worst	7,000	20,000	20

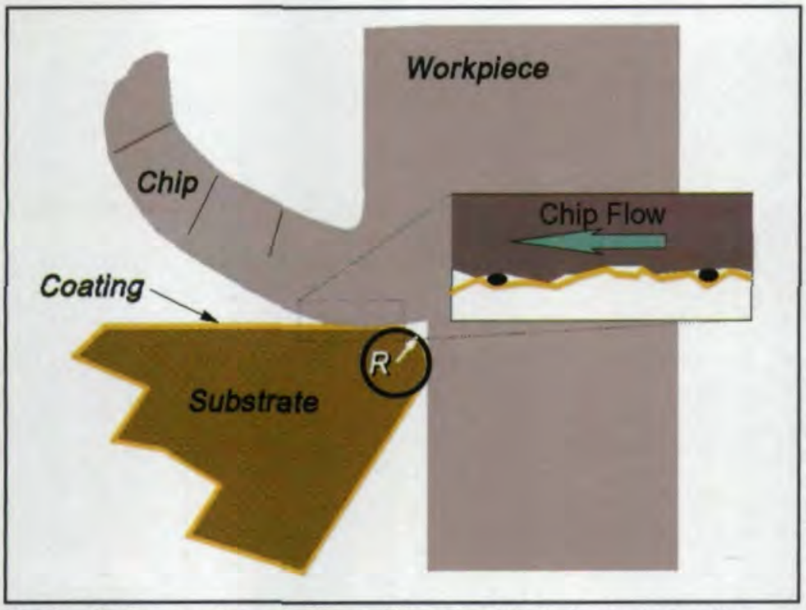

Fig. 5 — Optimum surface and edge conditions for a hob tooth prior to recoating.

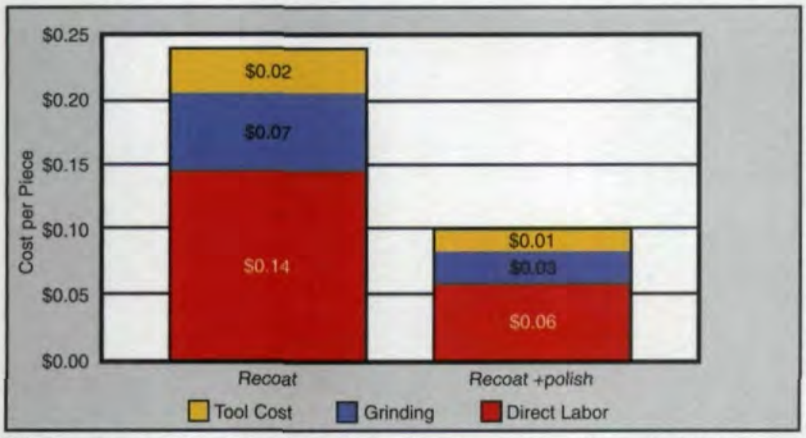

Fig. 6 — Comparative cost savings of recoating alone vs. recoating and polishing.

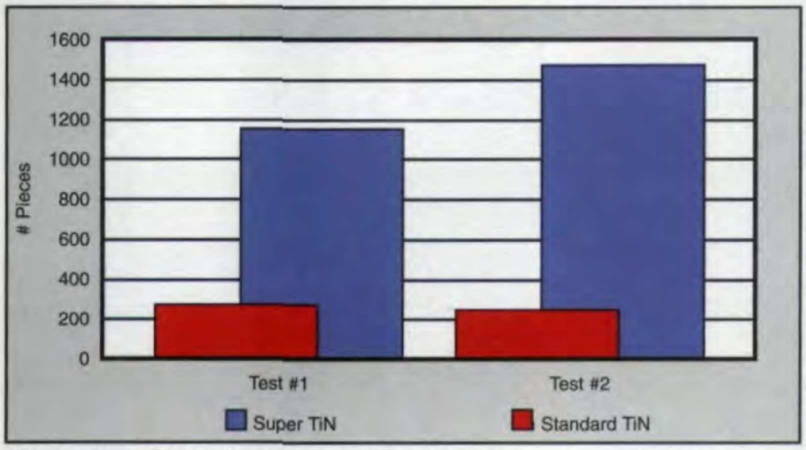

Fig. 7 — Super TiN performance tests at Land Rover.

quantity of defects is quite different. The only difference between the two deposition conditions is the waveform of the bias power supply used.

Some of the surface properties of the deposited TiN are summarized in Table 2.

The improved surface finish and reduced defect density observed with the best power supply tested is the result of its flat DC waveform, which minimizes the growth of macro-particles deposited on the surface. However, the waveform does little to eliminate the original source of macro-particles—the use of titanium ion bombardment to heat and condition tools prior to coating.

To eliminate this source of macro-particles, Multi-Arc developed and tested two alternative heating techniques: radiant heating and glow discharge heating. Radiant heating requires the installation of electric heating elements inside a coating chamber. These are used to heat tools to just below the desired coating temperature. Glow discharge involves the use of gas ion bombardment to heat tools. Typically, mixtures of argon and hydrogen gas are ionized and attracted to the tools by a pulsed bias power supply. This is similar to the process used for ion nitriding of tools, with the exception that ion nitriding uses nitrogen gas.

Laboratory and production testing of radiant and glow discharge heating indicates that both techniques can reduce the macro-particles and improve the surface finish of polished samples to less than 1,500 angstroms (6 micro-inches). More significantly, a practice which incorporates radiant heating followed by glow discharge heating and then a brief titanium ion bombardment can produce surface finishes of 500 angstroms (2 micro-inches). This best practice for smooth, defect-free coating is a key component of the Super TiN process.

Polishing and Edge Conditioning

Several polishing processes were investigated, including harperizing, mikrofinishing and hand polishing. Both harperizing and mikrofinishing are centrifugal polishing processes. Harperizing uses wet $Al_2 0_3$ media, while mikrofinishing uses a dry media consisting of $A1_2 0_3$ or SiC impregnated walnut shells.

Preliminary testing indicated that both harperizing and mikrofinishing hone the cutting edges of hobs and polish the flank and face. The honed radius of the cutting edge was dependent on the polishing time with both processes. The radius varied from .0005–.0007" (0.013–0.018 mm) with the harperizing process. The hone produced with the mikrofinishing process was typically .0003–.0005" (0.008–.013 mm) by comparison. The optimum surface and edge conditions for a hob tooth prior to recoating are shown in Fig. 5.

Field testing was carried out at a manufacturer of marine and industrial transmissions. The objective of the field testing was to produce more pieces between resharpenings, translating into more machine up time. The protocol called for testing of TiN recoated hobs versus polished and TiN recoated hobs. TiN recoated hobs were processed according to Multi-Arc's standard process path. The nominal TiN coating thickness was 2–4 microns. Polished and recoated hobs were polished in a mikrofinish centrifugal polisher both before and after recoating.

A Liebherr LC255 CNC hobber was selected for the test. Test tools were 3.25" (83 mm) diameter TiN coated M2 hobs with 33 teeth and D.P.s of 11.3937. The material machined was 4047 steel with a hardness of 180–210 BHN. Hobs were run at 430 rpm and feed rate of 0.115" (3 mm) per revolution. Hobs were sharpened in-house on a Star CNC grinder with a borazon wheel. The material removal on both TiN recoated and polished and recoated hobs was 0.012" (0.3 mm).

Test results showed that polishing improved the hobs' as-ground surface finish from 11–12 micro-inches (Ra) to 6–7 micro-inches (Ra). A similar improvement was observed when the hobs were polished after recoating. The polishing also honed the cutting edge and removed a burr that was normally observed on as-ground hobs. This was a subtle, but significant benefit. Burrs can be problematic when they are coated with TiN. Forces encountered during cutting cause the burr to break off, exposing uncoated substrate and a possible initiation site for peel-back.

The most significant result was the reduction of the shift rate from 0.007" (0.18 mm) per piece to 0.003" (0.08 mm) per piece. This more than doubled the life of polished and recoated hobs compared to those that were only recoated. The cost savings achieved are illustrated in Fig. 6.

Similar results were obtained at a Big Three automotive manufacturer when TiN recoating was replaced with recoating plus polishing. Flank wear was reduced from 0.008" to 0.004" (0.20 to 0.10 mm) when hobbing with normal operating parameters and a shift of 0.0016" (0.040 mm) per piece. This allowed the shift rate to be reduced to 0.001" (0.025 mm) while still obtaining the normal 0.008" (0.20 mm) flank wear on hobs. The net result: The recoated and polished hobs had almost twice the tool life compared to recoated only hobs.

Pre-coat and post-coat polishing techniques were combined with improvements in stripping practice, surface preparation and coating process in the United Kingdom around 18 months ago, thereby establishing the Super TiN recoating process.

The process specification for Super TiN encompasses the following improvements:

- Strip any old coating prior to recoating.
- Microhone or liquid hone with alumina to remove residual oxides from the stripping process. This dulls the surface, but actually achieves an improvement in surface roughness.
- Mikrofinish to further smooth the uncoated substrate and achieve a controlled hone on the cutting edge, thereby eliminating microscopic burrs, strengthening the cutting edge and providing a better coating growth site.
- Heat tools to coating temperature using radiant heaters and/or glow discharge.
- Coat/recoat to a minimum thickness of 4 microns.
- Finish polish to remove droplets and surface defects.

TiN-coated shaper cutters.

Land Rover began testing Super TiN in late 1994. The high surface finish and excellent adhesion of Super TiN allowed an increase in the number of passes per grind on some of the hobs used in the transmission manufacturing department. The results of testing at Land Rover are illustrated in Figs. 7 and 8.

Results for a 4" (102 mm) diameter x 6" (152 mm) long solid ASP 23 hob with 16 gashes appear in Figure 7. This hob machined helical gears (7 DP, 40 Teeth, 20° pressure angle, 168 mm diameter) on a Hurth WF10 hobber at 200 rpm and a feed of 0.120" (3 mm) per revolution.

Standard TiN coated hobs ran for 1 pass with a shift rate of .010" (0.3 mm). Super TiN coated hobs ran for 3–5 passes with the same shift rate. This increased the number of pieces per grind from 400 to over 1,200 on average.

Fig. 8 shows the results for a 4" (102 mm) diameter x 8" (203 mm) long solid ASP 23 hob with 15 gashes. The test was run on a Gleason 777 CNC hobber machining 590 Mi7 steel gears.

With Super TiN, it was possible to increase the spindle speed from 300 to 345 rpm while maintaining a feed rate of .090" (2.3 mm) per revolution. This resulted in a cycle time reduction of over 10%. In addition, the number of passes was increased from two with standard TiN recoating to four with Super TiN. This doubled the hob life from 400 to 800 pieces per grind.

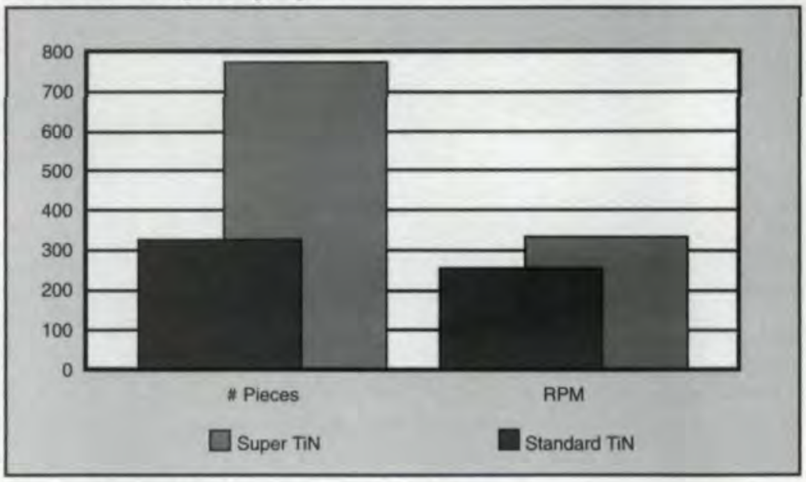

Fig. 8 — Super TiN performance tests at Land Rover.

Table 3 — The Effect of Super Surface Finish	
Super TiN Process Step	**Surface Finish (micro-inch, Ra)**
As Received	~35
Micro-Polish (6 minute cycle)	~35
Vapor Blast + Micro-Polish	18–20
TiN Coat	15–20
Post-Coat Micro-Polish (5 minute cycle)	12–15

The improvement in hob performance with Super TiN is directly related to the improved surface finish created by the combination of surface preparation, coating and post-coat polishing. Data obtained at Eaton, another U.K. account, illustrates this point. A 5" (127 mm) x 7" (178 mm) hob was evaluated for surface finish at each step of the Super TiN recoating process. The surface finish measurements, which are summarized in Table 3 above, show that this hob was quite rough as received. Micro-polishing alone had no significant effect on the rough surface finish. Vapor blasting followed by micro-polishing, however, improved the surface finish from 35 micro-inches to 18–20 micro-inches. Following coating, the surface finish was still in the range of 15–20 micro-inches. This was further improved to 12–15 micro-inches by post-coat micro-polishing.

Looking Forward

Based on the successful test results, Multi-Arc has upgraded its coating systems and installed polishing equipment at multiple coating centers in North America and the United Kingdom. Surface preparation and polishing are now a routine part of the recoating service provided by these centers. With Super TiN now available to customers in the gear cutting industry, Multi-Arc is looking at new ways of making recoating even more cost effective.

Titanium aluminun nitride (TiAlN), titanium carbonitride (TiCN), molybdenum disulfide (MoS_2) and multilayers of these coatings offer advantages over TiN in specific gear cutting applications. Further in the future, research and development projects are focusing on optimizing coating properties for high speed machining and dry hobbing.

Conclusion

• Polishing before and after recoating improves the surface finish and hones the cutting edge of hobs, shaper cutters, broaches and other tools.

• Super TiN, which combines pre-coat and post-coat polishing techniques with improvements in stripping practice, surface preparation and coating process path, further improves the life of gear cutting tools. Tool life increases of 200–500% are possible.

• Super TiN can reduce cost per component by over 50%.

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