Improved Wire Quality with Advanced TCHP Dies

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Abstract

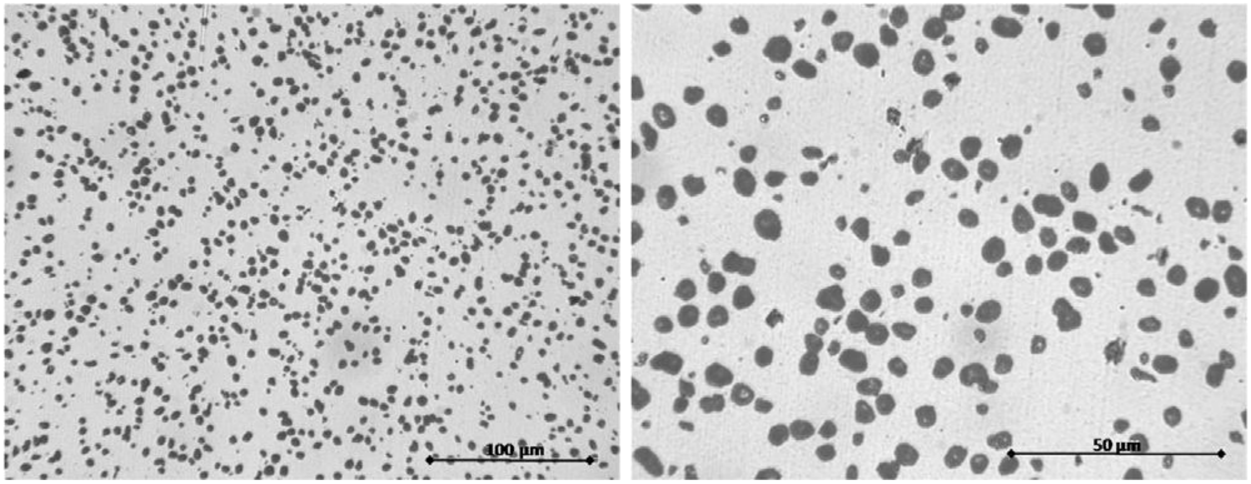
The manufacturing industry is driven by the desire to increase production rates while keeping costs low. In the wire die market, this necessitates increased die performance and longevity under extreme processing conditions. Additionally, the continued evolution of the "standard" for wire properties in products such as steel tire cord filament can be witnessed through the tensile strength increase from 2500MPa to nearly 5000MPa today. These improvements in the strength/weight ratios have opened many new doors in the wire industry, but the decreased toughness associated with this strengthening has also presented many challenges. Productivity improvements in secondary processing, such as stranding and cabling of high strength steel tire cord, have been an area of interest for Allomet Corporation as it continues to expand the use of its advanced TCHP materials throughout the wire die industry. The superior quality of wire drawn through these TCHP dies manifests up to a 55% reduction in wire ruptures in secondary processing operations compared with wire drawn using conventional WC dies. This paper will highlight the characteristics of wire drawn through these TCHP dies and also provide insight into the factors governing these improvements in wire quality.

Introduction

Tough Coated Hard Powders

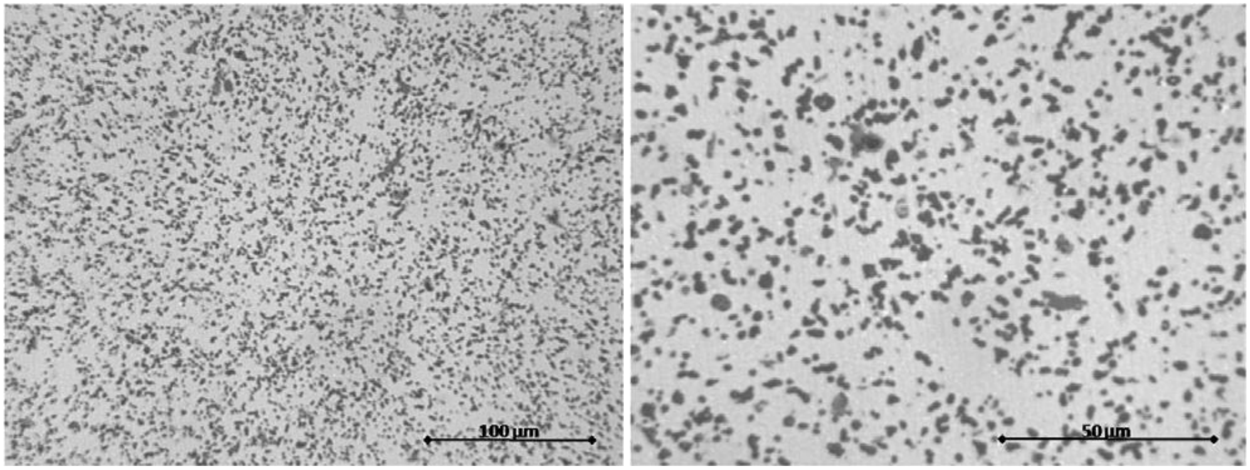
Tough Coated Hard Powders (TCHPs) are a new family of patented, high performance metallurgical powders that incorporate unprecedented combinations of property extremes. They represent a class of engineered microstructure P/M-based hardmetals having combinations of critical properties that improve performance and productivity. These engineered property combinations include *toughness, abrasive and chemical wear resistance, low coefficient of friction, and light weight…*at levels not previously seen. TCHP powders can be fabricated into a multitude of industrial metal-cutting and wear parts while leveraging their key attributes to improve manufacturing productivity. These TCHP powders are created by incorporating hard particles in a tough matrix using proprietary manufacturing technologies. Engineered nanostructures are created by encapsulating extremely hard "core" particles with a tough outer layer(s), for example tungsten carbide and cobalt, which in the consolidation process become a contiguous matrix. TCHP powders and consolidated die blanks are manufactured and sold by Allomet Corporation (North Huntingdon, PA) as EternAloy®. The processing, structure and properties of TCHP have been described in previous publications.[1, 2] Representative "core" particles include those traditionally used for extreme wear resistance [*e.g.,* diamond, cBN, Ti(C,N), TiN, Al_2O_3, …]. One typical TCHP material utilizing alumina (Al_2O_3) as the core particle has shown to be highly resistant to abrasive wear and is especially suited to wire draw dies and similar applications. Example microstructures of an alumina TCHP grade are shown in Figure 1. Another recently developed EternAloy® material utilizes titanium carbonitride Ti(C,N) core particles to provide higher thermal conductivity along with high hardness in a tungsten carbide and cobalt matrix. Microstructural photos of this material are shown in Figure 2. The Ti(C,N) TCHP grade is beginning to demonstrate significant performance advantages over the alumina TCHP in high speed wire drawing where high heat generation at the die-wire interface rapidly wears WC-Co dies. Allomet continues to develop additional TCHP grades as this group of new materials expands to meet performance demands of more applications.

Figure 1. Alumina TCHP Microstructure



Shown in Figure 1 are SEM photos, collected in backscattered electron mode (BSE) at 200x and 500x, of the alumina TCHP consolidated microstructure. The dark circular areas in the microstructure are the hard, alumina core particles and the bright regions illustrate the WC and Co matrix.

Figure 2. Titanium Carbonitride TCHP Microstructure



Shown in Figure 2 are SEM photos, collected in backscattered electron mode (BSE) at 200X and 500X, of the Ti(C,N) TCHP consolidated structure. The dark areas in the microstructure are the hard, Ti(C,N) core particles and the bright regions illustrate the WC and Co matrix.

Manufacture of Steel Tire Cord

Considerable literature exists regarding the manufacture of high carbon steel wire or filament, its cabling into strand, and the ultimate assembly of these strands into tire cord. A detailed review may be found in the *Steel Wire Handbook*.[3] Suffice it to say that electric arc furnace and basic-oxygen furnace practices are used to directly cast billets or continuous blooms which are hot rolled to rod diameters in the 5 to 11 mm range at speeds of 60 m/s or higher.

The rod stock is processed so as to develop a *patented* microstructure. This microstructure consists of fine pearlite, containing alternating layers of ferrite and iron carbide. In its cold drawn form, the "patent wire" has the highest tensile strength range of any structural metal. This pearlitic microstructure can be largely developed by in-line controlled cooling of the hot rolled rod, such as with the Stelmor process. More rigorous transformations to fine pearlite can be achieved through isothermal exposures using fluidized beds, molten salt, lead baths, and other media.

The patented rod may be directly drawn to a diameter of approximately 2 mm, at which point it is electrolytically plated with brass. The brass thickness is a few tenths of a micron. This coating enhances lubrication in the final wet drawing and facilitates the wire's adhesion to rubber. The brass plating may also be undertaken after patenting the initially drawn wire. In any case, the final drawing process generally involves wet drawing through 20 to 25 dies to a final diameter in the 0.25 to 0.4 mm range.

Subsequent to drawing, the filament wire is processed to various cord configurations, starting with the stranding operation.

The efficacy and options of filament wire use in tire reinforcement are increased with increases in wire strength and decreases in wire diameter. Strength increases can be achieved with extended drawing and increased carbon content, and current development and state-of-the-art practices involve carbon levels as high as 0.90%, diameters as low as 0.1 mm, and tensile strengths as high as 5000 MPa. It is a major issue that the drawing and forming of such fine, ultra-high strength wire is complicated by increasing break frequency, as strength increases. Breakage during drawing and stranding results in lost product and increased down time. For example, it is estimated that the typical stranding break results in twenty minutes of down time.

Optimized process design is, of course, fundamental to these continuing achievements, and die selection and management have been important. For example, a combination of PCD and WC dies may be employed when drawing 1080 steel. That is to say, many producers have transitioned to a split die line involving both polycrystalline diamond (PCD) and cobalt bonded tungsten carbide (WC) dies. A typical split die line includes PCD dies at several of the entrance and exit locations and conventional WC dies in the central locations. The PCD entry dies "clean" the freshly brass plated wire and produce a uniform wire for the central die section. The PCD exit dies produce an improved surface finish and minimize the diameter variations at fine wire diameters. This also allows the WC central die positions to have a somewhat steady wear scenario, and practical die replacement protocols are possible.

Objective of This Study

The context stated above allows for a direct comparison of the performances of TCHP dies and WC dies in the tire filament drawing and stranding processes. This comparison was the objective of this program, and the results and implications are presented below.

Results and Discussion

Testing Overview

The results referenced in this paper were gathered over a period of seven weeks of continuous high speed drawing and stranding of high carbon steel tire cord filament. (The scheduled testing timeframe was eight weeks, and this was completed with an 85% machine uptime efficiency.) The results of two lines were compared. One line was a “Control” line with PCD entry dies, WC central dies, and PCD finish dies. The other line was a “Test” line that replaced the WC dies with TCHP dies . Schematic representations of these two lines are set forth in Figure 3. In addition, the results of these two lines and the plant-wide averages during the same period were also compared. The wire diameter and surface finish of the wire were checked daily and recorded, and representative scanning electron micrographs are shown in Figure 3. The parameters tracked throughout this test were the overall die life in wet drawing operation, and stranding performance of drawn wire in the secondary cabling operation. The overall die life was calculated by dividing the total mass of drawn wire by the total number of central section dies used during the testing timeframe. Similarly, stranding performance was determined by dividing the total mass of stranded wire by the number of ruptures during stranding. That is:

$$Die\ Life\ (kg/die) = \frac{Wire\ Drawn\ (kg)}{Dies\ Used}$$

$$Stranding\ Performance\ (kg/Rupture) = \frac{Wire\ Stranded\ (kg)}{Wire\ Ruptures}$$

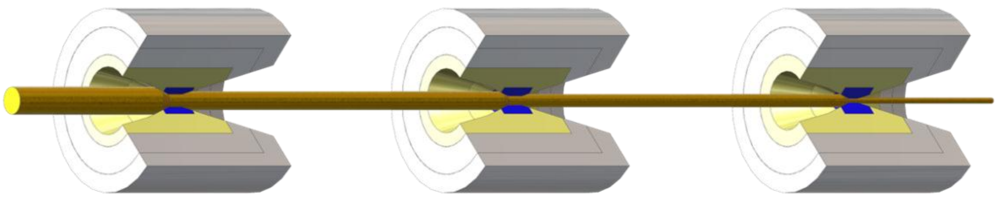
Test Results

At the completion of the scheduled test timeframe, the line segment with the TCHP die sequence showed an increase in overall die life of greater than 85% compared to the corresponding WC dies in the conventional WC control line. Tracking showed that the wire diameter was consistent after each die throughout its service life. Analysis of the tested TCHP dies showed only minor wear, and future testing will be extended to determine the critical drawing time for these TCHP dies.

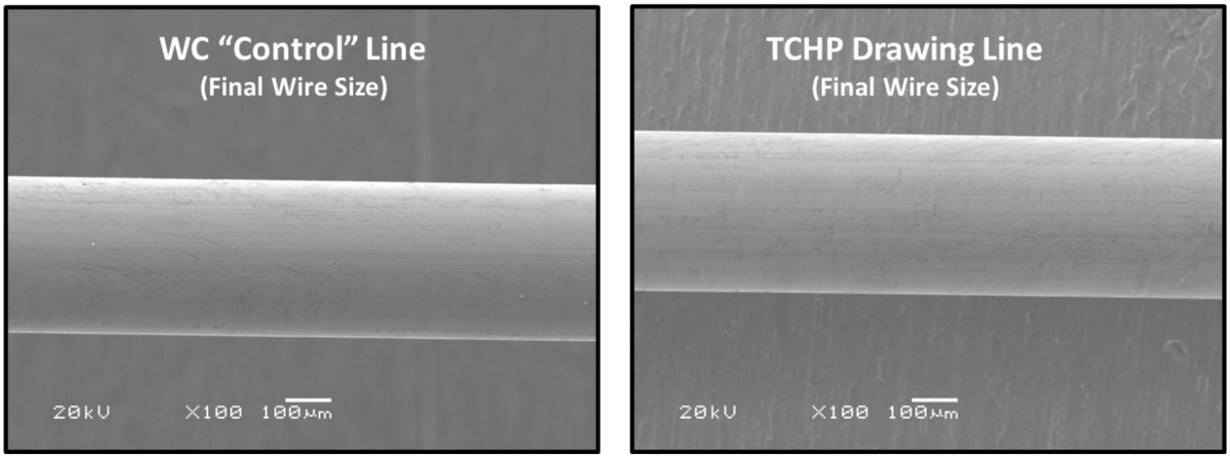
Beyond this, the TCHP-die-containing test line reduced the number of stranding breakages by over 55%. In other words, the mass of stranded wire per break more than doubled (increased by a factor of 2.21).

This reduction in wire breaks during stranding is a significant benefit to the tire cord manufacturer due to: a) significant reductions in stranding operation downtime, b) increased product yield, and c) improved strand quality. That is, each break represents either a segment of time where an operator is dedicated to welding and re-stringing the machine, or scrapping the remaining spool. (If the required amount of stranded wire on a spool is small, it may not be cost effective for an operator to bother restringing the machine in order to complete the spool.) Moreover, the stranded wire is more valuable to an end user with fewer or no welds and other inconsistencies that could potentially increase downtime at their facility.

Figure 3. Schematic representation of “Test” and “Control” lines, together with scanning electron micrographs of the as-drawn wire surfaces.



	Entry Dies	**Central Die**	**Finish Dies**
TCHP Test Line	PCD	TCHP	PCD
“***Control” Line***	PCD	WC-Co	PCD



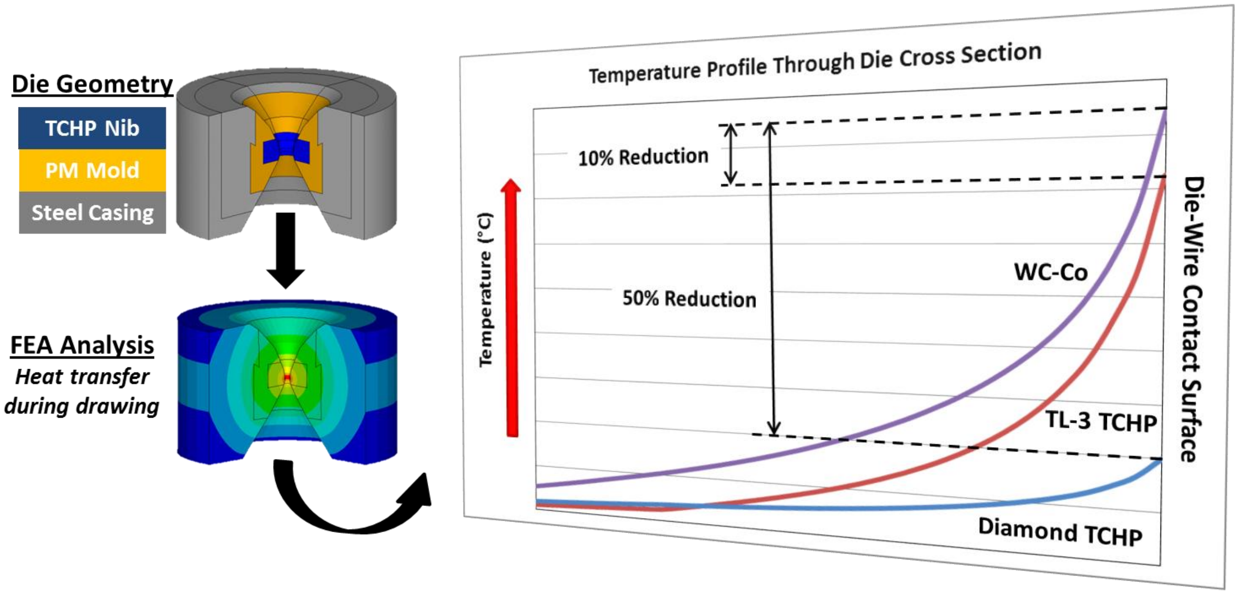
Potential Factors Affecting Steel Tire Cord Wire Breakage

For the TCHP dies, the increased die life and decreased number of stranding breaks reflect advantageous conditions at the wire-die interface during the central drawing, and this improvement must be attributed to the unique composite of TCHP at the interface. A comparison of the as-drawn wire surface characteristics (Figure 3) suggests that, in this instance, the frictional conditions do not change much when TCHP dies are used. However, a strong argument can be made, through the use of Finite Element Modeling, that the temperature at the wire-die interface is not as high when TCHP dies are used.

Finite Element Modeling has been utilized in order to analyze the thermal performance benefits of using TCHP dies over conventional WC-Co material. Figure 4 shows the TCHP die configuration used in the thermal-linear simulation. In the case of the modeling of the WC-Co die, the disk geometry was replaced with an R-2 nib. A constant heat flux was applied on the die-wire contact interface while convection cooling was applied to all of the exposed die faces. During this analysis, a steady state temperature profile throughout the radial component of the wire die monitored.

Using ambient temperature as a "zero" reference base, Figure 4 shows that a TL-3 TCHP grade wire drawing die has an estimated operating temperature at the die-wire interface that is roughly 10% lower than that of a conventional WC-Co die. This operating temperature could be reduced even further, by over 50%, through the use of a diamond core TCHP material. This heat reduction at the wire-die interface may be fundamental to improved resistance to breakage during stranding.

Figure 4. Comparison of die cross section temperature profiles for the cases of a WC die, a TL-3 TCHP die, and a diamond TCHP die.



Shown in Figure 4 is the model used in Finite Element Modeling simulations to determine the temperature profile throughout the die cross section.

Suggestions regarding a possible effect of die-wire interface temperature must be regarded as preliminary at the point and should not obscure the strong empirical evidence that TCHP dies are very advantageous in the manufacturing and stranding of tire filament. That having been said, some important points can be made. Temperature effects in fine wire drawing are often discounted because the high surface-to-volume ratio of the wire allows for substantial interpass cooling. However, the wire surface can get quite hot during the pass, particularly as the wire approaches the exit of the drawing zone. This undoubtedly affects the behavior of the lubricant. However, in this study, the use of TCHP dies instead of WC dies seems to have had little effect on the friction conditions, even though the TCHP dies are more wear resistant. Surface heating is also related to tensile residual stress development at the wire surface. However, this is unlikely to be a factor with stranding breaks, since the residual stress pattern is wholly re-established with each pass, and at stranding will surely reflect drawing through PCD dies.

The phenomenon that seems most compatible with the observed behavior is that of dynamic strain aging near the steel wire surface. Dynamic strain aging is very sensitive to temperature and strain rate, with the maximally strain aged steel having a greater strength, together with reduced toughness. In principle, either factor (strength or toughness) could be fundamental for reducing the vulnerability to stranding breaks, since any changes in the mechanical properties generated during central die drawing could carry through to the finish-drawn condition. Actually, at the high strain rates involved with wire drawing, drawing temperature reduction can be associated with reduced strain aging [4], and *greater toughness*, and this seems likely to be the dominant factor. In any event, a full understanding will require further basic studies.

Looking Forward

New Grades of TCHP Materials

Allomet is currently developing new grades of TCHP materials that address specific market needs. The most recent addition to the TCHP portfolio is a diamond "core" particle coated with an outer shell of tungsten carbide, and subsequently, cobalt. This new TCHP composition, along with several others that are in the development pipeline, allows Allomet to produce specific mechanical and thermal properties in order to address specific applications. In the case of wire drawing, this diamond TCHP grade will have a toughness well above that of standard PCD, and a hardness and thermal conductivity that far exceed any conventional tungsten carbide dies. These targeted material properties should increase the robustness of standard PCD dies and also lead to significantly lower operating temperatures than those of conventional tungsten carbide dies. As the portfolio of TCHP materials grows, Allomet will strive to continue addressing technical market challenges and pushing the envelope on material development.

Conclusions

A study has been undertaken to evaluate the use of TCHP dies in the drawing of high carbon steel filament, preparatory to its stranding en route to tire cord manufacture. The results of two different lines were compared. One line was a "Control" line with PCD entry dies, WC central dies, and PCD finish dies. The other line was a "Test" line with TCHP dies in the central locations instead of WC.

At the completion of the scheduled test timeframe, the line segment with the TCHP die sequence had an overall die life increase of greater than 85% compared to the corresponding WC dies in the conventional WC control line. The wire diameter was tracked after each die and was consistent throughout its service life. Actually, an analysis of the tested TCHP dies showed only *minor wear*, and future testing will be extended to determine the critical drawing time and full life for these TCHP dies. Beyond this, the wire from the TCHP-die-containing test line displayed over a 55% reduction in stranding breakages or an increase in the mass of stranded wire per break at a factor of 2.21.

The observed behavior is consistent with dynamic strain aging near the steel wire surface. Finite Element Modeling reveals that TCHP dies experience reduced heating at the die-wire interface, which should increase the toughness of the near-surface wire metal. The development of diamond TCHP dies will even further decrease the die-wire interface temperature.

References

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