Commercial Evaluation of TCHP Dies

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Abstract

Tough Coated Hard Powders (TCHPs) are a new family of highly wear resistant materials involving hard "core" particles, such as aluminum oxide or titanium carbonitride, firmly embedded in a tungsten carbide/cobalt matrix. Carbon steel wire drawing dies are an obvious application for TCHP, and TCHP die lives are typically seven times those manifested by conventional carbide dies. This paper reviews pertinent structure-property-processing aspects of TCHP materials, along with commercial availability and process economics considerations. This paper also summarizes recent results from commercial drawing trials for fine, high carbon steel wire. Recommendations for further applications and evaluations are made, and prospects for further die material development are cited.

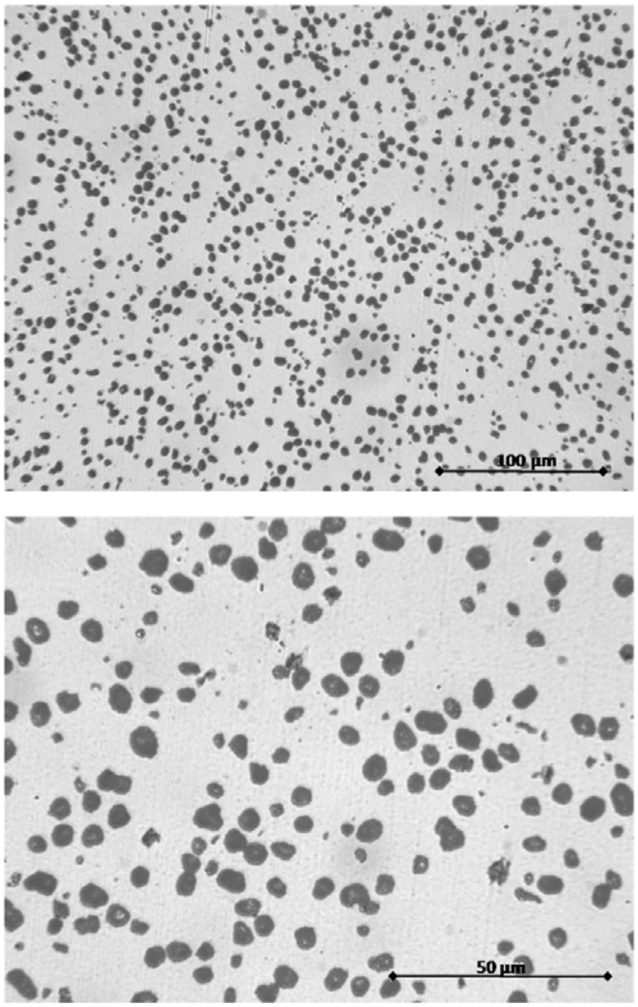
Introduction

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 provide improvements in 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 to leverage their key attributes to achieve manufacturing productivity improvements. These TCHP powders are created by incorporating hard particles in a tough matrix using proprietary manufacturing technologies. Engineered nanostructures are designed by encapsulating extremely hard "core" particles with a tough outer layer(s), for example tungsten carbide and cobalt, which in the consolidation process becomes a contiguous matrix.

TCHP powders and consolidated die blanks are manufactured and sold by Allomet Corporation (North Huntingdon, PA) as EternAloy®. TCHP processing, structure and properties 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 utilizes alumina (Al_2O_3) as the core particle and this material 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.

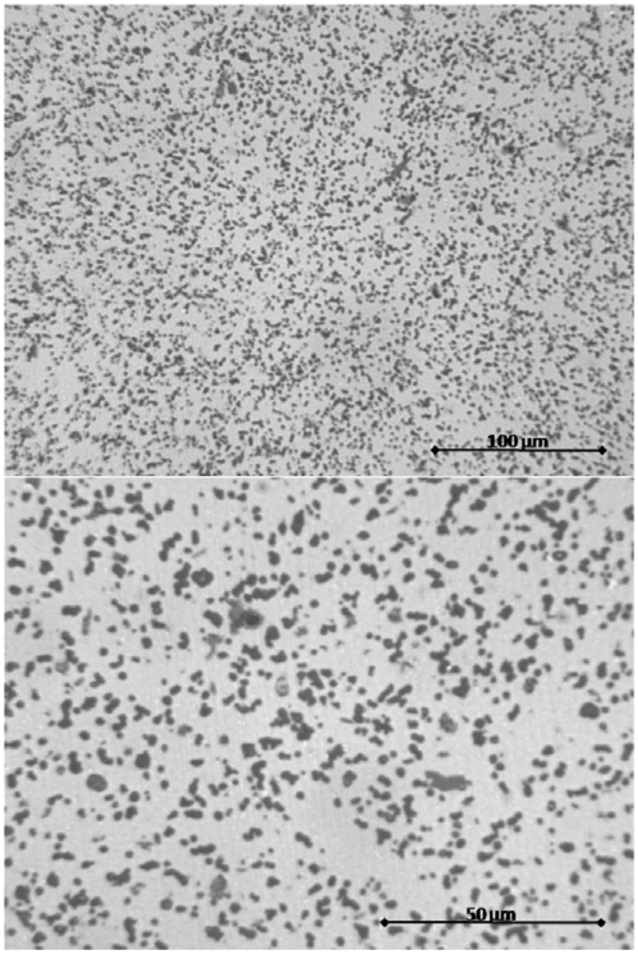
Another new recently developed EternAloy® material utilizes core particles of titanium carbonitride Ti(C,N) which provide higher thermal conductivity along with high hardness, in a similar tungsten carbide and cobalt matrix. Microstructural photos of this are shown in Figure 2. The Ti(C,N) TCHP grade 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 structure. 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.

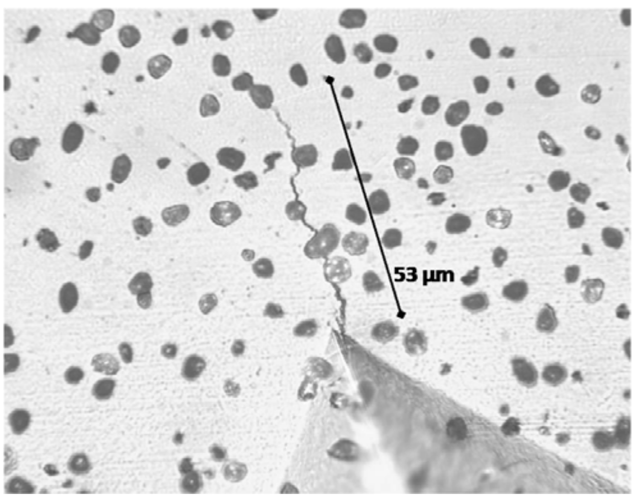
Performance Benefits of TCHP

Under typical working conditions, such as those experienced at the die surface in high speed wire drawing or during high speed metal cutting, the wear rate of the die/tool accelerates as it begins to soften and deform at the higher operating temperatures. Conventional WC-Co materials are certainly limited by loss of hardness at these temperatures. In contrast, TCHP materials retain their higher hardness at these higher temperatures due to the incorporation of hard "core" particles in the tough microstructural matrix. Different core particles impart varying thermal conductivity to the consolidated material as needed to meet demands of different wire drawing and cutting tool applications.

The ability of TCHP grades to maintain high hardness at elevated temperatures is a key benefit that is unmatched by WC-Co parts. This is especially critical for high speed machining using sintered TCHP cutting tools for achieving productivity gains (and higher metal removal rates) under challenging machining parameters. Managing and properly distributing the heat created during a wide variety of cutting conditions is important for determining the optimal application of TCHP inserts. Similarly, the higher hot hardness of TCHP grades, relative to WC-Co dies used in wire drawing, enables a much longer die life and a more consistent wire diameter throughout the spool.

The capability to resist crack propagation is another important attribute of TCHP grades. As shown in Figure 3, an indenter was used to intentionally start a crack in a sintered alumina TCHP part; the resulting path of crack progression was then observed. It can be seen that the crack is deflected by, into, and around the core particles. Thus much of the crack energy is partially absorbed by the core particles, resulting in a higher toughness material. In addition, Allomet has performed Palmqvist Toughness Tests on sintered TCHP materials and find higher toughness for both alumina and Ti(C,N) TCHP grades when compared with WC-Co grades of similar particle size.

Figure 3. Resistance to crack propagation



Shown in Figure 3 is an example of TCHP's resistance to crack propagation. An indenter was used to intentionally start a crack in a sintered alumina TCHP part, and its path of crack progression was observed. It can be seen that the crack is deflected by, into, and around the core particles. Thus much of the crack energy is partially absorbed by the core particles resulting in a higher toughness material.

TCHP Part Fabrication

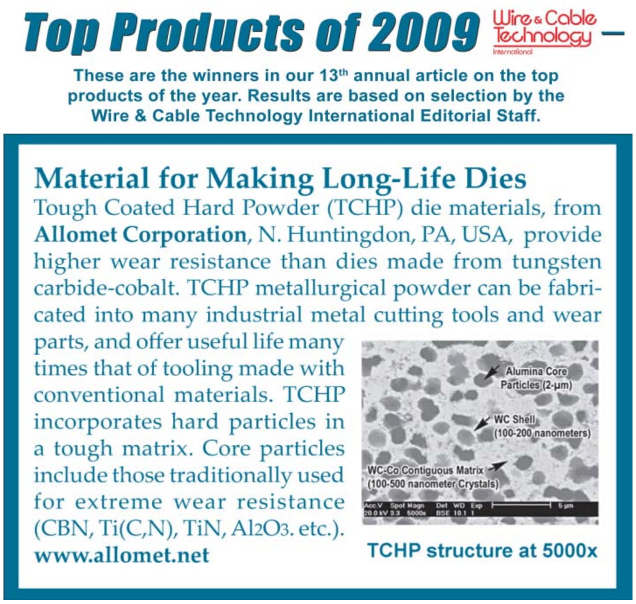
TCHP powders can be consolidated into solid parts utilizing the same equipment and very similar processing parameters as conventional tungsten carbide materials. Allomet has established the technology for TCHP powders to be pressed and sintered or sinterHIPped using conventional carbide manufacturing practices and existing equipment.

TCHP parts can also be ground and final shaped in the same manner as conventional tungsten carbide grades. Additional applications include: round tools, nozzles, construction products, mining products, oil and gas, automotive, aerospace, various cladding applications, and many other applications where wear resistance is critical.

WCTI Top Products Citation

In January 2010, Allomet's TCHP materials were selected as one of *Wire & Cable Technology International's* Top Products[3]. This citation is shown in Figure 4. As Allomet expands its TCHP grade offerings to target many diverse applications, further mentions of Allomet's products for potential industry-changing productivity gains will emerge as publication of performance benefits continue to grow in the technical literature.

Figure 4. *Wire & Cable Technology International* Top Products citation


Top Products of 2009 — Wire & Cable Technology International

These are the winners in our 13th annual article on the top products of the year. Results are based on selection by the Wire & Cable Technology International Editorial Staff.

Material for Making Long-Life Dies

Tough Coated Hard Powder (TCHP) die materials, from **Allomet Corporation**, N. Huntingdon, PA, USA, provide higher wear resistance than dies made from tungsten carbide-cobalt. TCHP metallurgical powder can be fabricated into many industrial metal cutting tools and wear parts, and offer useful life many times that of tooling made with conventional materials. TCHP incorporates hard particles in a tough matrix. Core particles include those traditionally used for extreme wear resistance (CBN, Ti(C,N), TiN, Al_2O_3. etc.). **www.allomet.net**

TCHP structure at 5000x

Shown in Figure 4 is the January 2010 citation in *Wire & Cable Technology International* naming TCHP die materials as a WCTI Top Product.

Nature of Product Availability for Die Makers

Producers of wire dies are currently facing a challenging and highly competitive environment; customers are seeking critical productivity gains in their manufacturing operations. Increasing customer concerns about quality and customer willingness to try innovative solutions to improve quality and productivity are two important aspects for die producers. Allomet's EternAloy® products address both of these issues and we believe that leading die companies which market this new technology will be able to develop new customers and gain significant market share in finished drawing dies.

EternAloy® Wire Die Blanks are available in ADDMA standard D-12, D-15 and D-18 disk sizes, as well as other typical ADDMA sizes (D6 through D24). Allomet can also produce other standard or special sizes on order. EternAloy® disks have been processed into finished wire dies by several die finishers using techniques similar to their existing processes for making finished PCD dies. In addition, dies utilizing EternAloy® disks can be resized and reused several times similar to standard carbide dies, increasing their economic value.

Process Economics

Experience has shown that TCHP dies exhibit die life 7X that of conventional carbide drawing dies, and this increased life can have a major impact on process economics. Demonstrative process economics models have been presented in previous publications.[2,4] Standard wear equations lead to the relationship:

$$t = (H\,\delta) / (2\,S\,K\,P), \tag{1}$$

where t is die life, H is the hardness of the die material, δ is the die diameter increase due to wear, S is drawing speed, P is average die pressure and K is a proportionality constant. Equation 1 can be simplified to:

$$t = Q/(SP), \tag{2}$$

where Q is a "constant", (H δ) / (2K). Therefore, the die life is seen to decrease as pressure increases and drawing speed increases. Basic drawing analysis allows average die pressure to be estimated as a function of die angle, drawing reduction and wire flow stress (strength). Nominal high carbon steel drawing parameters have been used in developing the die life comparison of Table 1, based on the seven-fold die life advantage displayed by TCHP dies.

Die cost estimating often employs the relationship:

$$C = [(T\,B) + D] / L, \tag{3}$$

where C is die cost per unit length drawn, T is time required for die set change, B is the cost of labor and overhead per unit time, D is die set depreciation per use (inclusive of die costs, die refinishing costs, recut possibilities, etc.), and L is the length of wire drawn before die replacement is necessary. On this basis, a cost comparison has been made as follows:

$$(C_{WC\text{-}Co}) / (C_{TCHP}) = 7 \times [(E + (D_{WC\text{-}Co}) / (E + D_{TCHP})], \tag{4}$$

where $(C_{WC\text{-}Co}) / (C_{TCHP})$ is the ratio of WC-Co die cost to TCHP die cost, where $D_{WC\text{-}Co}$ and D_{TCHP} are the die set depreciations per use, and where E is simply the product of T and B, which should be constant for the case of simple comparisons. Therefore, the relative costs of WC-Co and TCHP dies involves a tradeoff between increased die life for TCHP and the comparative values of die set depreciation.

The comparison of Equation 4 involves the assumption that the cost of down time (E = BT) during die replacement will be essentially the same for shorter and longer life dies. This certainly need not be the case, however. Consider that the projected TCHP lifetimes for the first three die positions (Table 1) generally exceed the drawing time expected for a month of 3-shift production. For that matter, die positions 4 through 7 could reasonably be inspected on a two-week basis. This certainly implies that the dies could be inspected and replaced, as necessary, as part of a scheduled maintenance effort. Hence failure of such dies need not involve unscheduled interruptions in drawing productivity, and loss of time, T, in Equation 3.

From an arithmetic point of view, the considerations of the previous paragraph imply that the value of E in Equation (4) should be considerably less for the TCHP case than for the WC-Co case, and it may be useful to restate Equation (4) as:

$$(C_{WC\text{-}Co}) / (C_{TCHP}) = 7 \times [(E_{WC\text{-}Co} + D_{WC\text{-}Co}) / (E_{TCHP} + D_{TCHP})]. \qquad (5)$$

Table 1. Estimates of TCHP and WC-Co die lifetimes for drawing carbon steel with reductions of 15%, a die semi-angle of 6° and a final speed of 6 mps.

Die Position	WC-Co Die Life	TCHP Die Life @ 7x
1	101 hr	710 hr
2	83	580
3	70	490
4	56	390
5	45	320
6	37	250
7	31	220
8	25	180
9	21	150
10	17	120
11	14	100

New TCHP Grades Developed for Industrial Applications

Allomet's initial TCHP grade, based on an Al_2O_3 core particle, exhibited extreme wear resistance and long life in wet wire drawing, especially of 1070 steel. These EternAloy® dies enabled performance that was 7X that of conventional WC-Co dies. Earlier trials at major carbon steel drawing houses have also indicated that the alumina TCHP has a lifetime roughly seven times that of WC-Co in several applications, with almost no change of wire diameter or shape over the life of the die.

Although this first Al_2O_3 TCHP grade is much more wear resistant and chemically inert than WC-Co dies, an upper limit to performance was discovered in some other applications, notably high speed wire drawing. Allomet determined that the heat generated at the wire-die surface during very high speed drawing was isolated at that surface and not distributed through the alumina TCHP, which is a good thermal insulator. However, this did not result in rapid wear (in fact there was still very little wear) but on occasion this caused formation of small heat cracks that eventually grew over extended time. As a result of this characteristic of alumina TCHP, Allomet accelerated efforts to bring an advanced grade for applications that required better heat conduction and thermal management. A more thermally conductive grade using a Ti(C,N) core particle was developed to expand opportunities for additional grades of TCHP dies.

Thus Allomet broadened its novel TCHP grade offerings to include a grade targeted for high speed drawing based on a Ti(C,N) core particle. This Ti(C,N) TCHP grade complements the alumina TCHP grade but offers higher thermal conductivity and good toughness without sacrificing the abrasive wear resistance under conditions required for wire drawing. Both TCHP grades exhibit much better hot hardness than WC-Co grades. This provides higher deformation resistance under operating conditions with elevated temperature, which is important for improved performance in cutting tools but also permits very tight control of wire diameter. The very low wear rate of TCHP dies allows them to last many life multiples of traditional WC-Co dies, approaching 10-12X life or greater dependent upon heat generated during drawing conditions. Thermal management of heat generated during wire drawing is an important consideration when determining the proper TCHP grade selection.

Allomet has developed some basic finite element modeling capabilities to predict specific grade performance to select the best available TCHP grade, and for the design of new TCHP grades. This allows us to understand specific application requirements and to target appropriate performance improvements. For example, the temperature at the die-wire interface is a critical aspect for die life but it is very difficult to measure. Allomet's modeling indicates that the interface temperature is higher than generally thought, even in wet drawing steel wire.

A representative example of Allomet's modeling of the heat distribution during wire drawing is presented in Figure 5. Thermal simulations were performed using ANSYS finite element software. In this process, a 2 or 3 dimensional structure is discretized into smaller "element" structures. Boundary conditions are then applied to these elements. For this specific scenario, a heat flux across the die-wire interface, convection cooling and thermal material properties are all defined. Analysis was then performed both as a function of time and under steady state conditions. This is illustrated in the thermal model (Fig. 5).

Figure 5. Temperature profile comparison.

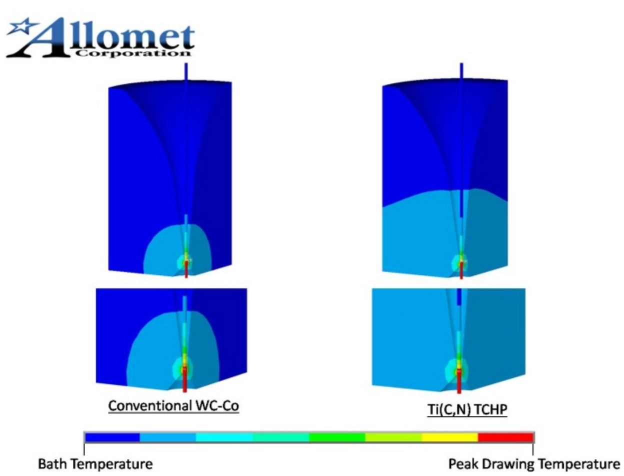


Figure 5 illustrates the temperature profiles of a conventional WC-Co and a Ti(C,N) TCHP drawing die under identical conditions. A cut-away view of the die orifice and body is depicted here. The TiCN TCHP die allows the heat generated during drawing to be better transported away from the wire drawing zone and distributed throughout the die. This reduces TCHP die wear even further, extending TCHP die life over WC-Co dies at higher drawing speed.

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Industrial Evaluations of TCHP Dies

Allomet has continued to progress with industrial wire drawing applications and have now performed evaluation tests both using TCHP dies only in the last several die positions and using entire lines of TCHP dies as well, confirming the results expected and described in an earlier publication.[2] Allomet has tested complete lines of all TCHP dies at a major manufacturer in drawing 0.35 mm tire cord (1080) with excellent results. There was no wear in any upstream TCHP die and only very slight wear in the final die of the drawing line. This data confirms the predictions in the technical article previously published in *Wire & Cable Technology International* of potential economic savings of improved die management programs for long life TCHP dies.[2]

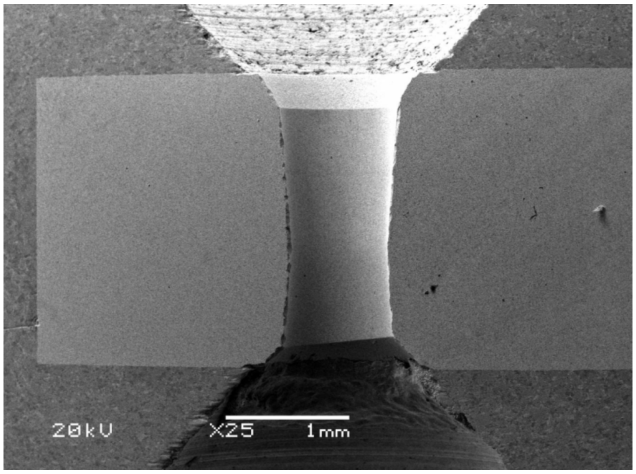
Allomet was able to measure and document the wire diameters at the exit of every die position when the machines were stopped at the completion of a wire spool. The dies were eventually replaced well before reaching their end of life and thus the dies could be examined using optical and scanning electron microscopy. The upstream TCHP dies were removed after they exceeded a 6X life multiple of WC-Co dies and did not show any discernable wear along the approach or at the initial wire contact surface. Allomet has not yet learned their full capability due to their extreme wear resistance. These dies are in a condition that would allow them to be used for a much longer working lifetime and, as predicted last year, be treated essentially as maintenance instead of consumable supplies in many drawing operations.

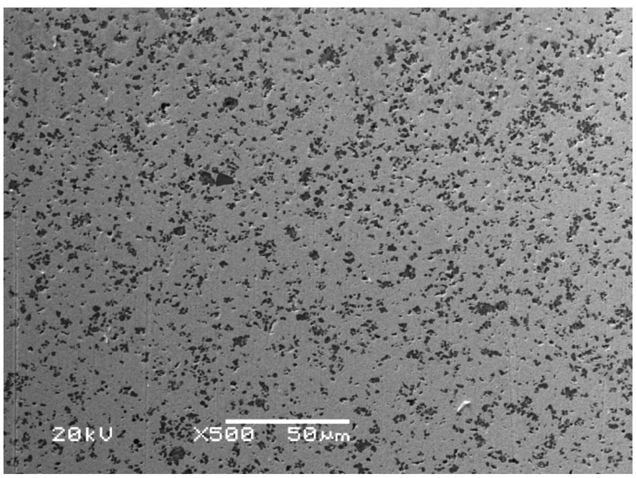
In some of the smaller ID TCHP dies, the beginning of a wear ring was observed after 5X life of a typical WC-Co die. However when these TCHP dies were later cross-sectioned, no significant depth to the wear rings was found. This indicates that TCHP dies at these positions could continue to perform for much longer as well.

Tested TCHP dies were sectioned through the center in order to evaluate the wear patterns and to investigate their performance characteristics. Both optical and scanning electron microscopy were used to assess the quality of TCHP microstructure, the quality of the TCHP die finishing, and any wear characteristics or patterns in the tested dies.

Shown in Figure 6 is a cross-section of a tested TCHP die. This TCHP die was removed and cut in half to evaluate its condition after drawing approximately 4X the lifetime of a typical WC-Co die. The top SEM photo taken at 25X illustrates the TCHP disk and the wire drawing channel. The bottom SEM photo taken at 500X shows that the TCHP microstructure is intact, with little to no wear anywhere along the contact surfaces. Also visible in the photo are some minor scratch marks parallel to the drawing direction.

Figure 6. Cross-section images of tested TCHP die





These test results indicate that Allomet has broken the die lifetime barrier of standard carbide dies. The greatly extended die life of the TCHP products leads directly to opportunities for improved process economics, including advantageous new die maintenance and die replacement strategies from both engineering and financial viewpoints.

Recommended areas for applications and evaluations

Recent trials at major carbon steel drawing houses have indicated that TCHP has a lifetime roughly seven times that of WC-Co in given applications. In wet drawing of steel tire cord, commercial evaluations of the product has so far shown more than six times the lifetime of WC-Co dies. TCHP dies have been particularly successful in applications such as drawing 1080 and 1090 steel at speeds up to 6-10 m/s, or less.

In very high speed applications, implementation of TCHP drawing dies at upstream, slower speed locations nonetheless can result in very long die lifetimes as those estimated in Table 1. Product development efforts are aimed at expanding the high speed capability of TCHP dies.

Prospects for Further Development

Allomet continues development of other TCHP grades that incorporate very hard particles, such as B_4C and cBN. TCHP grades with these core particles will greatly expand the range of applications for TCHP materials within the cutting tool industry, as well as for wire dies and wear part applications.

Other planned EternAloy® grade development includes TCHP materials based on diamond core particles. This will complement the existing TCHP die performance by further raising TCHP's extreme abrasion resistance, while at the same time offering the high toughness found in WC-Co grades. Furthermore, a diamond TCHP grade will allow excellent thermal management of the heat generated at the wire-die surface and increase the wire drawing performance window to compete favorably with diamond wire dies in many applications. The much higher toughness provided by the TCHP structure will differentiate it from conventional diamond dies.

Summary

The basic structure-property-processing aspects of TCHP materials have been reviewed. Commercial availability for drawing die applications has been noted, and the process economics for these long-life dies have been presented. Recent results from commercial drawing trials for fine, high carbon steel wire have been summarized. Recommendations for further applications and evaluations have been made, and prospects for further die material development have been cited.

References

1. R. E. Toth, J. M. Keane and I. Smid, *Wire Journal International*, 2008, Vol. 41, No. 1, p. 68.

2. J. M Keane and R. N. Wright, *Wire & Cable Technology*, 2009, Vol. 37, No. 5, p. 52.

3. *Wire & Cable Technology*, 2010, Vol. 38, No. 1, p. 47.

4. R. N. Wright, Wire Technology – Process Engineering and Metallurgy, 2011, Butterworth-Heinemann (Elsevier), Oxford, p. 102.

List of Figures