CEMENTED CARBIDE MATERIAL FOR HOT ROLLING APPLICATIONS

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ABSTRACT.

Carbide rolls are widely used in Metalforming especially in hot rolling industry mainly for intermediate and last finishing stands to ensuring superior surface finish and dimensional stability of processed metal products. However, at the first stands of the hot rolling mills the usage of carbide rolls is somehow limited due to hot cracking problems of the cemented carbide rolls versus competing materials being fabricated from cast iron or tool steels.

With this regard, developed GenTuff[TM] cemented carbide grade seems to resolve hot spalling issues because of its unique material design comprising high thermal conductivity binder coupled with wear resistant carbide matrix, which has predetermined grain distribution of tungsten carbide grains.

Results of comparative testing for developed carbide composition material versus renowned tool steel D2 including physical and mechanical properties like hot hardness, creep and toughness fracture as well as analysis of obtained structure are presented and discussed.

INTRODUCTION.

For more than twenty-five years, carbide manufacturers have historically devoted considerable amounts of funds and research to retard the inherent formation of thermal cracking in conventional cobalt-based cemented carbide rolls for the steel industry. Techniques such as increasing cobalt content, decreasing the percentage of tungsten carbide, increasing the size of tungsten carbide grains, adding nickel and chromium in the cobalt binder were used. The use of Hot Isostatic Pressing (HIP) was also included in the process. These changes improved the resistance to thermal cracking, but due to the inherent nature of cobalt-cemented carbide, the changes were not totally successful in improving thermal shock resistance. Thus, work rolls like Morgan Mill Rolls and Kocks Mill Rolls that were made out of regular WC-Co carbide grades had been enduring heat checking, fractures and total failure [1] while being used as prime and guide rolls at first stages of rolling mills, i.e. cycling temperature conditions were too difficult for regular carbide grades to handle.

In the same time, rolls being fabricated from various tool steels and steel-bonded carbides like various Ferro-TiC[®] [2] grades exposed insufficient performance behavior at first hot stands of rolling mills revealing surface defects, spalling and buckling due to their susceptibility to hot deformation.

In consequence of this fact, the objective to develop GenTuff[TM] material (*further in the text to be named as* ***Carbide Composition***) has been set as to fabricate tungsten carbide grade for the steel industry that could provide efficient combination of good wear, mechanical and thermal shock resistance for a variety of challenging applications such as guide rolls, looper rolls, etc., hereby, surpassing conventional cobalt-bonded tungsten carbide hardmetals as well as alloyed tool steel materials. Properties of newly developed material were evaluated in comparison to well known AISI D2 Steel that is frequently used as a material for a hot rolling die tools at hot rolling operations due to its relatively high wear resistance being combined with thermal dimensional stability, and a quite good shock resistance [3].

MATERIALS DESIGN AND CONSIDERATIONS FOR USE OF CEMENTED CARBIDES IN WORKING ENVIRONMENT OF SIMULTANEOUS THERMAL SHOCKS AND WEAR.

Per performed analysis of working conditions for hot rolling and some other hot metalforming manufacturing processes like, for instance, hot forging and hot extrusion, it is possible to conclude that utilization of cemented carbide composition makes hot forming tools to be quite sensitive to the thermal fatigue loading because of unique combination of physical and mechanical properties of cemented carbides. That properties combination is derived from the inherit nature of carbide crystals and their structural interactions with binders while forming hard composite material. For this reason, it seems

advisable to address concerns of thermal shock working environment aiming better utilization of carbide materials under such challenging conditions.

In the technical literature [4-6] the phenomena of thermal fatigue (also known as thermal shocking) is described as a phenomena that is the result of obstructed expansion and shrinkage of solid body segments being accompanied by significant thermal stress loads of the cyclic nature.

As it is known, thermal shock in cemented carbides may be caused by rapid temperature change of the material resulting in cracking or breaking, if the thermal stress amplitude overcomes some critical threshold of the stresses, which the given cemented carbide can sustain [5]. While, for instance, in the steel class of materials the thermo-fatigue is triggering micro- and macro-plastic deformation, the principal difference of thermal shock phenomena in composite materials with sizable share of brittle constituents (like cemented carbides) is that the level of emerging thermal stresses is primarily defined by elastic-plastic properties of the given composite material [5, 6].

In addition to applied thermal stresses, many applications like hot rollers, extruders or forging dies, etc. are enduring considerable abrasive wear as well as shearing and tensile mechanical stresses that are applied sometimes onto the same area due to the specific working conditions. Those mechanical stresses can be associated with a performed metalforming process, when intensive plastic deformation at elevated temperatures tends to change a shape of the processed part's preform, being fabricated from solid or particulate metal alloy, which may contain hard (abrasive) constituents like oxides, carbide or nitride inclusions, etc. Moreover, it is worth mentioning that on the top of the fracturing damage being caused by simultaneous application of thermal shocking, wear and mechanical impacting, additional creep deformation may also contribute to the material disintegration due to continuous presence of elevated temperature in the existing hot metalworking process.

Thus, such intricate pattern apparently results in crack origination that is tending to propagate under continuous complex stress mode into the other areas resulting eventually in micro- and macro chipping as its schematically shown in Figure 1, below.
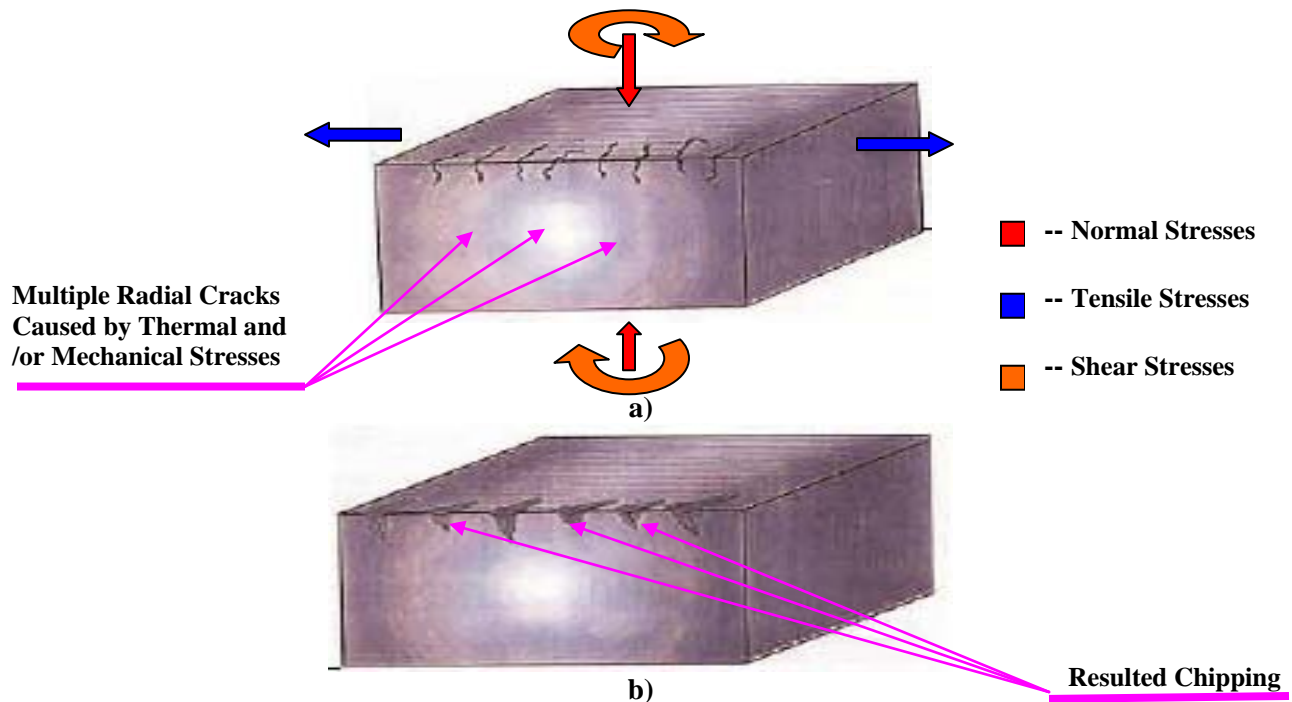

Figure 1. Schematic of Cracks and Chipping Formation under Influence of Thermo-Mechanical Cyclic Load Pattern.

It should be noted that temperature conditions, i.e. maximal and minimal temperatures are affecting the thermo-fatigue in the most significant way, first of all due to direct link between temperature gradients

and the thermal stress amplitudes from one side, and potential phase transformations that may take place within material enduring those conditions from the other side [.6]. Moreover, as it was found by calculations and experimentally [7], the maximal temperature is usually responsible for compression of the solid body segments while the minimal temperature of the thermal cycle causes tensile stresses of thermally shocked solid body. Beside referenced above temperature gradients being applied onto the tool by thermal shocking, many other factors can influence behavior of materials at the conditions of thermal fatigue. Among the most impactful carbide material characteristics are thermal conductivity, coefficients of thermal expansion, heat capacity, density and toughness of the given material [8-11]. For instance, as it has been demonstrated by various research works [8-10], the increase in materials' thermal conductivity is directly associated with improvement in thermal fatigue resistance due to the simple fact that boost of that characteristic leads to diminishing of thermal gradient between the surface of the solid body and its core volumes. With this regard, cemented carbides have relatively modest thermal conductivity (Tungsten Carbide at 84.0 W /m·°K and Cobalt at 100 W/m · °K), whereas conductivity of, for instance, Copper is 401.0 W /m·°K [12] i.e. is 4-5 time higher than typical constituents of traditional hardmetals. However, increase in coefficient of thermal expansion (CTE) results in deterioration of the material's capability to resist thermal fatigue [6, 9, 11].

Another concern to consider is the toughness of cemented carbides to be linked to the whole class of those materials with relation to both thermal shocking and mechanical impacts. As is well known, thermal shock phenomena and mechanical fatigue exhibit themselves through the crack origination and propagation within a part's body [6-9]. Thus, the higher the material's toughness level (which by definition is the ability of the solid body to resist crack propagation), the better is its resistance for cyclic stresses including those from thermal shock environment and mechanical fatigue [9-11, 13]. In application to cemented carbide materials, whereas their properties, in general, are sizably affected by the relationship between carbide grain size(s) and amount of binder within carbide composition, influence of referenced above material structural factors on toughness and thermal shock resistance might be summarized based on numerous experimental testing [8, 11, 13-16], as it depicted schematically below at Figure 2 (a & b).

As it may be seen from Figure 2a, that with larger grain size of carbide particles (Figure 2a) and the bigger amount of binder are used in carbide material (Figure 2b), the higher the toughness and shock resistance of that grade. However, as it may be also seen from Figure 2, certain diminishing of the hardness may occur simultaneously with a such coarsening of the carbide phase, and together with the increase of binder content in a carbide composition that may result in a lowering of wear resistance of carbide material, hereby, undermining the objective of using carbide materials for tooling application as the first choice at the material selection consideration process.

Based on the vast research data [1, 6, 9-11, 17], the robustness of a material with relation on resistance to thermal shock (R_{TS}) might be cumulatively summarized and expressed (characterized) by the consolidated thermal shock parameter as given below:

$$ R_{TS} \sim \frac{K_c \sigma^m_s (1\text{-}\nu) \lambda}{E \, \alpha} \qquad \{1\} $$

Where:
- λ is Thermal Conductivity,
- σ_s is Tensile or Shear Strength of the material, whereas **_m_** within range 1.5-2.0.
- α is the Coefficient of Thermal Expansion (CTE);
- **_E_** is the Young's Modulus of Elasticity and **_v_** is the Poisson ratio;
- **K_c** is the Toughness of the material.

Thus, according to the referenced above equation **{1},** thermal shock resistance is going to be the highest, when that material exhibits the highest level of strength, fracture toughness and thermal conductivity while possessing in the same time the lowest coefficient of thermal expansion a well as Young's Modulus of Elasticity (YME). In consequence of this fact, even cemented carbides demonstrate relatively small

values of CTE and excellent density (i.e. practically no porosity), that group of materials, however, is known for its high YME level. Hereto, cemented carbides belonging as is known, by structure to the class of brittle materials (i.e. exposing rather small fracture toughness level) are also not the best in resistance to tensile and shearing stresses.
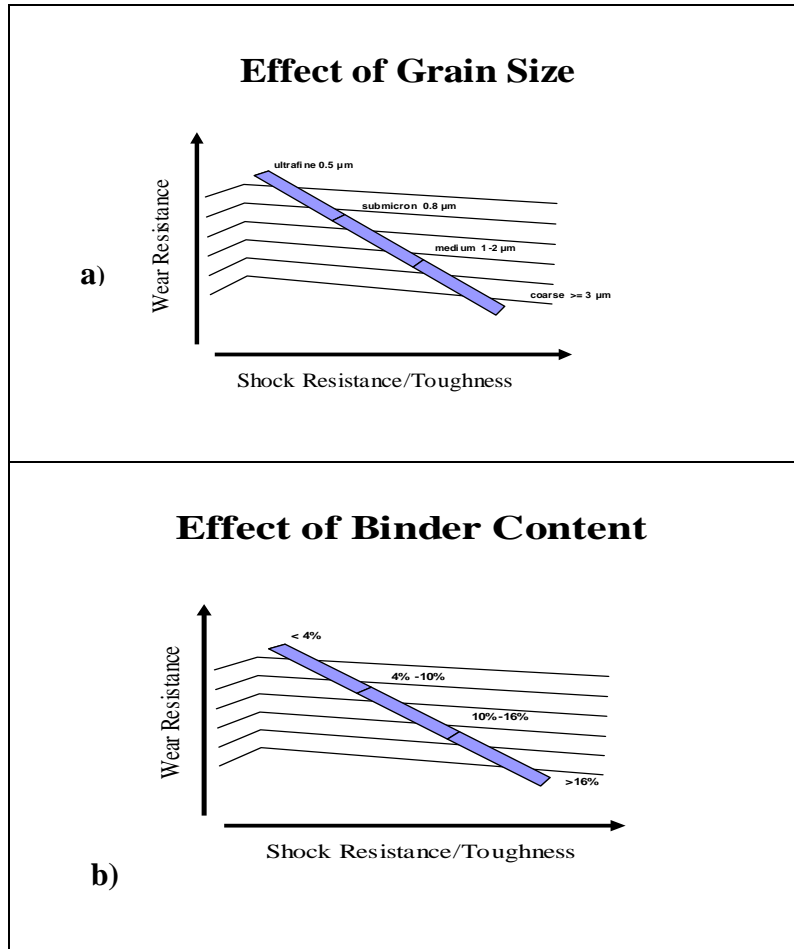
Effect of Grain Size

a)

Wear Resistance

ultrafine 0.5 µm
submicron 0.8 µm
medium 1-2 µm
coarse >= 3 µm

Shock Resistance/Toughness

Effect of Binder Content

b)

Wear Resistance

< 4%
4% -10%
10%-16%
>16%

Shock Resistance/Toughness

Figure 2. Effect of Carbide Particles Grain Size and Binder Amount on Wear, Toughness and Shock Resistance of Cemented Carbides.

Therefore, the high level of thermal shock resistance is not typically associated with the whole group of cemented carbide materials in comparison, lets say, to steels or even cast irons. However, due to their outstanding wear resistance and compressive stress, exceptional hardness and rigidity as well as to their ability to resist aggressive wear and intensive mechanical stresses, cemented carbides in many cases are outperforming many other materials, especially in tooling applications [11-16]. With this regard, an intelligent balanced approach should be taken in choosing or designing of proper carbide grade for such harsh working conditions as hot metalforming applications due to intricate stress pattern that derives from thermal shocks being applied simultaneously with dynamic mechanical loading and wear.

In consequence of these facts and, a thorough understanding of key characteristics such as hot hardness, creep, toughness, coefficients of thermal expansion, etc. should be learned or tested in order to ensure solid practical success in such industries like hot rolling or hot extrusion.

Based on these data, a properly selected or designed carbide grade should be capable of withstanding simultaneously applied thermal shock stresses, impact mechanical loading, and aggressive wear at working conditions, thereby, ensuring maximal tool service life in challenging manufacturing operations.

ALLOYING DESIGN OF CARBIDE COMPOSITION AND ITS PROCESSING INTO PARTS.
In order to overcome common thermal fatigue weakness of traditional WC-Co cemented carbide materials discussed above, in the development of GenTuff [TM] composition a proprietary alloying concept, has been used utilizing a copper-based alloy binder (rather than cobalt) due to its heat conductivity. The microstructure of developed Carbide Composition is shown at Figure 3.
The proprietary technological process of parts fabrication from Carbide Composition applies the special large-grain Tungsten Carbide crystals (up to 2767 HV_{25} [18]) shown at Figure 3a with pre-determined particle size distribution designed to form wear resistant matrix (Figure 3b), where thermo-resistant binder is evenly distributed. Images of microstructures of Carbide Composition at Figure 3c provide comparison its grain size versus regular carbide grade microstructures.
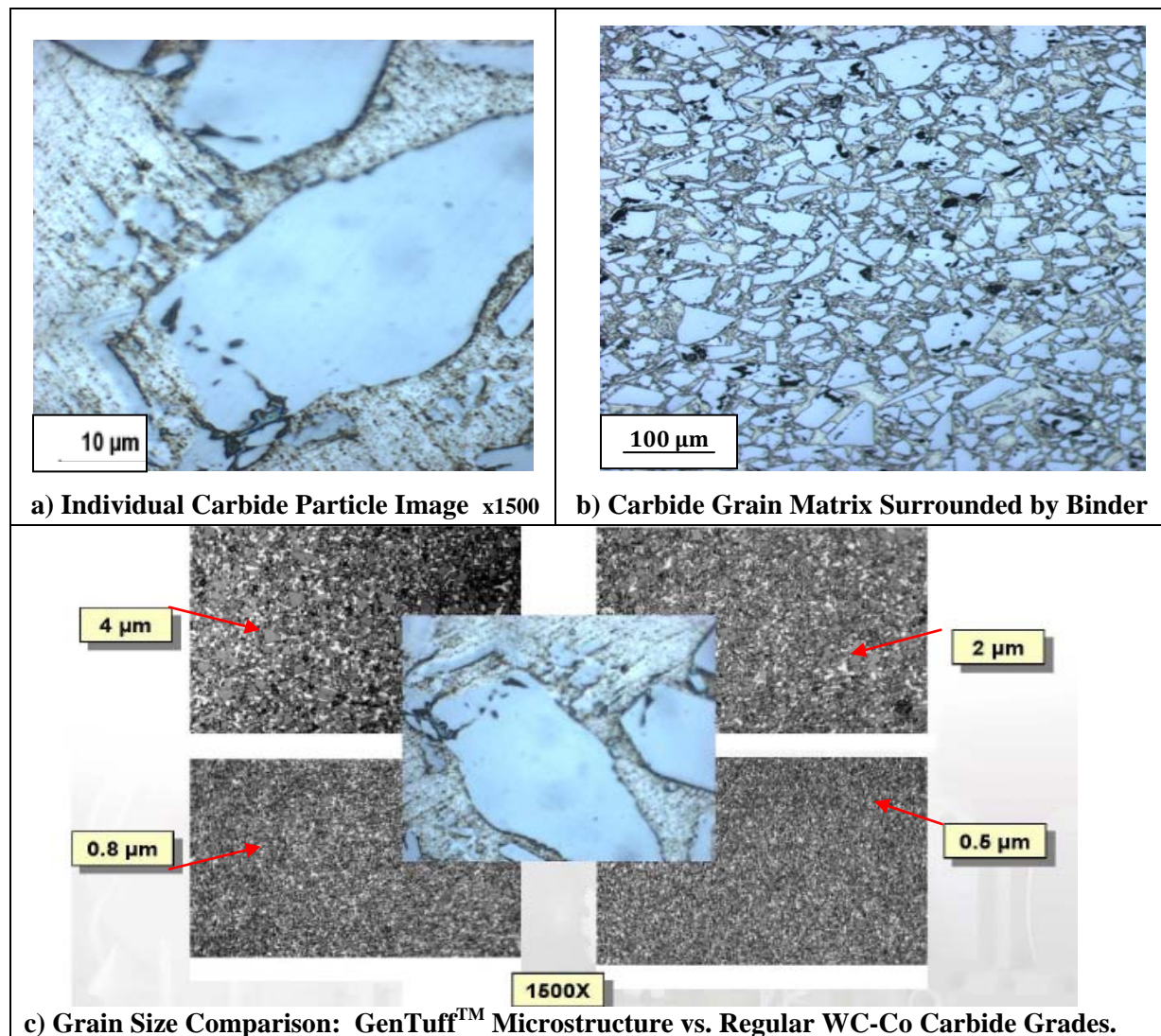

a) **Individual Carbide Particle Image x1500** | b) **Carbide Grain Matrix Surrounded by Binder**

c) **Grain Size Comparison: GenTuff[TM] Microstructure vs. Regular WC-Co Carbide Grades.**

Figure 3. Carbide Composition Microstructure Fragments at Various Magnifications

In general, the fabrication process of Carbide Composition includes shaping operations and furnace thermal consolidation that permits intensive liquid-phase sintering, encompassing up to 25-45 % (by weight) of thermo-resistant Copper-based binder into composite material with the rest to be wear resistant matrix from large size Tungsten Carbide grains. Per suggested material design concept, large special

crystals of Tungsten Carbide exercise high hardness level, whereas Copper-based binder provides superior thermal conductivity (being, as it was mentioned above [12], in times higher than regularly used Cobalt- or Nickel binders).

GENERAL CHARACTERIZATION APPLIED FOR MATERIALS EVALUATION.
For purpose of proper material selection and design of the components destined to work at a harsh environment discussed above, it is important to assess general mechanical and physical characteristics. With this regard, samples from developed Carbide Composition as well as from AISI D2 Tool Steel were machined into the final dimensions for further evaluation of physical and mechanical properties on comparative basis. Alloying content of AISI D2 Tool Steel as well as of developed Carbide Composition is exposed below in the Table 1.

Table 1. Alloying Content of AISI D2 Tool Steel (ASTM A681-02) and GenTuff ^{TM} Material.

Material ID	Average Material Alloying Content, w/o									Comments
	C	Mn /Si	Cr	Mo	V	Ni	Fe	Binder	WC	
AISI D2 Tool Steel	1.55	0.4/ 0.3	12.0	0.9	0.9	0.2	Bal.	-	-	**Heat Treated to hardness level within 58-63 HRC.**
Carbide Composition	0.02	-	-	-	-	-	-	30-40	Bal.	**Subjected to HIP as the final operation of thermal consolidation**

The structure of investigated samples has been analyzed on specially prepared metallurgical mounts by usage of optical microscope "Nikon" with general multiplication of microstructure at **x1500.**
Apparent porosity in analyzed mounts from cemented carbide materials has been analyzed based on recommendations of ASTM Standard B 276-91.
Hardness testing has been performed in accordance to ASTM Standard B 294-92
Density determination has been performed based on recommendations of ASTM Standard B311-93.
Also, in accordance to ASTM Standard D5335-08 series of Carbide Composition slugs and AISI D2 Tool Steel bars were machined to dimensions 10.0 x10.0 x 55.0 mm in order to measure linear coefficient of thermal expansion (CTE) by applying dilatometry technique. For that, accurate dimensions of each sample were measured and recorded and plotted together with temperature and expansion data. Experiments were run on each sample in Anter Unitherm pushrod dilatometer (model 1161V). A thermal ramp rate of 5°C per minute to 800°C was used in a flowing ultra high purity argon atmosphere. Average CTE (α) was calculated by the formula:

$$\alpha = (\Delta L/L_O)/\Delta T \qquad \qquad \{2\},$$

where
- L represents change in lengths at current (measured) temperature, mm;
- L_O represents the original starting length, mm;
- T represents change in temperatures, (°C).
Below, in the Table 2 some characteristics obtained by comparative testing are summarized and exposed for both Carbide Composition and AISI D2 Tool Steel.
Referencing to cumulative mechanical and physical characteristics, which are shown in the Table 2, it is possible to conclude that Carbide Composition demonstrates certain advantages vs. AISI D2 Tool Steel exposing higher hardness and compressive yield strength at room temperatures while at the same time its coefficient of thermal expansion is sizably lower within range of tested temperatures. Thus according to referenced above eq. {1} for consolidated thermal shock parameter and eq. {2}, low CTE is positively affecting thermal shock resistance of material.

Table 2. Some Tested Properties of Carbide Composition and AISI D2 Tool Steel.

SELECTED PROPERTIES OF TESTED MATERIALS	STANDARDS REFERENCE	CARBIDE COMPOSITION	AISI D2 STEEL
HARDNESS, HRC	ASTM B294-98	63-65 [1]	58-63
DENSITY, g/cc	ASTM B311-93	12.46	7.70
MODULUS of ELASTICITY, GPa	ASTM E9-89a	288.5	181.0
COEFFICIENT OF THERMAL EXP [2], m/m^{o}C	ASTM E228-00	7.29	12.06
COMPRESSIVE 0.2% YIELD STRENGTH, MPa	ASTM E9-89a	2614	2200
NOTES: {1} - Rockwell Hardness at Room Temperature of WC-Particles [within matrix material] being converted from HRA scale to HRC scale {2} - Within range 20 ^{o}C - 650°C			

EXPERIMENTAL TESTING PROCEDURE AND OBTAINED RESULTS.

Complementary to general material characteristics that have been measured and tested as it was discussed above, a set of additional tests has been performed, targeting functional performance of materials at conditions of thermal fatigue and intensive mechanical loading.

A.   Comparative Hot Micro-Hardness Test.

Hot micro-hardness testing has been performed on Carbide Composition and AISI D2 Tool Steel samples at temperatures up to 615 ° C. A Nikon Model QM high temperature microhardness tester with inert gas chamber was utilized for such hardness testing (Figure 4) at Touchstone Lab commercial testing facility. The built-in light microscope was used to measure the hardness indentation size.

Figure 4. Nikon Model QM Hot Micro-Hardness Tester.

For Hot Hardness Test, prismatic samples with dimensions (mm): 5.0 x 5.0 x 10.0 have been used. Tested samples were machined off and ground from the stock of Carbide Composition and AISI D2 Tool Steel to the final dimensions. Five indentations were made at each of three temperatures including 500, 550 and 600 ^{o}C. Test load was set at Test Load -- 9.8 N (1000 g*f), indent time -- 10 s, and reading magnification -- x200. Obtained hot microhardness results are reported in the Table 3.

Per exposed in the Table 3 data, it is possible to realize that with elevation of the temperature from 500 ^{o}C to 600 ^{o}C, the difference in hot hardness goes through quite a dramatic change.

Thus, the hot microhardness for Carbide Composition samples is slightly lower at 500 °C vs. D2 Tool Steel counterparts, but then microhardness of Carbide Composition gets sizably higher level at 550 °C. With further increase of testing temperature up to 600 °C, Carbide Composition is outperforming AISI D2 Tool Steel, demonstrating a 33-34% higher hardness level. Graphs exposed in Figure 4 are showing the trend in microhardness change, which may be explained by relative surface softening of AISI D2 Steel due to supposed "self-annealing" and self-tempering of local subsurface volumes of the tested samples.

Table 3. Hot Microhardness Results of Tested Materials at Various Temperatures.

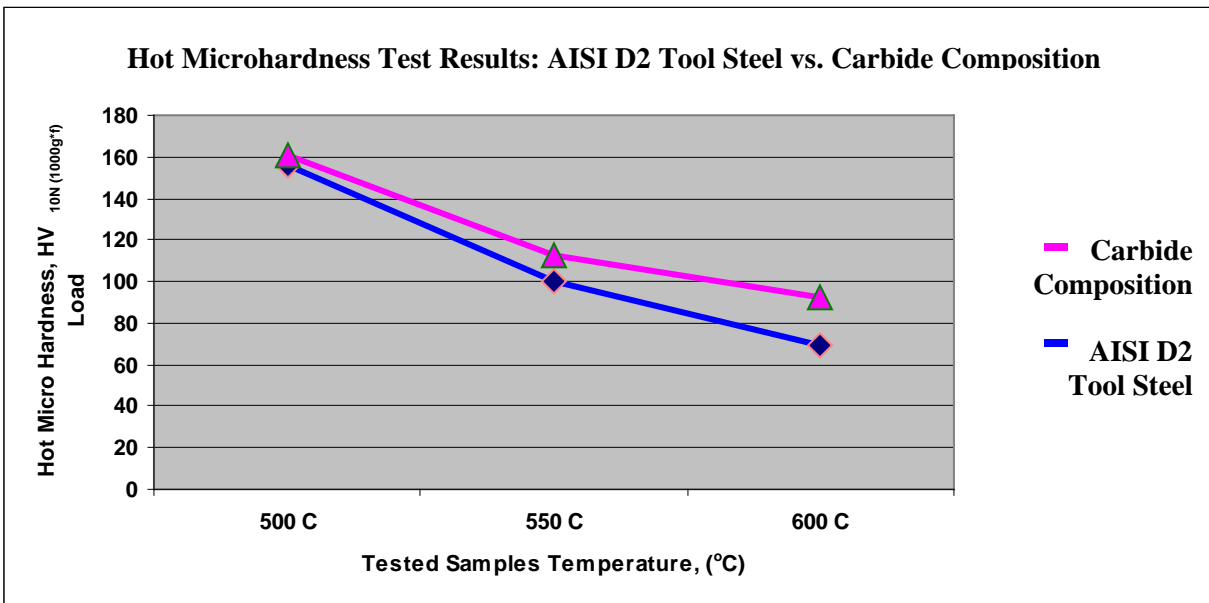| Material's ID	Run #	HV_{1000gf} Hardness Data @ Test Temperature, °C		
		500 °C	550 °C	600 °C
AISI D2 Tool Steel	1	130.7	97.7	67.8
	2	141.9	97.7	68.1
	3	178.2	90.7	67.0
	4	164.4	94.1	69.5
	5	166.2	119.1	71.8
	Average	156.3	99.9	68.8
	Std. Deviation	19.2	11.1	1.9
Carbide Composition	1	154.7	112.0	98.5
	2	147.3	100.6	88.1
	3	177.2	131.4	102.8
	4	155.8	113.2	84.3
	5	169.8	104.2	85.9
	Average	161.0	112.3	91.9
	Standard Deviation	12.2	11.9	8.2

Figure 4. Effect of Elevated Temperatures on Hot Microhardness of the Tested Materials.

Due to its composite structure, samples from the Carbide Composition show only an "annealing" effect on its binder, whereas its large WC-grain carbide matrix effectively resists hard indenter penetration. Thus, the ability of the Carbide Composition to provide strong resistance to indentation at elevated temperatures might play an important role for such applications as hot rolling, where the temperature of hot billets requires adequate hot hardness and associated tool strength at those temperature conditions. Moreover, higher hot hardness of samples from Carbide Composition versus counterpart samples from AISI D2 Tool Steel within the tested range of the temperatures indirectly suggests that composite hardmetal keeps rigidity at elevated temperatures better than tool steel.

B. Comparative Compressive Creep Testing.

As is known [6, 12, 19], creep is a time-dependent deformation of materials at room and/or elevated temperatures under an applied load that is below its yield strength
For both AISI D2 Tool Steel and Carbide Composition, the compressive Creep Test has been performed in accordance with ASTM E9 and ASTM E139 Standards requirements. For aforementioned creep test, the samples were originally machined as right cylinders with dimensions: 9.53 mm diameter x 25.4 mm in length. Samples from analyzed materials were tested at each stress level at constant uniaxial loading within range level of 620-760 MPa with three replicates.
Each sample was equipped with strain gage (Figure 5a) and placed into a special compressive fixture (Figure 5b) between two harden platens of lever arm at Applied Test Systems (ATS) Creep Machine, with a maximal capacity of 89 kN (Figure 5c).
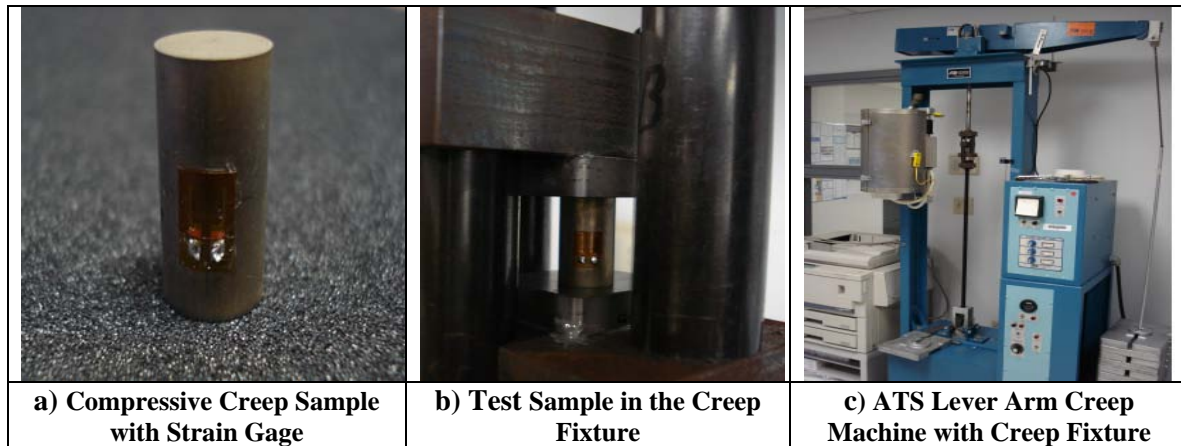

a) Compressive Creep Sample with Strain Gage	b) Test Sample in the Creep Fixture	c) ATS Lever Arm Creep Machine with Creep Fixture

Figure 5. Comparative Creep Testing Set-Up.

Creep strain magnitude and its rate changes within tested samples from Carbide Composition and AISI D2 Tool Steel while those samples were placed into special fixture of ATS creep frame, have been monitored and recorded for the test duration of 504 hours (or 21-day test period for each sample). Graphs of creep strain vs. time are exposed at Figure 6 (a & b), as below.
While the deformation rate of AISI D2 Tool Steel samples was not changed significantly through the test period, at both 620 MPa load as is shown at Figure 5a, and at the higher loading of 758 MPa as is demonstrated at Figure 5b, the time-dependent compression deformation pattern of both stress load level samples fabricated from Carbide Composition show a monotonically slightly increased deformation and strain rate during the first 120 hours (5 days) of test. Later on, the rate of deformation is slowing down, and after 240 hours (10-day period) the deformation rate becomes practically constant.
Increased deformation rate of carbide-based samples at initial period of testing can be supposedly linked to micro-plastic deformation associated with residual pores presence in the core of the Carbide

Composition as well as to supposed dislocation climb in binder phase and grain boundary sliding that according to study [19] might control the rate of deformation at initial stages of creep stress loading.

Carbide Composition vs. AISI D2 Steel: Compressive Creep Data at 620MPa Load.
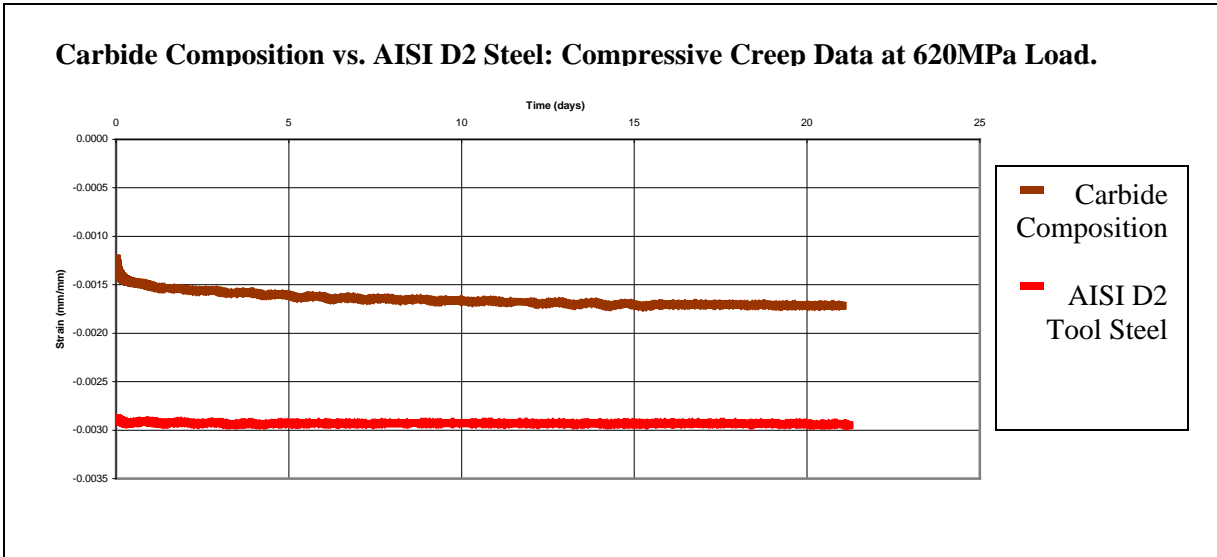
a) Creep Deformation at 620 MPa Applied Load during 21-day Compressive Creep Test.

Carbide Composition vs. AISI D2 Steel: Compressive Creep Data at 758 MPa Load.
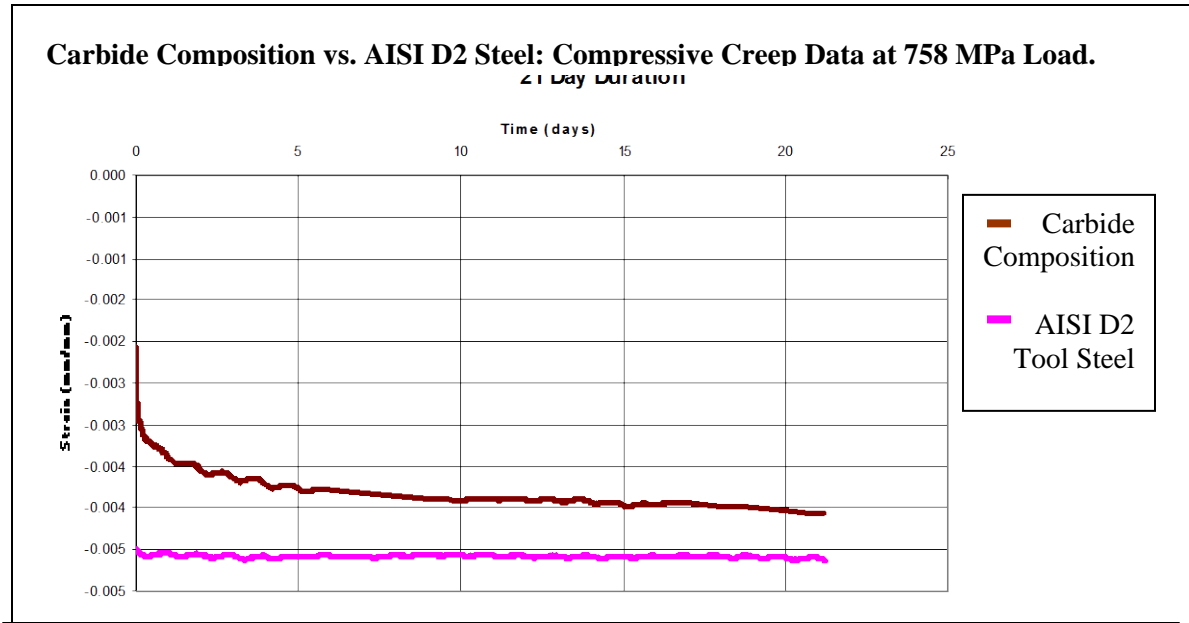
b) Creep Deformation at 758 MPa Applied Load during 21-day Compressive Creep Test.

Figure 6. Compressive Creep Data of Carbide Composition and D2Tool Steel at Various Loads.

It is necessary to mention that the rupture point through this quite lengthy interval of time (504 hours or 21-day period) was not achieved either for AISI D2 Tool Steel or for samples from Carbide Composition. However, at both 620 MPa and 758 MPa stress levels, creep deformation of Carbide Composition has been recorded to be lower at 1.25-1.75 times versus AISI D2 Tool Steel during quite long test period. Hereby, revealed robust resistance to creep deformation of Carbide Composition might be beneficial for applications that endure long-term significant creep stress load at operating conditions.

C. Fracture Toughness Testing Results.

In consequence of the fact that the Carbide Composition possesses within it a quite high amount (up to 30-40 w %) of relatively tough and ductile Copper-based binder, the attempt to evaluate materials toughness was taken by applying elastic-plastic material fracture mechanics approach, i.e. to consider evaluation of toughness by J-integral suggested by Cherepanov and Rice [20-21]. Referenced J-integral is representing strain energy release rate or work per unit fracture surface area in a body subjected to monotonic loading applied under quasistatic conditions, when material may experience small scale yielding at the initiated crack tip. It is necessary to mention that crack propagation is extremely difficult with cemented carbide materials because a low stress intensity factor is required so as to not prematurely fail the sample. Hereto, such low stress intensity also results in high cycle counts to achieve a properly pre-cracked mode for specimen to be correctly tested. Due to this fact and with an assumption that linear elastic fracture mechanics conditions may be not applied exactly [20-22], the efforts to infer a critical level of strain energy increase at the tip of the crack in elastic-plastic conditions have been undertaken. With this regard, performed test had preliminary character and aimed to get data derived from the samples of the same geometry and alike dimensions for comparing materials that are tested at identical trial conditions.

For such fracture toughness evaluation, testing was performed on AISI D2 Tool Steel and samples from Carbide Composition. The samples were machined to the shape and dimensions in accordance to requirements of ASTM E1820. After that, machined samples of AISI D2 Tool Steel and Carbide Composition were fatigue pre-cracked, and then side grooves were additionally machined in order to ensure that crack propagation will be extended from the pre-crack zone in perpendicular direction to the applied load.

Eventually, properly machined samples were tested on an Instron Servo-Hydraulic Testing Machine. The results are provided in Table 4.

Table 4. AISI D2 Tool Steel vs. Carbide Composition: Comparative Fracture Test Results.

Material ID	Toughness Characteristics.				Character of Crack Propagation
	J_Q	K_{JQ}	P_Q	K_Q	
Test Data Units (SI / US units)	kJ/m^2	MPa√m	kN	MPa√m	
AISI D2 Tool Steel	2.64	24.5	10.3	22.6	Unstable
Carbide Composition	2.69	27.0	10.9	24.8	Unstable
Where:					
J_Q --	Crack Initiation Fracture Toughness Energy characteristic of the crack tip, characterizing the critical level of strain energy release rate or work (energy) per unit fracture or per unit of surface area @ elastic-plastic stress conditions				
K_{JQ} --	Stress Intensity Factor at applied Crack Fracture Toughness Energy level				
K_Q --	Tentative (Apparent) Rapid-Load Plain Stress Fracture Toughness				
P_Q --	Fracture Load				
Note: For materials with increased plasticity characteristics (e.g. at explicit elastic-plastic mode of stress), fracture toughness is defined in the terms of J-Integral by ASTM E813 Standard					

As it might be seen from the data exposed in the Table 4, both materials demonstrate approximately equal level of energy (J_Q) being spent on crack initiation fracture. In the same time, Carbide Composition exhibits slightly higher level of stress intensity factor (K_{JQ}) obtained also at a higher fracture load (P_Q) versus values obtained from fracturing of AISI D2 Tool Steel samples.

In further, it seems advisable to perform more detailed fracture testing with utilization of quite suitable for cemented carbide materials techniques like Palmqvist Indentation Test [23- 24].

CASE STUDY.

Based on obtained data and established processing routine, the Upper Looper Roll (Figure 8) workpiece was fabricated from developed Carbide Composition, and then installed in a steel rod mill facility, located in the vicinity of Cleveland, Ohio.

Figure 8. Roll from Carbide Composition at Hot (~ 950 ^{o}C) Rolling Manufacturing Facility.

The hot rod temperature when it contacts with the roll was reported to be at approximately 950 ^{o}C. In these conditions, previously used rolls being fabricated from AISI D2 Steel (and hardened to 58-62 HRC range) reportedly lasted only within range 30-45 days in average. At the same rod hot mill line, the identical roll being fabricated from Carbide Composition has been performing without visible damage (wear, spalling, etc.) during the period of August, 2008 up to November, 2009. Thus, rolls being fabricated from Carbide Composition exposed longevity to be at least in 15 times longer than its counterparts that were manufactured from AISI D2 Tool Steel in service in a harsh working environment in the combined presence of both thermal shocking and impact wear.

In addition, the rolls from Carbide Composition that were utilized for hot rolling application exposed the following service characteristics:

- o Demonstrated extreme wear resistance properties, mainly due to its alloying concept associated with large-grain hardmetal matrix uniformly surrounded by binder. Hereto, after long period of exploitation worn surfaces can be re-machined, hereby, the application can be returned to service.
- o Did not thermally crack its working surface (correspondingly, rolls from Carbide Composition can remain in service for very long periods of time). That fact might be linked to use in developed Carbide Composition of Copper-based binder with enhanced thermal conductivity that enabled hot rolls to operate even without coolant water to be applied.
- o Due to sufficient toughness, fabricated hot rolls did not chip under the multiple impacts derived from the multiple contacts of the roll's front end of the hot rod billet and the roll mill.

In addition, it is important to mention that such extended service life between rolls change results in less disassembly-reassembly downtime, which translates to substantially increased operational productivity.

In pursuit of already achieved progress, developed Carbide Composition (**GenTuff^{TM}**) is presently considered to be introduced into other markets like hot forming and hot extrusion, where resistance to thermal shock and cracking is a problem for conventional carbides, while traditional tool steels are also not efficient.

SUMMARY.

1. Material design and selection consideration aspects on hardmetal composites performing at hot metalforming applications in conditions of simultaneous thermo-mechanical fatigue and wear have been discussed. Importance of structural factors specific of cemented carbide materials being linked to certain mechanical and physical properties has been outlined towards achieving maximal tool service life at challenging manufacturing operations.
2. Based on specifics of cemented carbide composite structure and its influence on key characteristics to be in control of material performance at combined affect of thermal shocks, mechanical stresses and wear, the alloying concept for GenTuff ^{TM} Cemented Carbide Composition has been suggested and includes the use of large WC-grain matrix combined with enhanced thermal conductivity binder.
3. Comparative testing of developed Carbide Composition exposed its certain advantage versus AISI D2 Tool Steel by achieving higher hot hardness level as well as obtaining lower coefficients of thermal expansion and lower creep deformation, exposing in the same time practically similar toughness characteristics.
4. Utilization of GenTuff ^{TM} Carbide Composition for Upper Looper Rolls, which were installed in a hot rod mill line, led to a sizable increase in service life for those hot metalforming tools, outperforming by approximately 15 times alike rolls from AISI D2Tool Steel.

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