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Strain Rate Dependency of Bronze Metal Matrix Composite Mechanical Properties as a Function of Casting Technique

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Strain rate dependency of mechanical properties of tungsten carbide (WC)-filled bronze castings fabricated by centrifugal and sedimentation-casting techniques are examined, in this study. Both casting techniques are an attempt to produce a functionally graded material with high wear resistance at a chosen surface. Potential applications of such materials include shaft bushings, electrical contact surfaces, and brake rotors. Knowledge of strain rate-dependent mechanical properties is recommended for predicting component response due to dynamic loading or impact events. A brief overview of the casting techniques for the materials considered in this study is followed by an explanation of the test matrix and testing techniques. Hardness testing, density measurement, and determination of the volume fraction of WC particles are performed throughout the castings using both image analysis and optical microscopy. The effects of particle filling on mechanical properties are first evaluated through a microhardness survey of the castings. The volume fraction of WC particles is validated using a thorough density survey and a rule-of-mixtures model. Split Hopkinson Pressure Bar (SHPB) testing of various volume fraction specimens is conducted to determine strain dependence of mechanical properties and to compare the process-property relationships between the two casting techniques. The baseline performances of C95400 bronze are provided for comparison. The results show that the addition of WC particles improves microhardness significantly for the centrifugally cast specimens, and, to a lesser extent, in the sedimentation-cast specimens, largely because the WC particles are more concentrated as a result of the centrifugal-casting process. Both metal matrix composites (MMCs) demonstrate strain rate dependency, with sedimentation casting having a greater, but variable, effects on material response. This difference is attributed to legacy effects from the casting process, namely, porosity and localized WC particle grouping.

Keywords casting, metal matrix composites, mechanical testing, non ferrous metals

1. Introduction

Aluminum bronzes have a wide range of uses—ranging from pump and valve components to propellers and propeller hubs; these materials are also widely used in bearings, wear rings, and bushings. Bronze is a preferable alloy for engineering applications due to its corrosion resistance, ease of machining, and relatively low cost compared with other nonferrous alloys. In addition, in some applications, the conductivity of bronze, coupled with its high strength, makes it attractive as a potential electrical conductor. Metal matrix composites (MMCs) of bronze filled with WC have potential for some of the previously cited applications, provided that the reinforcing particles can mitigate some of the damage mechanisms observed in high current density circuit breakers, mechanical switching mechanisms, or sliding metal-contacting devices. The contact resistance and wear behavior of a conducting contact surface are a function of hardness, applied load, and material constituents (Ref 1). Certain loading conditions present difficulties for traditional conductor materials (such as copper) in the form of accelerated wear and plastic deformation because of shear. This less than ideal situation may be remedied by materials fabricated as functionally graded MMCs—in particular bronze/tungsten-carbide. Bronze has been noted for its relatively higher hardness and strength compared with copper as a potential conductor (Ref 2). Specifically, the aluminum-bronze ternary alloy C95400 comprising 85% Cu, 11% Al, and 4% Fe is one of the strongest copper alloys available with hardness comparable with stainless steel. In this article, we examine the use of bronze as the matrix material in a MMC being evaluated as an electrical conductor subject to high strain rate loading. Very little data are available regarding the physical and mechanical properties of these types of bronze MMCs, and, hence the need for evaluation and examination of casting techniques.

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A functionally graded MMC can be fabricated by either centrifugal casting or by sedimentation casting. In the case of centrifugal casting, the matrix material is placed in a centrifuge within an induction heater. After melting the matrix alloy, a high melt temperature-strengthening material is added in the form of small (typically on the micron scale) particles to the matrix.

The mold is then rotated to generate accelerations in the 50-60 G range. Depending on the density of the reinforcing particles relative to the molten matrix material, the particles will migrate because of centripetal force either to the outside or inside of the casting. This results in a MMC with significantly different physical and material properties depending on radial location through the sample. Figure 1(a) is a schematic of the casting process and supporting equipment used by the Naval Surface Warfare Center (NSWC)—Carderock to produce MMCs. This creates a composite with different properties on the inside and outside radii, hence, the phrase "functionally graded composite". Figure 1(b) is an illustration of a centrifugally cast ingot with a strengthened region on the outer surface of the casting. In the case of sedimentation casting, strengthening particles are added to molten matrix material, stirred, and then poured into a preheated mold. Gravitational force is relied upon to overcome buoyancy and drag forces acting on the particle as settling occurs. Although the resulting concentration of the filler particles is not as pronounced as in centrifugal casting, the addition of the filler particles still results in a gradation in properties from upper to lower regions of the casting.

Figure 1(c) shows a cross section of a sedimentation-cast ingot. Note that the heavier particles concentrate toward the bottom of the ingot before solidification. The material properties should be a function of the volume fraction of the strengthening additive, but because of the inherent complexity of trying to analytically predict MMC material properties, it is necessary to determine them experimentally. The present study compares and contrasts mechanical properties of two MMCs composed of the same matrix material (C95400 bronze) and the same nominal volume percent (~5%) of WC particles. We shall now turn our attention to a discussion of the process by which specimens were selected for analysis, techniques used, and the results.

2. Specimen Testing and Analysis Results

Initially, a visual inspection of each casting was performed to determine the optimal location for removal of test samples. These samples are subsequently subjected to the following analyses: Vickers microhardness (H_v) property mapping as a function of original location; strengthening particle volume fraction determination by optical microscopy; and conductivity determination as a means of validating volume fraction using the rule of mixtures. Again, all of these tests are catalogued as a function of original position within the casting. For additional information regarding analytic techniques, the reader is referred to Ref 3. Microhardness measurements were begun on the strengthened side of the specimen and continued at a spacing interval of approximately one millimeter in between test locations through the thickness of the casting. The determination of hardness as a function of location within the casting served as a "roadmap" for later correlation of other mechanical or material properties to position within the casting. Figure 2(a) provides the hardness profile for bronze/WC centrifugally cast material, while Fig. 2(b) provides the hardness profile for bronze/WC sedimentation-cast material.

For the centrifugally cast material in Fig. 2(a), the hardness profile as a function of location is similar in character to a step function. The H_v values are similar to that of the C95400

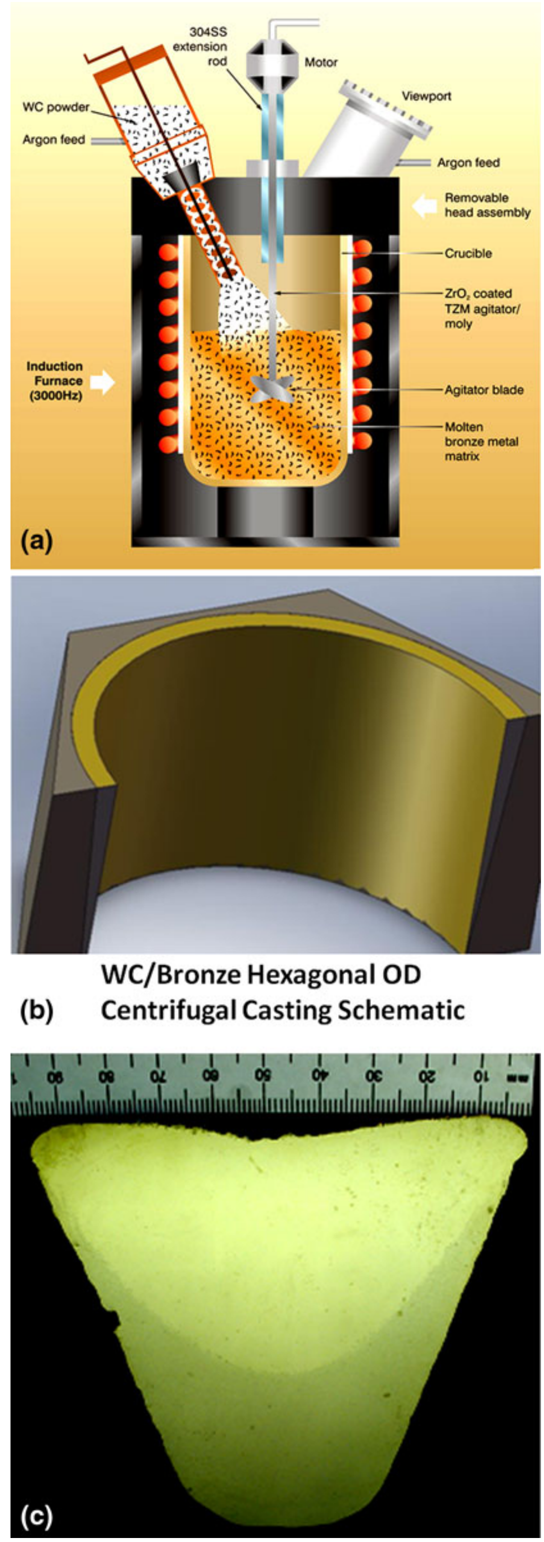

Fig. 1 (a) Schematic of centrifugal-casting apparatus. Figure used by permission from Naval Surface Warfare Center Carderock Division. (b) Illustration of hexagonal, centrifugally cast ingot, with segregation of strengthening particles shown by darker outer region of the cross section. Figure used by permission from Naval Surface Warfare Center Carderock Division. (c) Cross-section of sedimentation-cast ingot. Strengthening particles (within darker region) have settled to bottom of ingot before solidification because of gravitational effect. Figure used by permission from Naval Surface Warfare Center Carderock Division

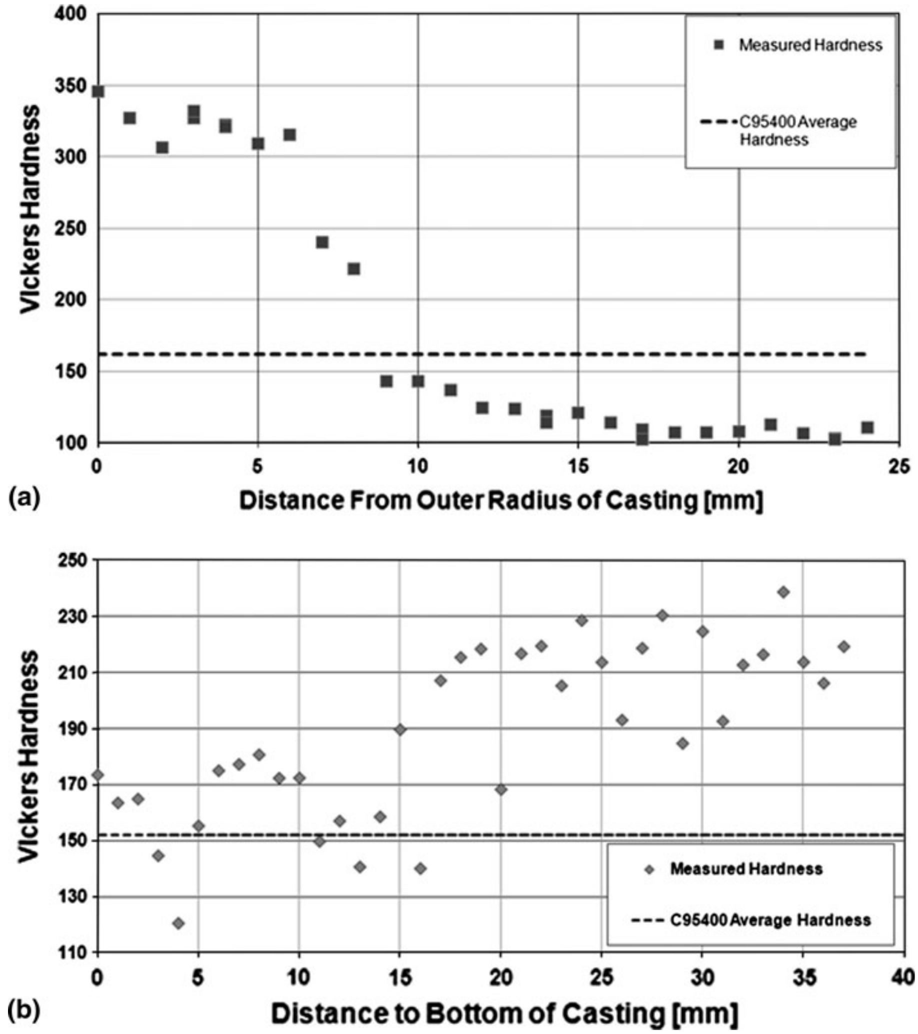

Fig. 2 (a) Hardness values of centrifugally cast bronze/WC MMC as a function of radial position within the casting. Average hardness values of C95400 bronze found in Ref 4. (b) Hardness values of sedimentation-cast bronze/WC MMC as a function of radial position within the casting. Average hardness values of C95400 bronze found in Ref 4

bronze (Ref 4) until strengthening particles are encountered within the matrix. Then, the H_v value increases over a short spatial distance to a characteristic elevated value. The cause for scatter in H_v values within WC particle-rich region of the MMC is discussed in detail in Ref 3, but can be attributed to similarities in scale between that of the microhardness indenter and the concentration and size of the WC particles (~20–30 μm dia).

For the sedimentation-cast material, the H_v test results presented in Fig. 2(b) demonstrate a less obvious shift in hardness as a function of location within the ingot compared to that of the centrifugally cast MMC. This can be attributed to the lower concentration of WC particles in the sedimentation casting because of the lack of a strong driving force for WC particle migration within the melt as was present in the centrifugal mold, which was less than approximately 50× gravity (G) loading. Specifically, in the case of sedimentation casting, the 1 G load with tendency to pull the WC particles to the bottom of the melt is opposed by both buoyant and drag forces. These opposing forces yield a less concentrated volume fraction of WC particles as a function of location within the casting than the centrifugally cast ingot. The reduced concentration of WC particles is reflected in the lower average H_v values in the strengthened regions of the MMCs, with average H_v for centrifugally cast material being approximately 320, while that of sedimentation-cast MMC is 220. Scatter in sedimentation-cast MMC H_v values can be attributed to two effects: the previously discussed scale similarity noted for the centrifugally cast MMC; and the high level of porosity observed in the sedimentation castings which was not present in the centrifugally cast MMC.

Optical microscopy techniques were used to estimate volume fraction of the strengthening particles in the castings. These volume fraction measurements were also checked using a rule-of-mixtures calculation based on the conductivities of C95400 bronze and WC. Figure 3 provides the results for both centrifugally and sedimentation-cast bronze/WC. Additional discussion of use of the rule of mixture to aid in determination of properties is provided in Ref 5. To illustrate the difference in particle loading found between the two types of castings, Fig. 4(a) and (b) is provided. Both micrographs were taken at a magnification of 200× and were selected from regions of maximum WC particle content of the respective MMCs. In Fig. 4(a), note the much higher fraction of particle content in the case of centrifugally cast material than that found in the sedimentation-cast material of Fig. 4(b). Also note that the sedimentation-cast material demonstrates significant instances of porosity which can be seen as randomly distributed dark regions. This effect of this variation in particle loading and porosity will be revisited, when discussing results of strain rate effects on strength values.

Strain rate dependency of mechanical properties were evaluated for both types of castings, along with unmodified C954000 bronze matrix material for comparison purposes. High strain rate mechanical testing was conducted using a Split Hopkinson Pressure Bar (SHPB) with three nominal strain rates of 2000, 2800, and 3500 s^{-1}. Details of SHPB construction, operation, and data analysis may be found in Ref 6. An annealed C11000 copper pulse shaper of 2-mm thickness and 5-mm diameter was used to obtain an equilibrium stress state in the specimens. The use of pulse shapers to aid in obtaining the desired stress state are discussed in Ref 7.

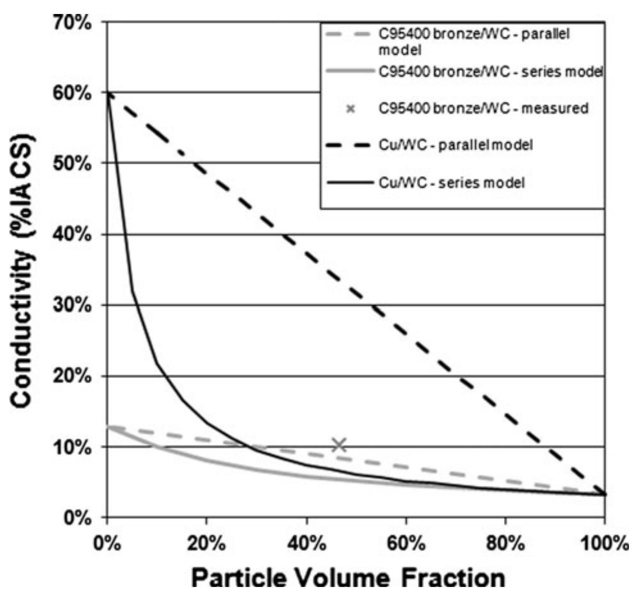

Fig. 3 Using rule of mixtures to predict conductivity of MMCs

3. Results

To aid in comparison of strain rate-dependent material property results, the same approximate strain rates were used for each type of material. In addition, specimens of matrix material C95400 bronze were tested to demonstrate the improvement of MMC tensile strength as a function of strain rate over that of pure matrix material. Finally, the two types of MMCs were tested to evaluate casting techniques against one another. Figure 5 provides strain rate results for centrifugally cast bronze/WC MMC and is used as an example to demonstrate how maximum strain rate was determined. Note that each curve has region of relatively constant strain rate, typically in the range of 0.05-0.10 strain, and this plateau in the curve is considered as the value of constant strain rate for that particular test. The presence of constant strain rate is used to confirm that an equilibrium state of stress was obtained within the specimen, which is an underlying assumption of the governing equations found in Ref 6. The SHPB apparatus used by the authors of Ref 6 relied on compressed gas to drive a striker bar to create the desired strain rates in the specimens. Similar strain rate vs. strain tests were conducted on specimens of C95400 bronze and sedimentation-cast bronze/WC, but are omitted here for the sake of brevity.

Data shown in Fig. 6 can be used for comparing casting techniques based on the performances of the two MMCs. SHPB data were analyzed to obtain these results. True stress is plotted on the vertical axis, while true strain is plotted on the horizontal axis for three different nominal strain rates (750, 1100, and 1850 s^{-1}). First, note that the centrifugally cast MMC ultimate strength is approximately 100% greater for all the strain rates of that of the ultimate strength exhibited by the sedimentation-cast MMC. This large increase in ultimate strength is predicted by the elevated hardness demonstrated in Fig. 2(a) as compared to Fig. 2(b). This improvement can be attributed to the significantly higher fraction of particles demonstrated in the micrographs of Fig. 4(a) and (b). No significant evidence of strain rate dependency for either of the casting methods of MMC is seen when comparing ultimate stress values over the range of

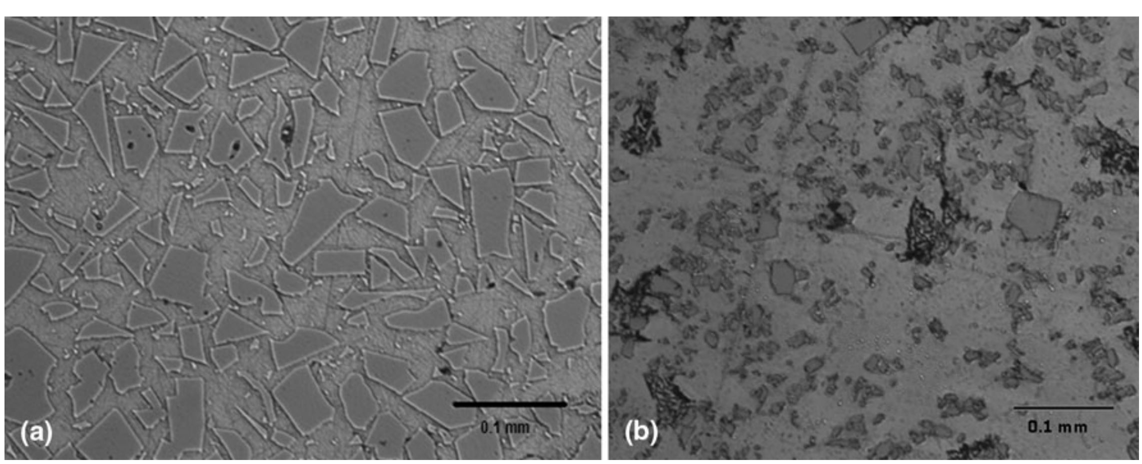

Fig. 4 (a) Particle loading of centrifugally cast C95400 bronze/WC MMC at 200×. (b) Particle loading of sedimentation-cast C95400 bronze/WC MMC at 200×

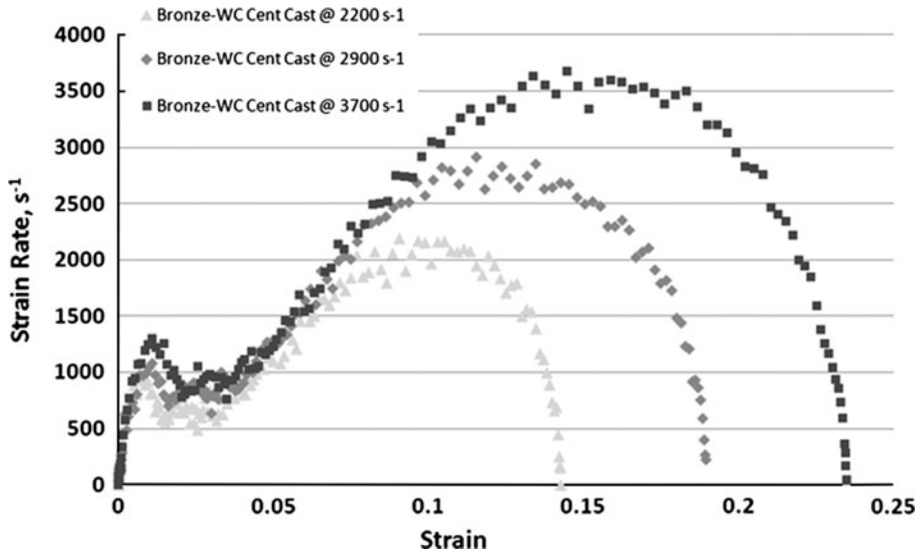

Fig. 5 True strain rate vs. true strain for centrifugally cast bronze/WC MMC

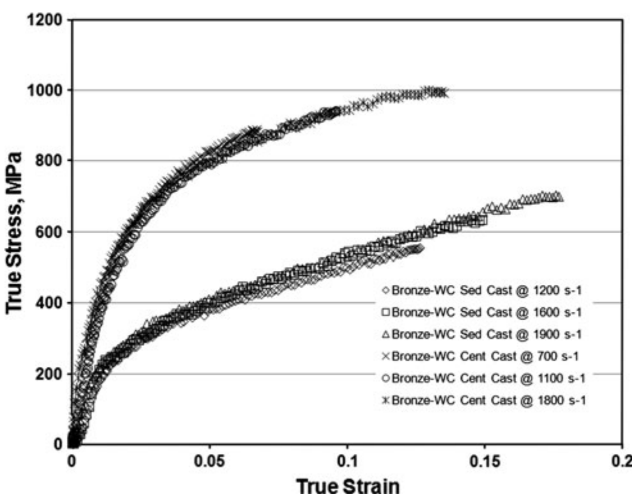

Fig. 6 True stress vs. true strain for centrifugally and sedimentation-cast bronze/WC MMC at nominal strain rates of 750, 1100, and 1850 s^{-1}

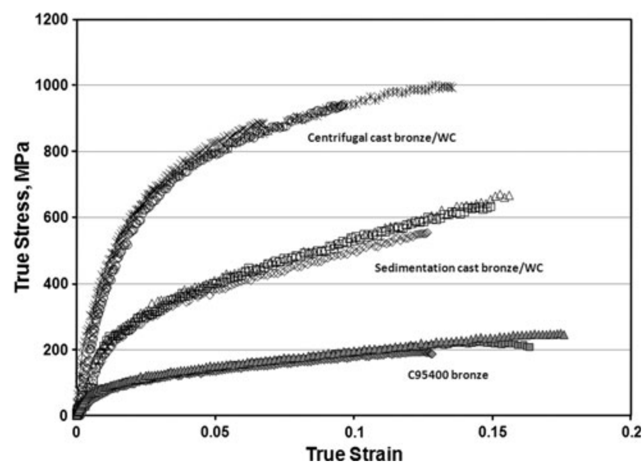

Fig. 7 True stress vs. true strain for C95400 bronze, and centrifugally and sedimentation-cast bronze/WC at nominal strain rates of 750, 1100 and 1850 s^{-1}

tested strain rates. For example, the sedimentation-cast MMC ultimate stress values increase approximately by 6% between the strain rates of 1250 and 1890 s^{-1}. This variation in tensile strength values can be attributed to the presence of porosities as shown in Fig. 4(b) that were dispersed throughout the sedimentation casting. Coupled with the porosity effects were the effects of localized concentrations of particle loading either above or below the overall volume fraction of WC within that region of the MMC. Figure 4(b) shows localized concentrations of WC particles, in particular when compared to the more uniform particle distribution of Fig. 4(a).

Figure 7 provides tensile strength data for three alloys at the nominal strain rates discussed previously. Plotted as true stress vs. true strain, note that C95400 bronze has consistently lower ultimate strength at all strain rates when compared with its MMC counterparts, which is as expected. C95400 displays little strain rate sensitivity, with an approximate tensile strength increase of 7% between the lower strain rate of 750 s^{-1} and the upper strain rate of 1850 s^{-1}. The addition of WC particles to the bronze matrix, either through sedimentation casting or centrifugal casting, resulted in a marked improvement in ultimate strength, as discussed previously.

4. Conclusions

Although the sedimentation-cast bronze/WC MMC shows significant improvement in ultimate strength above that of C95400 bronze, it is clearly outperformed by the centrifugally cast bronze/WC MMC. The sedimentation-casting technique is simpler than that of centrifugal casting; however, this casting method comes at the price of increased porosity, less concentrated particle loading and suboptimal hardness, and ultimate strength. For optimal performance with respect to strength and hardness, the centrifugally cast bronze/WC MMC is the better approach.

5. Comments and Recommendations

No attempt was made to evaluate thermal effects on strain rate-dependent mechanical properties. Note that these results were obtained using compressive loading because of the nature of classic SHPB testing techniques. The centrifugally cast bronze/WC evaluated in this study had a volume fraction of WC approaching to 45% at the outer mold walls. An attempt has been made to quantify high strain rate tensile behavior of bronze/WC MMCs (Ref 8); test results showed a brittle failure mode at high strain rates. Further tensile testing is required for a more complete quantification of mechanical properties as a function of strain rate. Sedimentation-casting results might be improved by means of WC particles of greater mass, which would aid in increasing the magnitude of the body force required for effective concentration of particles before solidification. Additional effort should be put into minimizing the porosity introduced during the sedimentation-casting process by using inert atmosphere during the casting process and insuring that molds and melt chambers are as clean as possible before pouring the melt.

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