

**Metal-Matrix Composites and Thermal Spray Coatings for Earth Moving Machines
Quarter 5 Report**

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Quarter 5 Report

Abstract:

In the fifth quarter, tooling for the steel MMC effort was redesigned based on the findings from the pressure casting trials of the previous quarter. While awaiting the arrival of that tooling, gravity casting trials were performed to assess modified performing technology and new hard particle systems. Steel-boride composite systems demonstrated good wetting and infiltration behavior, and fully infiltrated steel-boride composites were obtained under certain conditions. However, preform floating and particle dissolution are challenges which must be overcome. Ceramic oxide composites successfully pressure cast in a hot isostatic press at UC Santa Barbara were characterized and subject to fracture toughness testing. Resulting differences in fracture toughness are believed to be due to differences in matrix hardness, potentially imparted through reaction of the molten steel with the particles. Some evidence of bonding between the steel and oxide particles was noted on fracture surfaces. Arc lamp processing trials at Oak Ridge National Laboratory demonstrated that thermal spray coatings were successfully designed to facilitate fusion. All coatings investigated developed some degree of metallurgical bond after lamp fusion and for most coatings lamp fusion also further increased coating hardness.

An overview of the progress during the 1st quarter of this project is given below. Research details are provided in the limited rights appendix to this report.

Experimental

Steel Matrix Composites

Based on findings from pressure casting trials in the previous quarter, some features of the pressure casting tooling were redesigned. To increase cycle time and reduce the chance of premature solidification, the punch used to apply the infiltration pressure was attached to the press (previously the punch was manually placed on top of the melt). The use of thick walled ceramic die inserts is also being eliminated. These inserts were costly and their fabrication process did not allow for required dimensional tolerances. These inserts are being replaced with reusable steel inserts which will be protected from the molten steel using ceramic coatings evaluated in the previous quarter.

Borides are promising candidates for wear resistant materials. A ternary boride based cermet was developed for use as the hard abrasion resistant phase in the composites. The hard particles were made by a reactive liquid phase sintering of a mixture of molybdenum and Fe-B powders, followed by crushing and screening.

Various preforms were made by powder metallurgy techniques including preforms consisting of boride cermet, cemented tungsten carbide, mixtures of cemented tungsten carbide with alumina, and mixtures of boride cermet with alumina. The preforms were preheated with ceramic or steel dies. A thin ceramic coating was applied to the steel dies to protect them from the molten steel. Gravity casting was performed to evaluate the infiltration behavior of liquid steel on various preforms.

Pressure infiltration of ceramic oxide particles was accomplished at UC Santa Barbara using a hot isostatic press (HIP), configured to emulate squeeze casting. Two composite specimens were successfully cast, each about 25 mm in diameter and about 10 mm thick. One was reinforced with spherical alumina particles and the second with angular alumina-zirconia particles. In both cases the matrix was 4140 steel. The specimens were normalized for 16 h at 850°C. Changes in matrix hardness were determined using Vickers indentation, typically in 10-15 locations in each sample, both before and after normalization.

SEM micrographs of cross-sections through these composites are shown in Fig. 1. The notable features include uniform distributions of the particles and complete infiltration of the compact by the molten alloy. In the alumina/steel composite, the particles had partially sintered at the contact points. Such sintering was not evident with the alumina-zirconia particles.

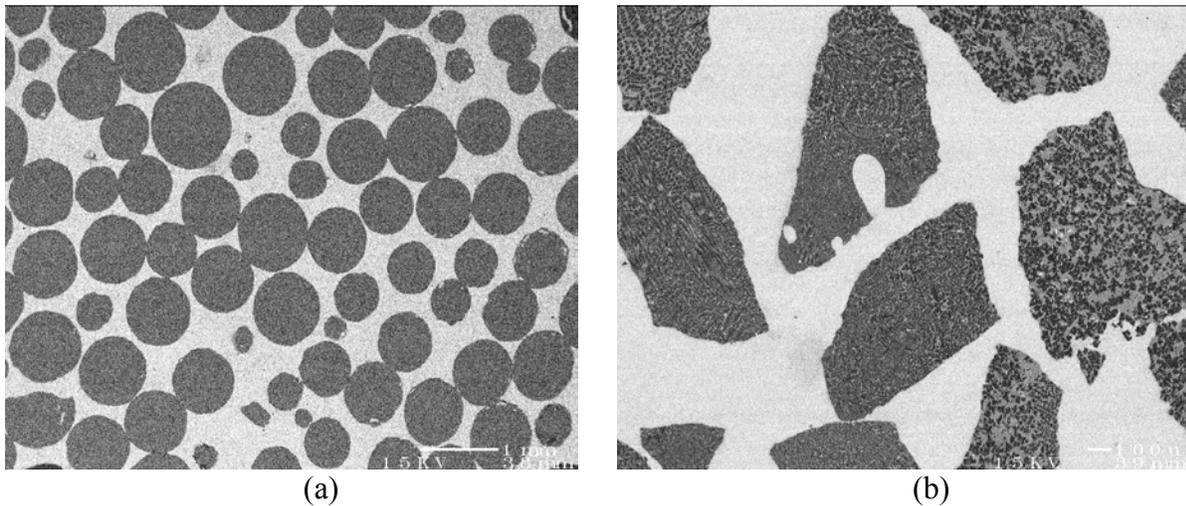


Fig. 1 Pressure cast ceramic-oxide/steel composites cast at UC Santa Barbara containing (a) spherical alumina particles, and (b) angular alumina-zirconia particles.

Thermal Spray Coatings

Twenty-two plasma sprayed coating compositions were fused with the plasma arc lamp at Oak Ridge National Laboratory (ORNL) in January 2002 and have been sent to the Albany Research Center (ARC) for ASTM G65 wear testing. Building on past experience, the coating compositions were designed to produce composites of hard, wear-resistant precipitates in a somewhat ductile matrix after fusing. Alloy and mixture compositions were varied systematically in order to determine both the most wear-resistant and the most compliant coating compositions. The goal of this particular effort was to gain enough knowledge to be allow for the design of a functionally graded material (FGM) coating in which the first layer will metallurgically bond to the underlying substrate and absorb solidification and coefficient of thermal expansion (CTE) mismatch stresses, while the uppermost layer(s) will be extremely wear-resistant. The substrate onto which all coatings were sprayed was case-hardened, low-alloy steel (25mm x 25mm x 152mm) with a surface hardness of approximately 50HRC.

Results and Discussion

Steel Matrix Composites

Design of the new tooling components has been completed, and the tooling will be available during the 2nd quarter of 2002.

Fully infiltrated steel-boride composites were obtained under certain conditions through gravity casting. Some boride cermet preforms were observed to float due to their relatively low density. This will introduce an additional challenge in the creation of reinforced components. Boride cermet particles were wetted by liquid steel due to the reaction of the liquid steel with the particles. The reaction also results in dissolution of the boride particles into steel. However, if solidification starts just after infiltration, an ideal composite macrostructure may be obtained for the steel-boride system.

The matrix hardnesses after normalization of the UC Santa Barbara cast composites were $154 \pm 36 \text{ kg/mm}^2$ and $430 \pm 32 \text{ kg/mm}^2$ for the alumina and alumina-zirconia composites, respectively. The resulting differences in hardness may be due to the steel matrix reacting with the reinforcing particles leading to a change in matrix alloying. It is believed that this hardness difference is also leading to a difference in observed fracture toughness, where the higher matrix hardness alumina-zirconia composite exhibited a higher fracture toughness of $16\text{--}20 \text{ MPa}\sqrt{\text{m}}$ vs. $8\text{--}10 \text{ MPa}\sqrt{\text{m}}$ for the alumina composite.

Preliminary fractography of the notched specimens reveals some plasticity within the steel and fracture along the particle-matrix interfaces. Some evidence of remnant steel on the particle surfaces was also seen. Fig. 2 shows a map of the opposing composite fracture faces from a test of an alumina-zirconia/steel composite. A “d” denotes debond, “f” indicates the particle fractured, and “m” indicates that there is evidence of both particle fracture and debond. The presence of remnant steel on the particles and occurrence of particle fracture, suggest that the bonding of the steel to the particles is at least moderately good, and probably a significant fraction of the strength of the steel itself.

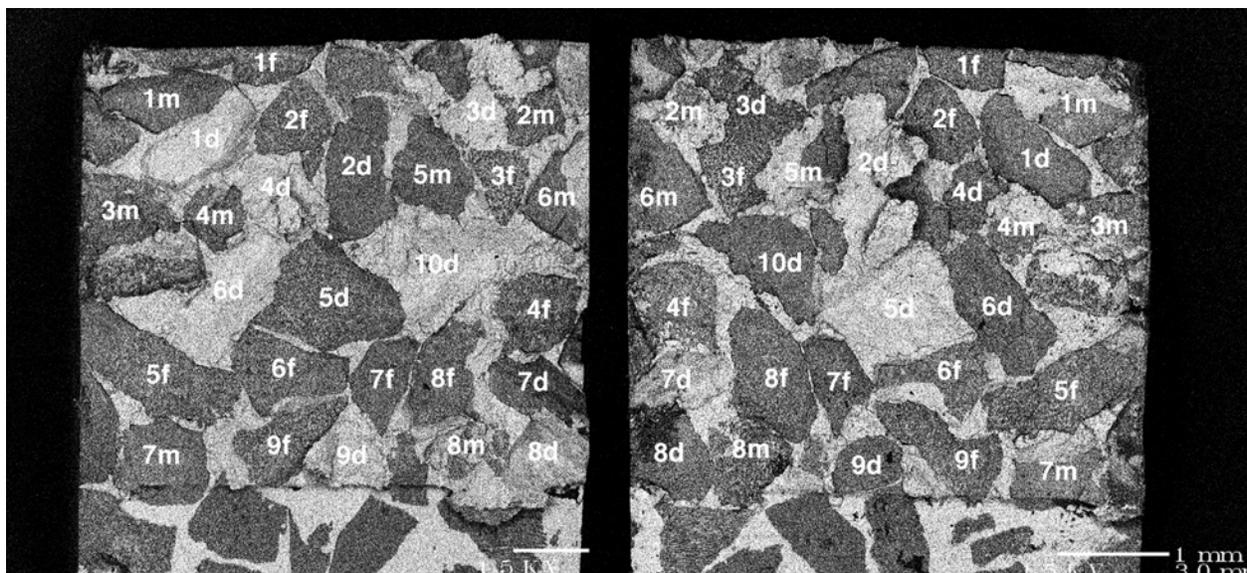


Fig. 2 Fracture map showing both halves of the fracture face from a test of the alumina-zirconia/steel composite. A “d” indicates debond, an “f” indicates the particle fractured, and an “m” indicates an apparent mix of debond and fracture.

Thermal Spray Coatings

All fused coating compositions investigated achieved some degree of metallurgical bonding. An example of the interfacial region of a fused coating is shown in Fig. 3. In nearly all cases, arc lamp fusing increased coating hardness and oftentimes hardness was approximately doubled. Bulk and inter-lamellar oxides and porosity were also agglomerated during fusing. Some oxides remained at the coating-substrate interface. No cracking was observed in any of the fused coatings, however some coatings did crack or spall during sectioning for metallography. This brittleness is of concern and somewhat inherent to extremely hard, fused materials that are under significant stress due to solidification, high temperature gradients during processing, and/or thermal expansion differences.

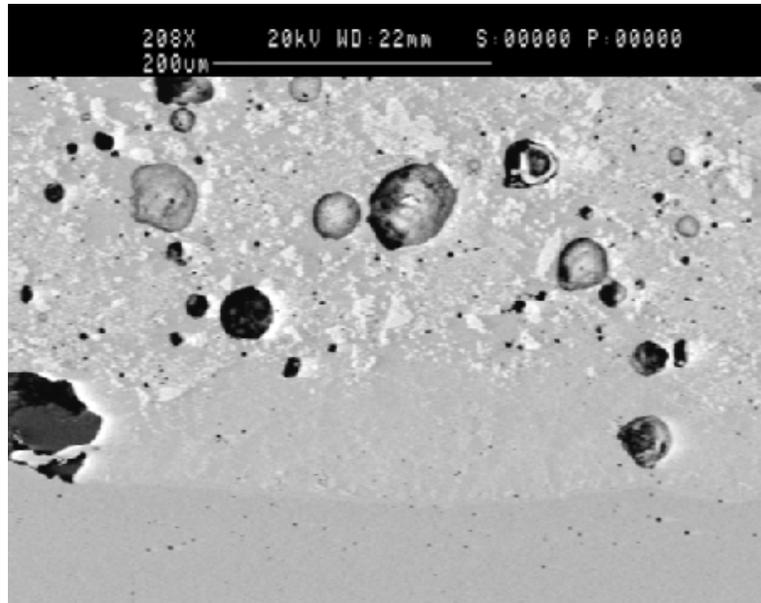


Fig. 3 Interfacial region of a thermal spray coating (top) which has been fused to the base steel using the high density arc lamp at ORNL. The light gray phase is the hard abrasion resistant phase and the darker spherical objects are likely agglomerated porosity (potentially containing some oxide).

Conclusions and Future Work

Steel Matrix Composites

Fully infiltrated steel-borides composites may be successfully fabricated by gravity casting under certain conditions. These experiments showed that boride cermets are promising hard materials to reinforce steel. However, as with cemented carbide, dissolution of these hard particles in molten steel remains a challenge. Fractography of alumina/steel and stoneblast/steel composites pressure cast in a HIP showed some evidence of interfacial bonding. Differences in fracture toughness of these two composite systems appeared to have a strong correlation with matrix hardness.

In the 6th quarter, pressure casting trials will continue with modified tooling. Fabrication of preforms and casting procedures will be further modified in an effort to make a fully infiltrated steel composites with limited dissolution of hard particles. Future activities at UC Santa Barbara will focus on the fabrication of larger steel-matrix composite specimens with alumina and

alumina-zirconia particles, for the purpose of further studying the deformation and fracture characteristics of these composites, both with and without notches.

Thermal Spray Coatings

Arc lamp processing served to agglomerate thermal spray coating porosity, dramatically increase coating hardness, and metallurgically bond the coating and substrate. The coating's melting and wetting characteristics have been optimized through composition sufficiently to allow for dimensional stability and metallurgical bonding. However, a great deal of further optimization is possible in terms of both coating chemistry and arc lamp fusing parameters.

Future work will involve further optimizing coating compositions for layers in an FGM design and likely investigations into fusible coating thickness limitations. Wear testing data from ARC will supply much needed information with regard to narrowing the coating compositions suitable for abrasion resistance. Upon completion of wear testing, a few FGM coatings will be sprayed, fused, and thoroughly evaluated in both terms of physical properties and wear performance.