PRESSURE DIE CASTING TRIALS ON MOLD MATERIALS FOR THE COPPER MOTOR ROTOR STRUCTURE

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ABSTRACT

The incorporation of copper for the conductor bars and end rings of the induction motor in place of aluminum would result in attractive improvements in motor energy efficiency. Die cast motor rotors are universally produced in aluminum today because rotor fabrication by pressure die-casting is an established practice. Lack of a durable and cost effective mold material has been the technical barrier preventing manufacture of the copper cast rotor. This project seeks to identify mold materials for copper pressure die casting that will allow economical production of copper motor rotors. To establish a base line for comparison, the first copper die-casting trial was conducted using the H-13 steel die inserts. Although the dies generally degraded with increasing usage, and some heat checking of the H-13 steel mold inserts and shot sleeve was evident, an extended run of copper against H-13 was accomplished. Over 800 die-castings were produced using one set of dies. Five copper die-castings were metallurgically, physically and chemically analyzed. The gate and runner macrostructures showed an outer columnar chill zone and a mixture of equiaxed and columnar grains in the bulk. Internal defects resembling oxide films, macroscopic pores and slag type inclusions were also found. Iron and oxygen was found to be between 10-350 ppm and 0.055-0.15 wt%, respectively. The electrical conductivity varied from 95% to 101% IACS. Additional die casting trials using non-traditional mold materials (nickel, tungsten and molybdenum) are planned.

INTRODUCTION

It is well known that incorporation of copper for the conductor bars and end rings of the induction motor in place of aluminum would result in attractive improvements in motor energy efficiency.

Die cast motor rotors are universally produced in aluminum today because of fabrication by pressure die-casting is a well established and economical method. Only small numbers of very large motors utilize copper in the rotors by mechanical fabrication. Such fabrication involves intensive hand labor and therefore is expensive. Die casting, when it can be performed, is widely recognized as a low cost manufacturing process. For these reasons, die-casting has become the fabrication method of choice and aluminum the conductor of choice in all but the largest frame motors. Tool steel molds as used for the aluminum die casting process have proved to be entirely inadequate when casting higher melting point metals including copper. Lack of a durable and cost effective mold material has been the technical barrier preventing manufacture of the copper cast rotor (CCR).

An important study sponsored by the Department of Energy found that motors above 1/6 HP used about 60% of the electricity generated in the United States.(1) Medium horsepower motors, 1-125 Hp, use about 60% of the electricity supplied to all motors. Because of the proliferation of electric motors in this horsepower range, the target of this project, the projected energy savings of the copper rotor motor is a significant national consideration. Efficiency increases (a function of motor size) are projected to result in total energy savings in the year 2010 of 20.2 E+12 Btu/yr at only 10% market penetration and 143 E+12 Btu/yr at the expected market penetration of 50 to 70% (dependent on motor size). These numbers are equivalent to the yearly output, respectively, of 0.5 to 3.5 600 MW generating plants operating at 75% of capacity.

The objective of the program is to identify high temperature, thermal shock resistant materials, and then to design, fabricate and demonstrate molds designed to withstand the copper motor rotor die casting environment for an economically acceptable life, i.e., thousands of casting cycles.

Program Summary

Several candidate die materials have been identified; beryllium-nickel, nickel-based superalloys, and one or more compositions in the tungsten-based composite family produced by a high speed chemical vapor deposition (CVD) technique by the ThermoTrex Corporation. This project will in its *first* phase fabricate and test simple end ring molds of the several materials on an 800-ton horizontal shot controlled pressure die casting machine located at the new Casting Development Center being established by Buhler North America in Denver, Colorado. In the second phase of this project, the most promising mold material from Phase I will be fabricated into motor rotor molds and run

(1) Classification and Evaluation of Electric Motors and Pumps, DOE/CS-0147, February, 1980.

for an extended number of shots at this same facility. For these runs, motor company partners will supply iron lamination stacks for appropriate motors designed to use copper rotor conductors. The motor partners will test the performance of the copper cast rotors.

Program Partners

The consortium of partners for this program was assembled during 1995 by the Copper Development Association Inc. A DOE-NICE^3 application was submitted in January, 1996 and awarded in May, 1996. The contracts were executed September 30, 1996 allowing the project to begin officially October 1, 1996.

The lead industrial partner for DOE-NICE^3 is ThermoTrex Corporation (TTC), a subsidiary of Thermo Electron Corporation. Partners in the program are Baldor Motors, Air Conditioning and Refrigeration Institute (ARI), Buhler North America and THT Presses. Each of the motor manufacturers has engineering, rotor stack production and appropriate motor test facilities needed to support this program. Buhler and THT Presses, both manufacturers of pressure die casting machines for the motor industry, will provide casting experience. The Buhler Casting Development Center will be the site of the mold material evaluation studies. Both Buhler and THT will test molds and cast rotors in Phase II of the project.

This consortium of partners has been formed by the Copper Development Association Inc. that is managing the project and providing technical expertise on the processing/handling of copper. Copper industry funding is provided by the International Copper Association.

Background

Recent analysis by two U.S. motor manufacturers shows that the economics of motor operation and manufacture favor the use of copper in all classes of motors if the die life in the pressure die casting process can be extended to the order of 20,000 shots.

Die Cast Copper Rotors (CCR's) can provide advantages to motor manufacture or performance in three ways:

- improvement in motor energy efficiency in operation
- reduction in overall manufacturing cost
- reduction in motor weight

The motor manufacturer can accentuate one of the advantages at the expense of the other two. For example, in the case of a premium 10 Hp motor recently analyzed, the motor efficiency is 91.0%. Three design scenarios using CCR have been analyzed: (1) seeking maximum efficiency improvement; (2) seeking maximum manufacturing cost reduction; and (3) seeking motor weight reduction.

Motors losses result from primary (stator winding) I^2R (usually 34% to 39%), secondary (rotor) I^2R (usually 16% to 29%), iron (core), friction and windage, and stray load.[(2)] In addition to direct reduction in rotor loss with CCR's, designs achieve additional reductions from overall motor re-optimization of iron, strays, etc. CCR-based designs show overall loss reduction from 15% to 20%.

(1) If motor re-design efforts were devoted solely to improving efficiency, it is estimated that the new design with CCR could achieve 92.5% efficiency. This CCR example creates a "super" premium efficiency motor with an efficiency level (i.e., 92.5%) higher than currently available premium efficiency motors.

(2) If motor re-design efforts were devoted solely to reducing manufacturing costs for the current 91.0% efficient premium motor, it is estimated that the new design using CCR could be manufactured at a $36 reduction in overall manufacturing cost (15% of current $240 estimated manufacturing cost), maintaining exactly 91.0% efficiency.

(3) If motor re-design efforts were devoted solely to reducing motor weight, it is estimated that the new design could reduce weight by 5% to as much as 10%.

CCR's can be used in specific motors to achieve a multiplicity of intermediate combinations of these design advantages. For example, where a smaller efficiency increase is required, the CCR could be used to achieve some reduction in manufacturing cost (stator winding, core, etc.) than would otherwise have been the case with traditional aluminum die cast rotor technology.

The problem encountered in attempting to die cast copper motor rotors is thermal shock and thermal fatigue of mold materials. Thermal cycling of the mold surface limits the mold life even in aluminum die-casting. However, cyclic thermal stresses are so severe in copper die casting that in at least one recent instance, a mold-gate-plate made of high strength steel (H-13, a die casting industry standard) being tested at a die machinery manufacturer's facility, fractured in just five casting shots. To be economically feasible, mold life must be measured in thousands of casting cycles.

A problem with common mold materials is that they lose strength at high temperature thus requiring low mean operating (and pre-shot surface) temperatures. A low initial temperature results in a large ΔT at the surface of the die, and thus the stress in the die, on each shot. The high melting temperature, high heat of fusion, substantial latent heat and high thermal conductivity of copper all combine to maximize the thermal shock. The solution to the thermal shock problem lies in the use of high temperature materials having thermal and thermoelastic properties and thermal properties conducive to minimizing thermally induced strain. Studies conducted by the International Copper Research Association (INCRA) in the 1970's confirm these expectations.

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(2) Steels for Laminations in Energy Efficient Motors, CMP/EPRI Report 9-11, June 91 Table 2-1

Innovation

Tungsten and molybdenum identified in the INCRA studies as good candidate materials for copper casting have not found use in the industry largely because of fabrication costs. ThermoTrex Corporation has developed a cost effective near-net shape material forming process, named Chemical Vapor Composites (CVC), a high growth rate variant of the well-known chemical vapor deposition method. TTC had been funded by ARPA through Fall 1996 to scale this process for a tungsten composite mold manufacture expressly for die casting the copper motor rotor. TTC recently fabricated the critical mold-gate-plate for a THT machine.

These tungsten CVC materials hold high promise for long life. However, they may be still more expensive than necessary for all components of the mold system. Several new materials not available in the 1970's have been developed for high temperature applications. Two promising candidates for parts of the die caster are the nickel-based superalloys and the beryllium-nickel alloys. None of these materials has the low expansion of tungsten or molybdenum, but they do retain exceptional strength at high temperatures. Hence, even if it is found that they cannot survive in the hottest sections of the die casting equipment, they may serve well in other areas.

RESULTS

Engineering and design of the modifications to the Buhler die casting facility to support copper die-casting were necessary. Buhler completed installation of the 50 KW Inductotherm melting furnace capable of continuously melting 8 pounds of copper at 2-minute intervals for successive die shots. A test mold was designed to simulate the action at one gate of a multi-gate mold. Die casting trials of candidate mold materials do not incorporate the iron lamination stack because of the high cost of lamination material involved in the thousands of shots anticipated. An extended run with the most promising mold materials from the first phase of the project will be run to produce thousands of rotor castings in the second phase in 1999.

Computer models of flow and heat transfer were used to predict temperatures and temperature gradients in the molds for various designs (Figure 1). These modeling exercises are described in a paper presented at the International Conference on Permanent Mold Casting of Copper-Based Alloys, Ottawa, Ontario, Canada, in October 1998.

To establish a baseline for the test mold, the first copper die-casting trial was conducted using the H-13 steel die inserts (Figure 2). As expected, the dies generally degraded with increasing usage. Quite surprisingly, although some heat checking of the H-13 steel mold inserts and shot sleeve is evident, an extended run of copper against H-13 was accomplished. This success is attributed to the dry mold release system, the fast cycle time which minimizes heat input to the mold, and through the use of advanced computer controlled casting equipment. Over 800 castings were produced using one set of dies, greatly exceeding expectations by an order of magnitude or more (Figure 3).

Five copper castings were metallurgically, chemically and physically analyzed. The samples were identified with the following shot numbers: 9, 111, 438, 600, and 800. Metallographic samples for microstructure and macrostructure analysis were removed form the gate section and samples for macrostructural analysis were removed from the runner section. The gate and runner macrostructures showed an outer columnar chill zone and a mixture of equiaxed and columnar grains in the bulk (Figure 4). The microstructures also showed the presence of an interdendritic phase (Figure 5) most likely a eutectic copper-oxygen phase. Surface cracks and tears were found in the gate sections, in general the number and depth decreased with shot number. The cause of cracking in the gate area is most likely the result of bending stresses during the removal from the mold. Internal defects (Figure 6) resembling oxide films, macroscopic pores and slag type inclusions were also found and again decreased in size and frequency with shot number.

Electrical conductivity was measured on milled and polished transverse slices from the runner sections using a MAGNAFLUX SM-400 digital surface meter. Areas adjacent to the surface and center were measured (Table I). The electrical conductivity varied from 95% to 101% IACS.

TABLE I.
IRON AND OXYGEN ANALYSIS

Shot Number	Iron Content ppm	Oxygen Content wt%
9	17	0.059
111	350	0.11
438	56	0.15
600	61	0.057
800	10	0.055

Samples for chemical analysis were taken from the runner sections. The oxygen was analyzed using a LEECO EF-400 oxygen determinator and the iron using a SPECTRO LAX-X7 Optical Emission Spectrometer. The iron content varied from 10 ppm to 350 ppm and the oxygen levels from 0.06% to 0.15% (Table II). No obvious correlation was found between shot number and chemistry.

TABLE II.
ELECTRICAL CONDUCTIVITY MEASUREMENTS

Shot Number	Surface %IACS	Center %IACS
9	100.7	94.8
111	95.8	94.6
438	98.4	95.1
600	101.3	98.0
800	100.5	98.2

CONCLUSIONS

Copper die cast motor rotors would result in attractive improvements in motor energy efficiency. Advances are being made toward the development of durable and cost effective mold materials, presently the last major hurdle preventing die casting of the copper rotors. The first copper die casting trial conducted using the H-13 steel die inserts was very successful. Although some heat checking of the H-13 steel mold inserts and shot sleeve is evident, an extended run of copper against H-13 was accomplished. The microstructure of the die cast copper exhibited some defects but none that significantly degraded the electrical conductivity. The authors believe that the use of high temperature die materials will significantly increase the mold life making possible the die-casting of copper and other high melting point materials. More work is planned toward this goal.

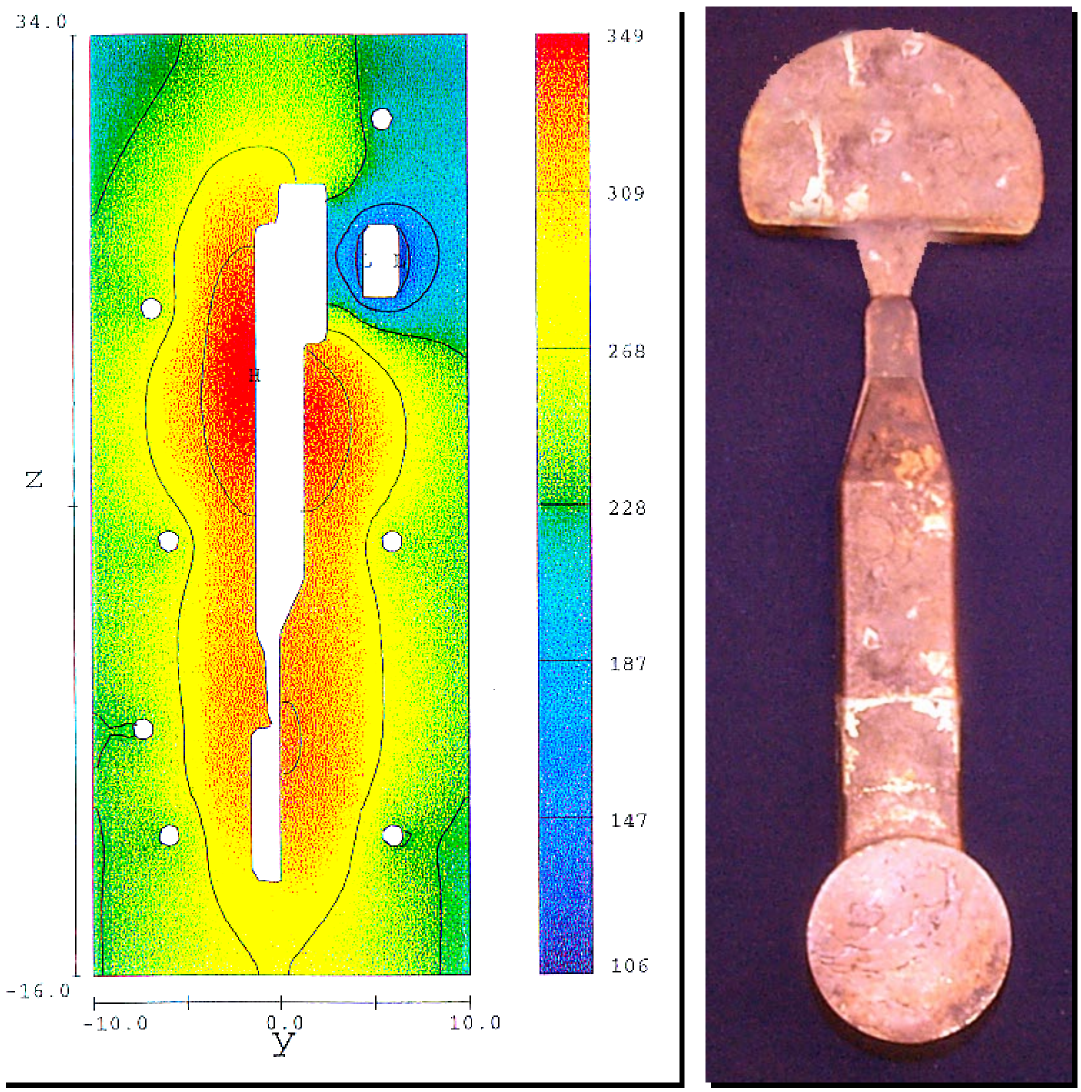

Figure 1. Flow 3-D computer simulation of temperature profiles of the H-13 steel die inserts during the cooling cycle (left). First copper die-casting in the test cavity designed to simulate a single-gate motor rotor (right).

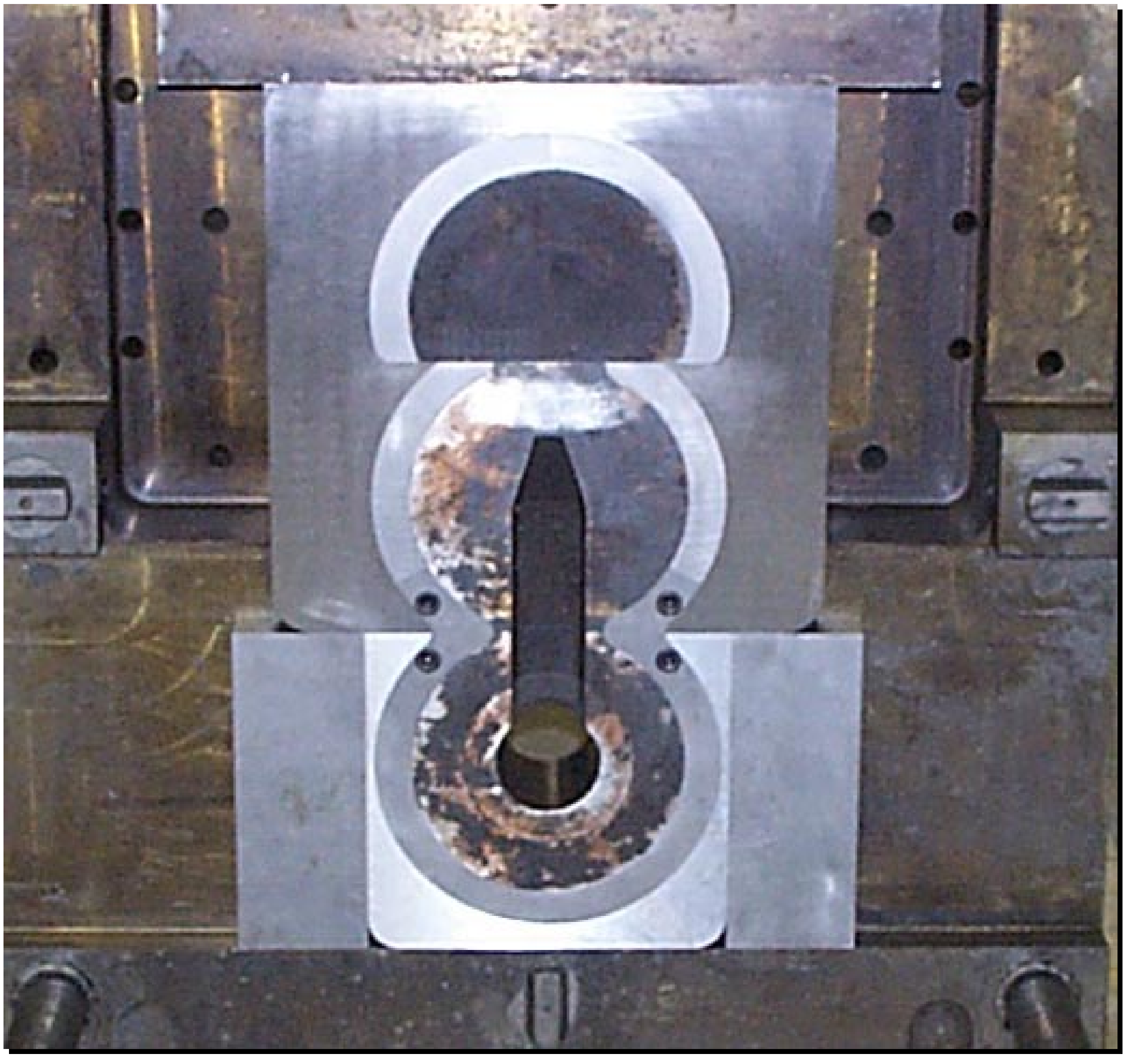

Figure 2. The H-13 steel test cavity tool set after the first several shots.

Figure 3. Comparison of die-casting shot numbers 9 (left) and 800 (right). Some degradation of the H-13 steel die inserts is evident from the increased width of the flash between inserts and by the erosion at the gate area.

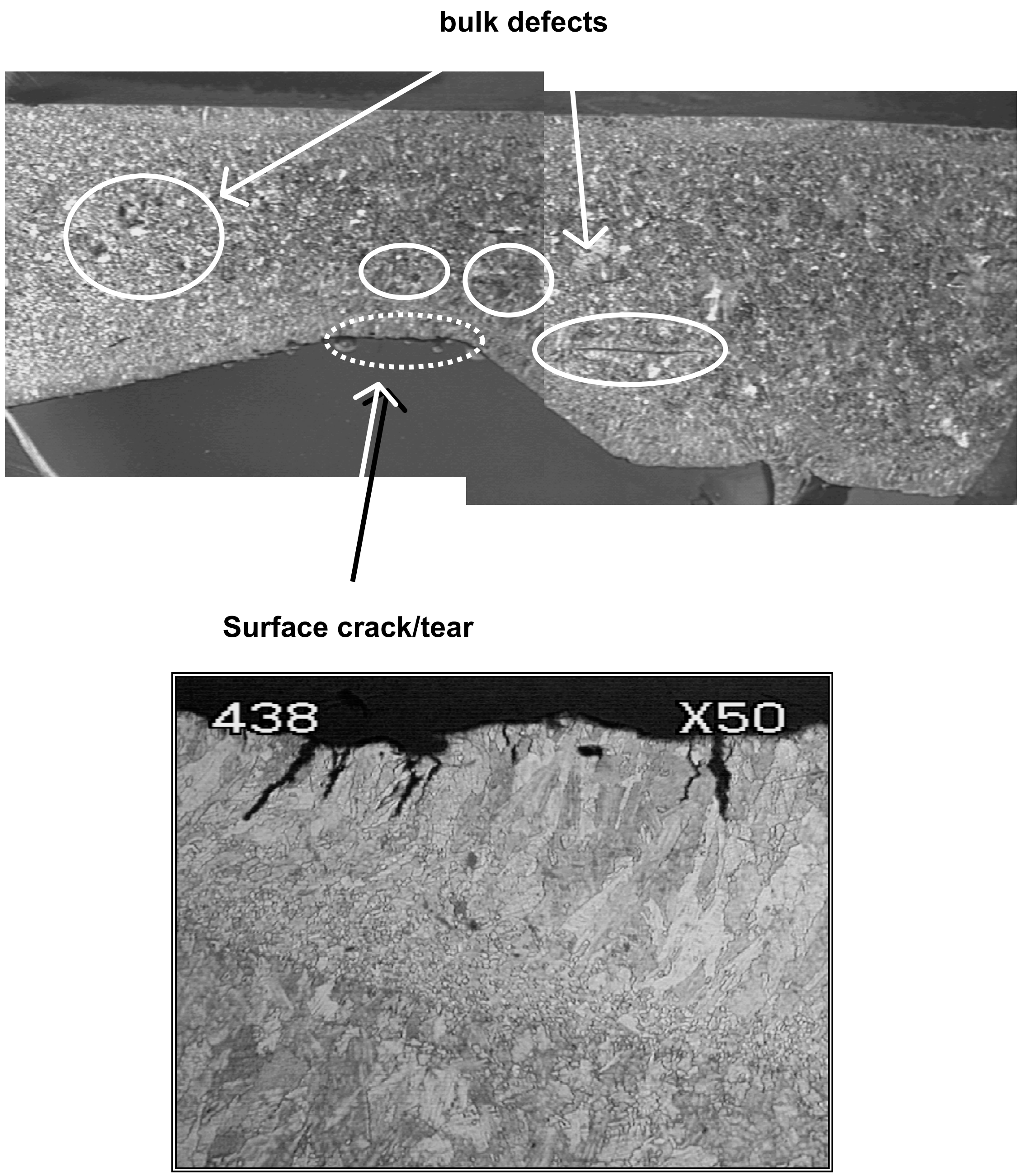

Figure 4. Macrostructure and microstructure of shot # 438 within the gate section of the casting (longitudinal). Cracks are most likely the result of high bending stresses generated during the removal from the mold.

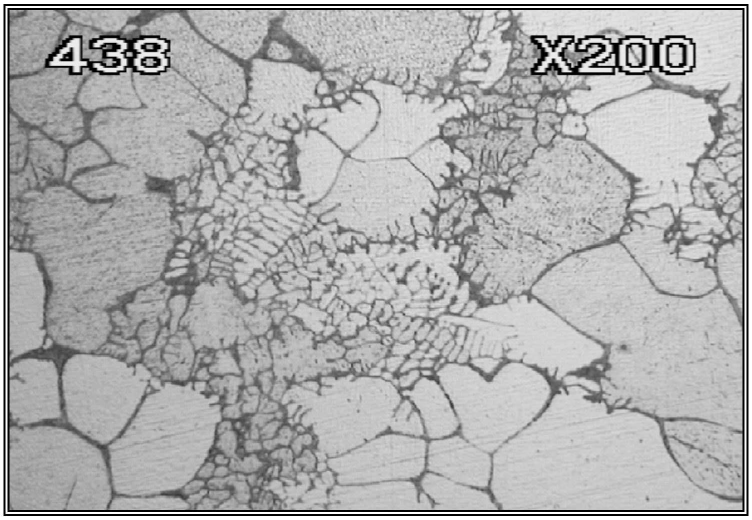

Figure 5. Typical bulk microstructure showing interdendritic phase (Shot # 438).

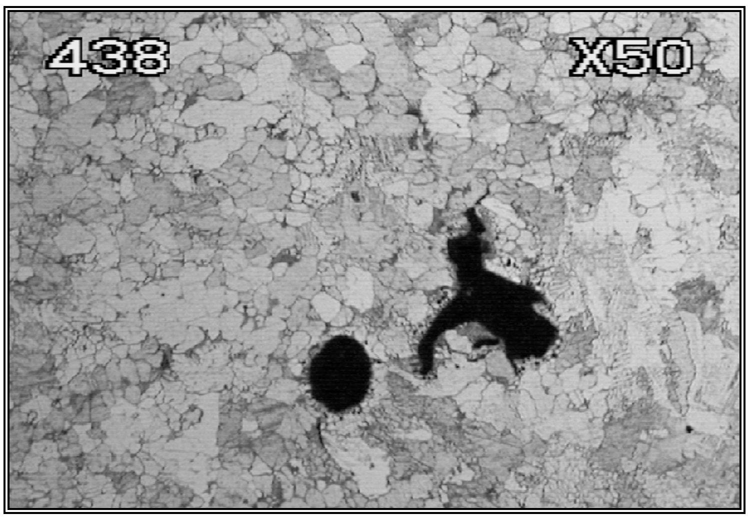

Figure 6. Bulk defects (micro-pores and oxide particles) found in shot # 438.

Figure 7. Tungsten chemically vapor deposited (CVD) onto a molybdenum substrate by the ThermoTrex Corporation.