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# MACHINE CASTING OF FERROUS ALLOYS

December 1977

by M.C. Flemings, K.P. Young, J.F. Boylan, R.L. Bye,
M.L. Santor, B.E. Bond

MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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This is the sixth and final report describing research conducted at the Massachusetts Institute of Technology as part of a joint university-industry research program on machine casting of ferrous alloys. It covers the period of the 42nd month to the 54th, the final one year research of the overall 4-1/2 year program.

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## ABSTRACT

During this year the basic Rheocasting system, which was fully operational at the beginning of the year, was improved in various ways to increase reliability and productivity. Specific improvements were the addition of a reducing gas in the melting chamber, a shield gas extension nozzle and graphite inserts at the bottom of the Rheocaster to eliminate "hot spots". Large quantities of 304 and 440C stainless steel alloys were cast during this period (approximately 800 pounds of 304 and 2000 pounds of 440C) and smaller quantities of other materials were also Rheocast including M2 tool steel, and HS 31 Cobalt base superalloy.

Improvements in details and automation of the Thixocasting process were also made during this perid. Work subsequently concentrated on casting large quantities of stainless steel into various die materials in order to determine die life and to optimize that die life.

Trials previously reported on H-13 dies were completed and similar work then conducted on H-21 dies. This latter die material showed significant improvement in performance over H-13. Also dramatic improved performance was found by using copper dies and dies of copper-chromium and copper-chromium-zirconium alloy. Special die quenching methods were employed to lengthen die life. In the Cu-Cr-Zr die, over six hundred shots of a casting were made with no mold cracking and only slight parting line erosion.

Computer and experimental study of heat flow in Thixocasting continued to aid in optimizing die life. Significant differences have been found depending on metal, die material, fraction solid, and mold treatment. Specifically, results show that copper dies heat to a much less extent and much less rapidly than do steel dies when metal is cast.

Detailed studies have been made on the structure of Rheocastings and Thixocastings, including solidification structure, and oxide inclusions. These have been related to operating variables of the continuous Rheocasting unit.

This report was supported by the Advanced Research Projects Agency of the Department of Defense and was monitored by the Army Materials and Mechanics Research Center under Contract No. DAAG46-73-C-0110.

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# I. INTRODUCTION

In January, 1973, a joint university-industry research activity was undertaken to develop an economical method of machine casting ferrous alloys. A portion of this program was conducted at Massachusetts Institute of Technology primarily on machine casting of semi-solid alloys into reusable metal dies. A variety of casting concepts have been explored as reported in previous reports,[1-5] but major emphasis of the work has been on two processes, Rheocasting and Thixocasting. In Rheocasting, a semi-solid slurry of a metal alloy is produced by vigorous agitation of a solidifying melt. This highly fluid slurry, typically the consistency of heavy machine oil at fractions solidified up to 0.5, is then cast directly to shape. In Thixocasting, fully solid ingots are first made from the semi-solid slurry and "charges" from these ingots are then reheated to the liquid-solid range and cast. Because the alloy slurries are thixotropic, these reheated charges retain their shape, behaving as soft solids, during transfer to the die casting machine. The high shear rates the charge undergoes within the gate entry and land area of the casting cavity reduce its viscosity to a level at which it flows smoothly into the cavity.

Previous reports in this series[1-5] summarize the program through the first three and one half years of activity (period ending June 30, 1976). Up to that point in the program, the major thrust of the effort had been to develop a pilot plant scale system for Thixocasting ferrous alloys, and then to demonstrate that significant numbers of castings could be made and to initiate tests on the die life that could be expected. This report summarizes the twelve month period from June 30, 1976 to June 30, 1977 in which emphasis has been placed on a) optimization of casting procedures and die life, b) die materials, and c) heat flow during the Thixocasting process. In addition, limited work has been conducted on mechanical properties.

Research emanating from this program and from the fundamental Army Research Office study preceding it has been summarized in twenty-two technical papers, twelve theses, four articles, and five reports. In addition, seven US patents, and three foreign patents have been received; other patents are pending. Appendix A lists these various publications and patents.

# II. RHEOCASTING

During this report period, more than 3,000 pounds of Rheocast high temperature metal was produced. Total production for the last twelve months and for the entire contract period is detailed in Table 1.

## Equipment

Several minor adaptations and additions have been made to the Continuous Rheocaster. A specially machined graphite piece has replaced the lower 3-3/4 inches of the Vesuvius crucible. This piece provides better support for the mixing tube nozzle and prevents the formation of hot spots around the exit port. To exclude oxygen from the upper reservoir an argon-4% hydrogen shielding gas is used and greater care is taken to seal the top of the furnace. These measures have improved metal cleanliness and reduced slag attack of the rotor. Contact between exiting metal and oxygen has been reduced by using a quartz tube to extend the argon-4% hydrogen shield at the exit of the Rheocaster to the top of the ingot molds. The capability for argon prefilling of the molds has also been added. The current design of the high temperature Continuous Rheocaster is shown in Figure 1. The Rheocaster and its support equipment are shown in Figure 2.

Maximum output of the 40 pound Rheocaster is approximately 300 pounds per hour. However, our power supply is large enough to supply only about 60 - 100 pounds of molten metal per hour, thus limiting the production rate to that level. When steel is cast, furnace life is generally limited to two runs, a total of 10 - 12 hours at operating temperatures. The most prevalent mode of failure is cracking of the mixing tube at the exit port. This is not generally a catastrophic failure but it destroys the seal between the rotor and the exit port and results in severe rotor vibration due to an uneven seating surface. In a machine operating at higher flow rates with a larger rotor exit separation, slight exit area cracking would probably not create the problems that it does with the present, small scale, Rheocaster.

## Operation

At the start of a Rheocast production run the rotor is positioned in the mixing chamber with a rotor-exit separation of about 1/8" to allow for thermal expansion. Approximately 20 pounds of feed metal is placed in the top chamber. Argon-4% hydrogen flow is turned on to both the top and exit chambers. Power to all three induction coils is then turned on and adjusted so that a relatively level temperature profile, as indicated by thermocouples at the exit, in the mixing chamber, and in the top reservoir, is maintained. Thermal shock is thereby minimized when the metal in the top reservoir first melts.

After the initial charge has melted, the rotor is seated at the exit port with the minimum pressure required to prevent metal flow. The power supplies are adjusted to stabilize the metal temperature with a superheat of about $40^{o}C$. The rotor is then rotated slowly while additional metal is added to fill the upper chamber.

When the furnace is full, the rotor speed is increased to provide a shear rate of 800 $sec^{-1}$ in the mixing chamber. The power to the middle coil is then reduced so that enough heat is extracted to produce about 80 pounds of 50% solid slurry per hour.

From this point on, the Rheocaster is controlled exclusively by monitering the amperage required to drive the rotor at constant speed. As the fraction solid of the Rheocast slurry increases, the viscosity increases, and the amperage needed to drive the rotor increases. (See

"Structure-Property Relations" section of this report.) When the amperage has increased the desired amount, the rotor is raised and adjusted to vary the flow rate until the amperage reading stabilizes. Increasing the flow rate results in a decreased metal residence time in the mixing chambers and, therefore, a decreased fraction solid. Decreasing the flow rate has the opposite effect.

Exiting Rheocast metal is teemed into stainless steel tubes or black iron pipes lined with Fiberfrax paper. The resulting ingots are 1-1/4" diameter and 6" long. Eight of the ingot molds are arranged in a transite cannister and are separated by Fiberfrax insulation. A cannister is rotated in the exiting metal stream until the eight ingots are full, and is then removed and replaced by another cannister. Water quenched drops of the exiting metal are collected periodically for subsequent metallographic examination. The ingots are withdrawn from the molds while still hot and allowed to cool. The molds are prepared for immediate re-use. After the fiberfrax paper has been removed from the ingots, they are sectioned into three separate charges for later Thixocasting.

# III. THIXOCASTING

## The Thixocasting Pilot Plant

The system for Thixocasting high temperature ferrous alloys has operated on a pilot production basis during this report period. This system is essentially that described in the previous report[5], and is shown schematically in Figure 3. Its basic components include a commercial 125 ton locking force horizontal cold chamber die casting machine (Figure 4), and a ferrous reheat station (Figure 5). This reheat station incorporates an induction furnace powered by a 60 kilowatt power supply, and a "softness indicator" which automatically ejects the reheated slug when it has reached the desired fraction solid. A Honeywell Visicorder Die Casting System monitors machine conditions during casting.

To date over 3000 shots of AISI 440C and 304 stainless steel have been cast in various shapes (Figure 6) for die life and mechanical property tests.

The Thixocasting process depends on the reheating of previously Rheocast charges to a reliable and consistent fraction solid on a repeatable basis. An important requirement is that the sample be heated with minimum internal temperature difference, so it is of uniform fraction solid when ejected. As described in a previous report[5], the current heating arrangement permits the heating of 440C and 304 stainless steel such that there is no more than $\pm 3^{\circ}C$ temperature difference throughout the sample. This uniform temperature profile is obtained by heating the samples first with a high power input (40 kw) for approximately 35 seconds, and then reducing the power input to 14 kw for the remainder of the reheating. In this manner the total heating time is approximately two minutes.

With a uniform sample temperature as described above, the softness indicator can provide an accurate and repeatable method of measuring fraction solid. Moreover, with a constant penetration distance, the fraction solid exhibited by the ejected sample can be varied by adjusting the pressure exerted on the probe. Calibration results for 440C stainless steel, using a 1/8" diameter flat bottom alumina probe and a penetration distance of 1/4" are shown in Figure 7. Reheating to reliable fraction solids between 0.30 and 0.75 is possible using a plot such as this.

## Die Life Studies

Six sets of die inserts were machined to cast either the M-16 rifle hammer (Figure 8) or a simulation of that part. Each set was prepared using a different material: AISI H-13 die steel, AISI H-21 die steel, TZM, tough pitch copper, Cu-1% Cr, and "Elbrodur RS" (Cu-1% Cr, 1% Zr). The actual part is 2 inches long and weighs approximately 0.1 pounds. In all cases the Thixocastings were made at 0.45 or higher fraction solid. Over two and a half thousand castings were made in these inserts in either AISI 304 or 440C stainless steel for die life evaluations.

A summary of results is given in Table 2, and will be discussed below.

## Steel Dies

AISI H-13 is a popular die casting chromium die steel used extensively for die casting low and intermediate melting point alloys such as magnesium and aluminum. AISI H-21 is a low carbon, medium tungsten hot work steel with outstanding red hardness, that has been used successfully to die cast the higher melting point bronze and brass alloys.

Identical cavities to cast the M-16 rifle hammer were prepared in both H-13 and H-21 die inserts. In both cases acetylene black was used as a die release agent. H-13 dies were operated at 275$^{o}$C while H-21 dies initially were operated at 350$^{o}$C and later lowered to 200$^{o}$C.

Shot weight in all cases was approximately 3/4 lbs after reheating. The shot was manually transferred to the shot sleeve, which was preheated to approximately 100$^{o}$C. While casting conditions were occasionally varied for die filling experiments, typical values for plunger speed and back pressure were 18 in sec$^{-1}$ and 1400 psi for 440C stainless steel, and 36 in sec$^{-1}$ and 1400 psi for 304 stainless steel. After full pressurization, the dies remained locked closed for approximately 2.0 seconds, at which time they automatically opened and ejected the part.

Over 500 shots of 304 stainless steel were cast into the H-13 inserts. Figure 9 shows a history of the parts produced in the as-cast condition. Following the same procedure, over 500 shots of 304 stainless steel were also cast into the H-21 insert set. Figure 10 shows a history of the parts produced.

Deterioration of the dies in both cases occurred by the same mechanism, heat checking at hot spots on the cavity surface (out-side corners) and erosion at hot spots along the die parting line. At no time was welding experienced. Results for both materials show a significant improvement over previously reported work.[6,7]

Parts produced in these dies were qualitatively analyzed and assigned a subjective mold crack rating on a scale from 1 (no cracks) to 5. Results are plotted in Figure 11. The 500th casting made in the H-13 insert set was assigned a crack rating of 5 and all other castings in both sequences were rated with respect to its condition.

It should be noted here that this is an arbitrary rating scale for mold cracking and a rating of 5 in no way indicates die failure. The condition of a die when it has "failed" can vary depending on the application of the part being cast, but typically a die is said to have failed when either the customer can no longer tolerate the condition of the parts it produces or when the cost of trimming and cleaning the parts produced becomes greater than the cost of reworking the die.

Initial fine cracks formed after about fifty shots in both the H-13 and H-21 die inserts; however, crack growth in the H-21 dies was much slower than in H-13. As stated above, the 500th casting in the H-13 die inserts was assigned a rating of 5, while after the same number of shots the parts cast in the H-21 inserts had reached a crack rating of only 3.25. Projections for H-21 suggest that approximately 1300 shots would be required to reach a mold crack rating of 5.

## Copper Dies

Initial tests were conducted by Thixocasting 440C stainless steel into a simulated M-16 rifle hammer cavity cut into a tough pitch copper die insert set. The Thixocasting process was adapted to allow for a minimum amount of heating of the die insert. To that end, dies were operated at close to room temperature, and die lock up time after full pressurization was reduced to a maximum of 0.4 seconds. In addition a water base graphite die release was sprayed on the die surfaces immediately after each shot. This served the dual purpose of coating the dies with die release, and of quenching the die surface to remove the heat taken up by the dies in the previous shot. All other casting conditions remained similar to those used for steel dies.

Another simulated M-16 rifle hammer die was prepared in a cast Cu-1% Cr alloy. This is a precipitation hardening alloy which was solutionized and hardened to $R_B$ 70. It has mechanical properties superior to those of pure copper and its thermal properties are roughly the same. The thermal conductivity of Cu-1% Cr is approximately 10 times greater than H-13 or H-21. Several overflows were eliminated and the remainder were cut as far from the cavity as possible.

649 shots of 440C stainless steel were cast in this insert set, following the same procedure as that for tough pitch copper. A significant improvement over not only tough pitch copper, but also H-13 and H-21 die steels was observed. Figure 12 shows a history of the parts produced in the as-cast condition. High temperature creep failure was eliminated. Erosion along the parting line was the major mode of die deterioration. While there is a major improvement over the erosion observed in tough pitch copper, it is still typical of that observed with both H-13 and H-21 die steels. Hardness measurements taken after the casting sequence indicate that no significant over aging occurred during the first 600 shots when the surface quenched copper technique for Thixocasting was used.

In addition, an identical insert set was prepared in Elbrodur RS, an age-hardening chromium copper alloy with additions of zirconium. The RS series is a high conductivity grade used primarily as electrode material for resistance seam welding of steel. It is known to withstand high stresses and is almost free from susceptibility to cracking.

638 shots of 440C stainless steel were cast in this insert set, by an identical procedure. Figure 13 shows a history of the parts produced in the as-cast condition. The major mode of die deterioration was again parting line erosion. The Cu-1% Cr and Cu-1% Cr-1% Zr both exhibited the same type of deterioration, however, flash buildup in the Elbrodur RS insert set was slightly slower than for the Cu-1% Cr alloy.

As a direct comparison, Figure 14 shows the five hundredth part cast in H-13, H-21, Cu-1% Cr, and Cu-1% Cr-1% Zr die insert sets. While the two parts cast in the copper base die inserts are very similar, they both show a significant improvement over the parts cast in steel die inserts. In addition, excluding the localized areas where die wear was excessive, dimensional stability in all cases was excellent. Micrometer measurements taken on the first and five hundredth castings made, show that in all four cases these dimensions remained constant through the entire sequence.

# IV. STRUCTURE PROPERTY RELATIONS IN RHEOCASTING AND THIXOCASTING

During this report period the structure and oxide inclusion content of Rheocast and Thixocast AISI 304 stainless steel have been characterized as a function of Rheocaster process variables such as flow rate, shear rate, cooling rate, and apparent viscosity. Segregation and hardness have also been investigated.

## Slurry Viscosity and Primary Metal Structure Versus Process Variables

The variation of viscosity with volume fraction solid for AISI 440C is similar to that previously reported for tin-lead alloys.[8] Figure 15 shows the results of several trials in which the Continuous Rheocaster was used as a viscometer. The rotor was seated to prevent metal flow while the mixing chamber was cooled continuously. Rotor drive amperage and temperature of the slurry were recorded as a function of time for several cooling rates and shear rates. Viscosity standards were then placed in the mixing tube and the rotor turned at varying rotation speeds to relate rotor drive amperage to viscosity. Metal temperatures were then related to fraction solid. Figure 15 is in qualitative agreement with earlier tin-lead results[8] in that it shows that the viscosity of a slurry with a given fraction solid decreases with increasing shear rate and decreasing cooling rate.

The volume fraction of primary solid particles in AISI 304 slurry increases linearly with decreasing flow rate from 0.85 at a flow rate of $9.1 \times 10^{-3}$ kg/sec (1.20 lbs/min) to 0.50 at $15.1 \times 10^{-3}$ kg/sec (1.99 lbs/min) from a Rheocaster extracting heat at the rate of 30 kcal/min (Figure 16).

Variations in the geometry of primary solid particles may be described by variations in the particle-liquid interface area per unit volume, $S_v$. $S_v$ increases with flow rate, from 10 $mm^{-1}$ at a flow rate of $9.1 \times 10^{-3}$ kg/sec (1.20 lbs/min) to 14 $mm^{-1}$ at $15.1 \times 10^{-3}$ kg/sec (1.99 lbs/min) (Figure 17). Thus, $S_v$ decreases with increased residence time of the slurry in the Rheocaster. The average size of primary solid particles decreases with increasing shear rate from 240 microns at a shear rate of 268 $sec^{-1}$ to 70 microns at 794 $sec^{-1}$ (Figure 18), although $S_v$ decreases slightly with increasing shear rate. Primary particle size was also found to decrease with increasing shear rate in tin-lead alloys[3], although direct comparison of results is difficult because of the different alloys and cooling rates used in the experiments.

Segregation and Hardness

Macrosegregation measurements were taken on Rheocast AISI 304 ingots using Electron Microprobe Analysis to investigate the effects of segregation on their reheating characteristics for Thixocasting. The chromium composition was found to be uniform from center to edge of the 1-1/4" diameter ingots while nickel composition was found to be an average of 0.26 wt% higher at the edge than in the center. This composition difference should make little or no difference between the melting points of the center and the edges of the Rheocast ingots.

The microhardness of primary solid particles and the dendritic liquid is compared to the feed stock 304 stainless steel in Table 3. Ferritic primary solid particles are nearly as hard as the feed stock, but the austenitic primary solid particles and the dendritic liquid are somewhat softer. The macrohardness of 304 stainless steel Thixocastings (Figure 19) shows an average hardness of 82.3 on the Rockwell B scale using a 100 kilogram load compared to 85.6 for the feed stock.

Inclusions

Non-metallic oxide inclusions have been investigated in water-quenched droplets of AISI 304 stainless steel slurry from the Rheocaster and in subsequent Thixocastings. The mechanism of formation, morphology, composition of phases present, and volume fraction of inclusions have been determined and related to the process variables of flow rate and shear rate. It should be noted, however, that the experiments from which these results have been taken were made before the installation of the argon-4% hydrogen shield in the top reservoir of the furnace and the extension of the shield at the exit. The volume fraction of inclusions appears to have been reduced as a result of these measures but no quantitative study has been done to determine the extent of the reduction.

Rapidly cooled water-quenched droplets from the Rheocaster contain only single phase, glassy oxide inclusions (MnO: 13.0%, $SiO_2$: 48.0%, FeO: 0.6%, $CrO_2$: 42.0%, by Electron Microprobe Analysis) less than 25 microns in size. Rheocast ingots and Thixocastings display two and three phase inclusions of up to 100 microns in size. The two phase inclusions consist of dendritic critobalite (nearly pure $SiO_2$) embedded in the glassy matrix. The three phase inclusions contain idiomorphic galaxite crystals (MnO: 13.0%, $SiO_2$: 48.0%, FeO: 0.6%, $Cr_2O_3$: 42.0%) in addition to cristobalite in the same glassy matrix. Reheating Rheocast ingots for Thixocasting causes partial or total devitrification with formation of dendritic cristobalite. The inclusions are spherical or spheroidal in shape except in Thixocastings where some deformation has occurred.

The size distribution of oxide inclusions was determined as a function of shear rate and flow rate in water-quenched droplets and Thixocastings. The average size of the inclusions increases as shear rate increases, except for the highest shear rate (at 800 rpm) where the size decreases significantly (Figure 20). At low shear rates there is an aggregation of particles whereas at the highest shear rate the particles appear to have dissociated. The average size of inclusions increases as flow rate decreases or residence time in the Rheocaster increases.

The volume fraction of oxide inclusions increases with shear rate (Figure 21) and decreases with increasing flow rate (Figure 22) in the Rheocast and Thixocast steel. The volume fraction and size distribution of inclusions is essentially unchanged by the Thixocasting process.

## V. DIE THERMAL ANALYSIS

### Summary

A study was made of the die thermal response during the machine casting of AISI 440C stainless steel into both plain carbon steel and high purity copper dies. Experimental measurements were made of the die temperatures and heating rates resulting from the casting of a range of volume fractions of primary solid. Measurements were at .0139" below the die surface. Computer simulations were coupled to these experimental measurements to predict the surface die thermal history.

Maximum die surface temperature and die heating rate decreases with increasing fraction solid. These variables decreased dramatically when copper dies were substituted for steel dies. As example, maximum measured die temperature increase was 499$^{\circ}$C for metal of 0.65 fraction solid in a steel die, but was only 195$^{\circ}$C for the copper die. Maximum measured rate of die temperature increase was 9000$^{\circ}$C/sec for the steel die and only 4620$^{\circ}$C for the copper die.

In practice, the improved die life of copper dies over die steels (as reported elsewhere in this report) can

be expected to result from four factors: (1) lower temperature increase of the copper die, (2) lower rate of temperature rise of the copper, (3) less time required for solidification in the copper die and therefore a shorter time of exposure of the die to heat, and (4) the fact that copper dies can be run initially at a colder temperature (e.g., room temperature) without cracking.

## Introduction

The susceptibility of die materials to failure by thermal fatigue generally increases as thermal conductivity decreases. One class of high conductivity materials finding applications in the die casting of bronze are the refractory metal alloys, such as TZM. However, these alloys are expensive and susceptible to other types of failure, most notably brittle failure. In this work, an alternate approach has been the use of high thermal diffusivity copper alloys operated at low die preheat temperatures. These alloys exhibit thermal conductivities greater than TZM and have improved ductility, but have hitherto been precluded as die materials since they soften at normal die operating temperatures.

This portion of the research program was to examine effects of casting variables on die heating; specifically to study effects of metal fraction solid and die material on (1) maximum die surface temperature, and (2) die heating rate. Metal used in the program was 440C steel. The work described above represents an extension of work carried out earlier in this program and previously reported.[3]

Experimental Procedure

AISI 440C stainless steel slugs were cast from various temperatures above the solidus ($1370^{\circ}C$) including that corresponding to fully liquid ($1500^{\circ}C$, approximately $20^{\circ}C$ superheat). Production of a range in volume fractions solid for Thixocasting was implemented by altering the probe pressure according to the normal operation of the Softness Indicator (Figure 7). Only castings which both completely filled the mold and exhibited no surface defects were included in the experimental data. The accepted castings were sectioned at the area corresponding to the thermocouple location. Exact determination of the casting volume fraction solid was by quantitative metallographic analysis of the resultant surface.

Typically, castings were made with ingate velocities of 2000 inches per second and final injection pressures of

8,000 psi. The shot sleeve temperature was maintained between 100 and 150$^{o}$C. The variation resulted from the volume fraction solid of the alloy cast and the frequency of casting cycles.

Cartridge die heaters were used to operate the steel dies at 250$^{o}$C. The copper dies which had no heat additions other than the actual castings, returned to approximately 40$^{o}$C prior to each successive casting. Both steel and copper dies were lubricated between shots with a water-based graphite spray. Castings were held in the dies longer than necessary for complete solidification in order to better study die thermal response. Hold times were approximately two seconds in the steel dies and one half second in the copper dies.

Temperature Measurement System

Both plain carbon steel and high purity copper die inserts were machined to fit through the back of existing H-13 die plates. Into each moving die half insert was machined a flat test bar cavity (4" x 5/8" x 3/8"). A plan view of the insert and a cross-sectional view of the insert situated in the die plate are shown in Figure 23.

Number twenty-eight gauge chromel/alumel thermocouples were chemically bonded to die insert plugs, 0.0139" from the plug surface. The plugs, machined from the same alloy as the die insert, were press-fitted into holes drilled in the inserts and backed by threaded forcing bolts. With this design, the plug formed a part of the die cavity surface. Attachment of the thermocouples was accomplished by spot-welding in the steel dies and silver soldering in the copper dies. The thermocouple plug, intact in the die insert is detailed in Figure 23.

Thermocouple emf's were recorded on the Honeywell Visicorder Oscillograph at a chart speed of ten inches per second. The chromel/alumel wires were run directly into the measuring instrument. Compensation for a cold junction was included electronically within the oscillograph and was utilized throughout all temperature measurement trials.

The present system offers distinct advantages over that previously reported.[3] First, constant contact of the thermocouple to the die (plug) is assured by chemical adhesion. Second, a larger volume of metal, removed to outfit the die with thermocouples, is replaced. Much of this is of the same composition as the insert. Third, the thermocouple/millivolt recording channels of the visicorder oscillograph are designed to increase the signal to noise ratio. Finally, a permanent, uninterrupted record of die temperatures and casting machine parameters is provided by the monitering system.

## Experimental Results

### 1. Steel Dies

Typical measured die thermal profiles during the casting of AISI 440C stainless steel into the plain carbon steel test bar cavity are shown in Figure 24. In general, the dies heated rapidly for one-tenth of a second, then continued to heat more slowly. Maximum temperatures often occurred from seven-tenths to one second after initial response. Only the higher primary volume fraction solid castings ($f_s > 0.60$ produced significant variations in the die heating rates and temperature rises.

This is apparent in Figure 24. Upon casting a 0.72 primary volume fraction solid sample the die temperature increased at a maximum rate of 8,000$^{o}$C/sec to a peak of 454$^{o}$C above the base die temperature. For the other castings shown ($f_s$ = 0.00, 0.28 and 0.48), die temperature increased with maximum rates between 10,400 and 11,600$^{o}$C/sec. The maximum temperature rises for the three castings fell between 535 and 541$^{o}$C.

Using the maximum temperature rise and rate of rise as parameters for the characterization of thermal response, the effect of the casting primary volume fraction solid was assessed.

The temperature rise above the 250°C base die temperature when casting various volume fractions solid of 440C stainless steel in steel dies is shown as Figure 25. A 550°C rise occurred when casting liquid stainless steel. A slight decrease to 540°C is apparent at volume fractions solid of 0.60. Above this there is a sudden drop to 460°C at 0.74 volume fraction solid.

The rate of rise or heating rate (°C/second) for these castings follows a similar pattern, Figure 26. The steel die initially increased in temperature at a rate of 11,500°C/second when liquid 440C stainless steel was cast. At sixty percent prior solidification the rate of rise was 10,500°C/second whereupon an abrupt drop to 7,000°C/second at 0.70 volume fraction solid occurred.

2. Copper Dies

Measured die thermal profiles representative of those found when casting various primary volume fractions solid of AISI 440C stainless steel into copper dies are shown in Figure 27. Die heating rates are initially high, then decrease. After reaching the maximum temperature, more rapid cooling occurred than found in the steel dies. At approximately 0.45 seconds the dies began opening which produced an additional temperature drop. Maximum temperatures were evident within the first three-tenths of a second. The time required to achieve the maximum appeared to decrease with increasing primary volume fraction solid of the casting. Unlike the steel dies, significant variations in the maximum rate of rise and temperature rise exist for volume fractions solid less than 0.50. As the casting volume fraction solid was increased from 0.00 to 0.23, 0.53, and 0.76, the maximum die heating rate was reduced from 8,470 to 5,870, 5050, and 3,820$^{O}$C/sec. Similarly, the maximum temperature rise decreased from 235 to 216, 195, and 169$^{O}$C, respectively.

The sensitivity of die thermal response to variations in primary volume fraction solid when casting 440C stainless steel into copper dies is presented in Figures 26 and 27.

The temperature rise upon casting liquid 440C stainless steel in 40$^{O}$C copper dies was 235$^{O}$C. A linear decrease to 190$^{O}$C at 0.75 volume fraction solid is apparent, Figure 28.

The rate of rise produced when casting various volume fractions solid in copper dies is shown in Figure 29. As with the temperature rise, the heating rate was linearly dependent upon volume fraction solid. Liquid castings produced die heating rates in excess of 7,500°C/second; 0.76 volume fraction solid castings caused an initial rise in the die temperature of 4,300°C/second.

A comparison of the results for steel and copper dies appears as Figure 30. The temperature rise versus primary volume fraction solid appears in Figure 30(a) while the rate of rise versus primary volume fraction solid is given in Figure 30(b).

## Computer Simulations

A computer program was utilized to simulate the flow of heat in the test bar die. The simulation employs a finite difference model of the standard explicit variety, considering unidirectional heat flow only. The physical assumptions of the model are as previously reported[3]. A change in the allocation of boundary elements and the subsequent finite difference form of boundary equations has been made.

The casting half-thickness has been redefined to include half-elements at each boundary. The die has also been redefined in this manner. Consequently, nodes are located exactly on each boundary (the casting centerline, both casting and die interfaces, and the exterior die surface). Increased precision of the simulation near the interface as well as a more accurate representation of the adiabatic surfaces at the casting centerline and exterior die surface result.

With the above changes the boundary and initial conditions are written as follows.

$$H_1(t+dt) = H_1(t) + \frac{2k}{\rho\Delta x^2}[T_2(t)-T_1(t)]\Delta t \qquad (1)$$

$$H_{11}(t+dt) = H_{11}(t) + \frac{2}{\rho\Delta x}[\frac{k}{\Delta x}T_{10}(t)-(\frac{k}{\Delta x}+h)T_{11}(t) + h\,T_{12}(t)]\Delta t \qquad (2)$$

$$H_{12}(t+dt) = H_{12}(t) + \frac{2}{\rho\Delta x}[\frac{k}{\Delta x}T_{13}(t)-(\frac{k}{\Delta x}+h)T_{12}(t) + h\,T_{11}(t)]\Delta t$$

$$H_{37}(t+dt) = H_{37}(t) + \frac{2k}{\rho\Delta x^2}[T_{36}(t)-T_{37}(t)]\,\Delta t \qquad (3)$$

$$t = 0, \quad 1 \leq i \leq 11; \quad T_i = T_o \tag{4}$$

$$t = 0, \quad 12 \leq i \leq 37; \quad T_i = T_D \tag{5}$$

while the change in enthalpy of general intermediate node, i, remains,

$$H_i(t+\Delta t) = H_i(t) + \frac{k}{\rho(\Delta x)^2}[T_{i+1}(t)-2T_i(t)+T_{i-1}(t)]\Delta t$$

where subscripts 1 to 11 and 12 to 37 represent specific nodes in the casting and die respectively. $T_o$ and $T_D$ represent the initial casting and die temperatures.

The strategy used was to match computer generated die thermal profiles to those experimentally measured. This was accomplished by adjustment of the numerical value of the interface resistance, h.

## Computer Results

### 1. Steel Dies

Comparison of measured and calculated temperature responses in the plain carbon steel dies, 0.0139 inches from the interface, are shown in Figure 31. For both the liquid ($T_o$ = 1500) and the 0.65 volume fraction solid ($T_o$ = 1400)

440C castings the initial interface heat transfer coefficient used in the simulations was 1 cal/cm$^2$-sec-$^o$C. After 0.15 and 0.45 seconds the h was reduced to 0.6 and 0.4 cal/cm$^2$-sec-$^o$C.

The calculated values corresponded with the measured temperatures for extremely short times ($t < 0.05$ sec) and longer times ($t > 0.35$ sec). During intermediate times the calculated temperatures fell below those measured. The liquid and 0.65 volume fraction solid calculations differed by a maximum of 40 and 60$^o$C from the respective experimental measurements. However, relative agreement was found for the rate of rise and the maximum temperature rise. For casting liquid 440C, the rate of rise was 11,608 (experimental) and 9,770$^o$C/sec (calculated) while the maximum temperature rise was 541 (experimental) and 565$^o$C (calculated). When casting a 0.65 $f_s$ charge, the rate of rise was lowered to 9,548 (experimental) and 8,260$^o$C/sec (calculated); the maximum temperature rise 498 (experimental) and 519$^o$C (calculated).

2. Copper Dies

Calculated and measured die temperatures in copper dies, 0.0139" from the die surface, are shown in Figure 32. Temperatures were not calculated after 0.35 seconds, the experimental die opening time. When simulating both liquid ($T_o$ = 1500) and 0.65 volume fraction solid ($T_o$ = 1400) 440C castings, an initial heat transfer coefficient, h, of 0.9 cal/cm$^2$-sec-$^o$C was used. The h was later reduced; first to 0.6 and then to 0.3 cal/cm$^2$-sec-$^o$C. For the liquid casting simulation the above changes occurred at 0.05 and 0.20 seconds while for the partially solidified casting they occurred at 0.05 and 0.15 seconds.

The experimental measurements were closely approximated by the calculated temperatures throughout the initial 0.35 seconds. The largest discrepencies were evident at or immediately after the interface coefficient, h, change times. Less drastic and more frequent changes in the value of h would remedy such errors.

## Prediction of Die Surface Temperature

The computer program may be utilized to predict the thermal history of any location in either the casting or the die. Of interest here is the die surface, where severe temperature gradients are found.

Calculated surface temperatures when casting both liquid (1500$^o$C) and semi-solid (1400$^o$C, $f_s$ = 0.65) 440C stainless steel into steel dies appear in Figure 33. The maximum temperature rise above the base die temperature

(250$^{\circ}$C) was 627 and 579$^{\circ}$C for the liquid and semi-solid castings. The corresponding heating rates were 52,800 and 48,600$^{\circ}$C/sec, while calculated surface die thermal gradients were 4,720 and 4,010$^{\circ}$C/cm.

Die surface temperatures, calculated for casting liquid (1500$^{\circ}$C) and semi-solid (1400$^{\circ}$C, 0.65 $f_s$) 440C stainless steel into copper dies, are shown in Figure 34. Although the maximum die surface heating rates were similar to those calculated for the steel dies, the maximum temperature rise was only 256 and 213$^{\circ}$C for the liquid and 0.65 $f_s$ charges. In addition, the surface die thermal gradients were reduced to 795 and 643$^{\circ}$C/cm, respectively. The above were calculated with a copper die operating temperature of 40$^{\circ}$C.

## Discussion

In this study both experimental measurements and computer simulations were employed to assess die thermal response to the Thixocasting of stainless steel. Experimental measurements in steel dies revealed an increase in the primary volume fraction solid of the charge material added little benefit to the reduction of peak temperatures and heating rates until fractions solid of greater than 0.60. In copper dies the benefit obtained by increasing the charge fraction solid is apparent throughout the range of fractions solid tested.

Of greater impact was the improved thermal response derived at all fractions solid when casting into copper as opposed to steel dies. For liquid castings a reduction of the temperature rise by a factor of 2.34 and the rate of rise by 1.53 resulted from the use of copper dies. Upon casting 0.75 volume fraction solid charge material, similar ratios were found, 2.42 (temperature rise) and 1.63 (rate of rise).

Computer simulations were generated by varying the numerical value of the interface coefficient, h, until calculated results approached experimental measurements. The use of a single value for h caused the model to break down after short times (0.15 seconds for steel and 0.05 seconds for copper dies) and necessitated a change in h. This has physical significance, i.e., the production of an air gap between the casting and die following solidification shrinkage of the casting.

For steel dies the interface coefficients and computer program change times were 1.0, 0.6 at 0.15 seconds, and 0.4 at 0.45 seconds (units: $cal/cm^2$-sec-$^oC$). This applied to casting volume fractions solid of up to 0.65. For copper dies the interface coefficients and corresponding change times were 0.9, 0.6 at 0.05 seconds, and 0.3 at 0.15 (semi-solid simulation) and 0.20 seconds (liquid simulation). Interface coefficients therefore apply for longer times with steel dies. This is consistent with the thermal diffusivities of the two die materials. Steel having a lower thermal diffusivity then copper, increases the casting solidification time, hence increases the time before solidification shrinkage alters the interface characteristics.

Predicted die surface temperatures further indicated distinct advantages when copper dies were employed. Initial heating rates ($^oC$/sec) at the copper die surface were comparable to those in steel. However in the copper dies, the heat was quickly diffused to reduce the maximum temperature rise ($^oC$) and the die surface thermal gradients ($^oC$/cm) by factors of 2.5 and 6.0 when compared to steel dies.

## Conclusions

1. An improved thermal measurement system and thermocouple technique has been utilized to measure internal die temperatures (0.0139" from the die surface) in both plain carbon steel and high purity copper dies.

2. Experimental measurements when casting 440C stainless steel into steel dies showed little change in the temperature rise and heating rate until the volume fraction of primary solid in the charge exceeded 0.60. Then a sharp drop in both the temperature rise and heating rate occurred.

3. Experimental measurements when casting 440C stainless steel into copper dies revealed a constant decrease in both the temperature rise and heating rate as charge primary volume fraction solid increased.

4. Both experimental measurements and computer simulations indicate a lowering of the temperature rise and the heating rate when casting 440C stainless steel into $40^{o}C$ copper dies as opposed to $250^{o}C$ plain carbon steel dies.

5. The interface heat transfer coefficient, h, can be estimated by matching computer simulated thermal profiles with experimental die temperature measurements. In steel dies h ranges from 1.0 to 0.4 $cal/cm^2$-sec-$^oC$, while in copper dies h varies from 0.9 to 0.3 $cal/cm^2$-sec-$^oC$ during the solidification process. The above values are applicable to primary volume fractions solid of approximately 0.65 and less.

6. Predictions of die surface behavior can be made using the estimated interface coefficients. By casting into copper as opposed to steel dies, a reduction of the surface temperature rise by a factor of 2.5 occurred. In addition, initial die thermal gradients near the surface were reduced by a factor of 6.0.

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Table 1

Production of Continuously Rheocast Alloys

| Alloy | Pounds Produced | |
|---|---|---|
| | Total Production | 6-30-76 to 6-30-77 |
| Copper alloy 905 | 1310 | 260 |
| H.S. 31 Cobalt Base Superalloy | 415 | 165 |
| M2 Tool Steel | 125 | 125 |
| AISI 440C Stainless Steel | 2940 | 1860 |
| AISI 304 Stainless Steel | 2070 | 770 |

Table 2

Summary of Die Deterioration for Various Die Materials When Thixocasting Stainless Steel

| Die Material | Alloys Cast | Number of Shots | Mode of Deterioration |
|---|---|---|---|
| H-13 Die steel | 304 | 504 | Extensive checking at outside corners. Erosion along parting line. |
| H-21 Die steel | 304 | 502 | Checking at outside corners. Erosion along parting line. |
| Tough pitch copper | 440C | 228 | Extensive erosion along parting line. Creep failure along cavity edges. |
| Copper-1% chromium | 440C | 649 | Erosion along parting line. Checking at gate. |
| Elbrodur RS (Cu~1%Cr~1%Zr) | 440C | 638 | Slight erosion along parting line. |

Table 3

Microhardness of Thixocast Ferrous Alloys

| AISI 304 Stainless Steel | Knoop Hardness 100 gram load |
|---|---|
| Ferritic Semi-Solid Particles | 216.3 |
| Non-ferritic Semi-Solid Particles | 178.1 |
| Liquid Matrix | 200.7 |
| Raw 304 Feed Stock | 223.5 |

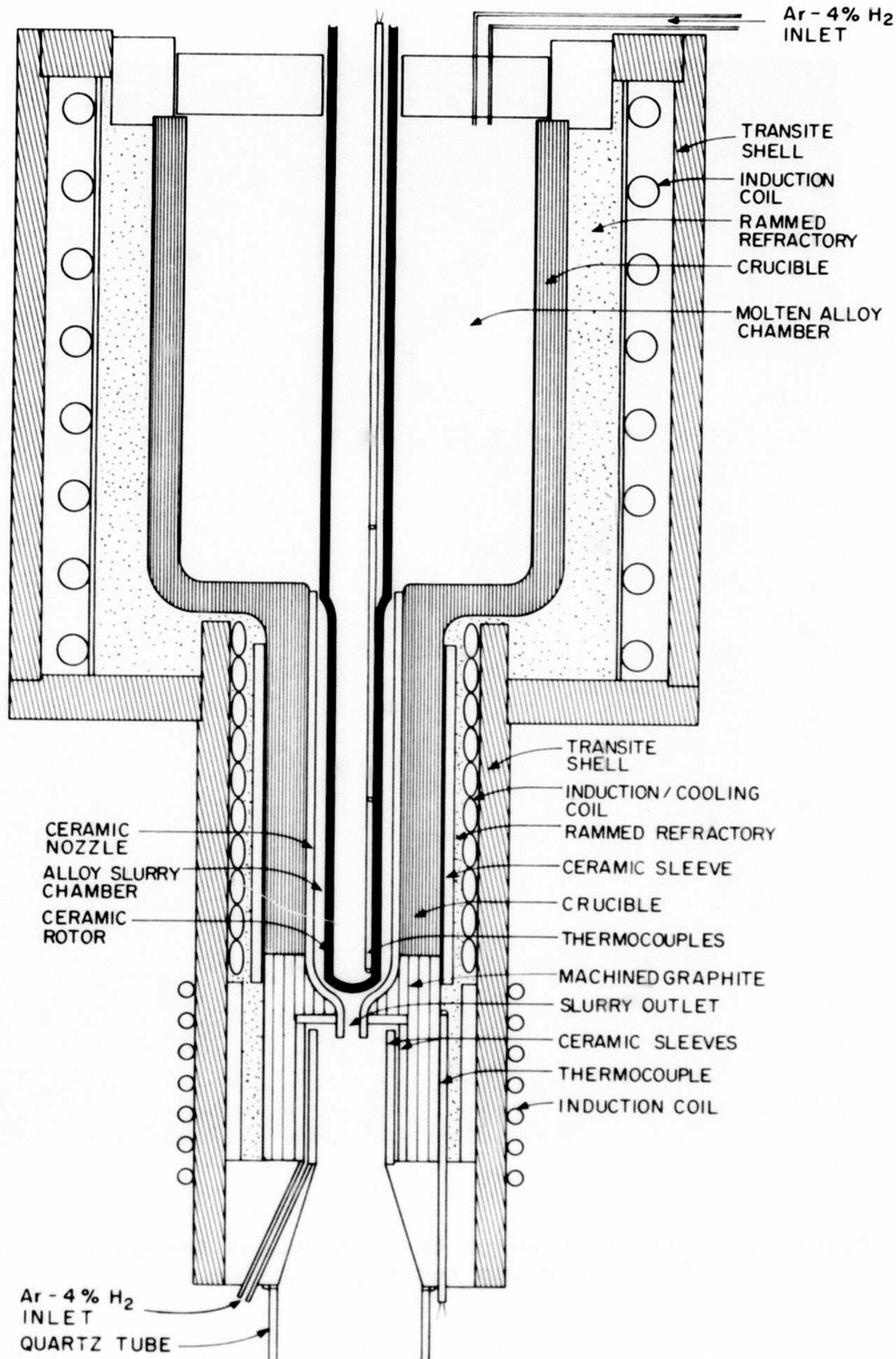



Figure 1: Schematic cross section of the high temperature Continuous Rheocaster with upper chamber steel capacity of 40 pounds.

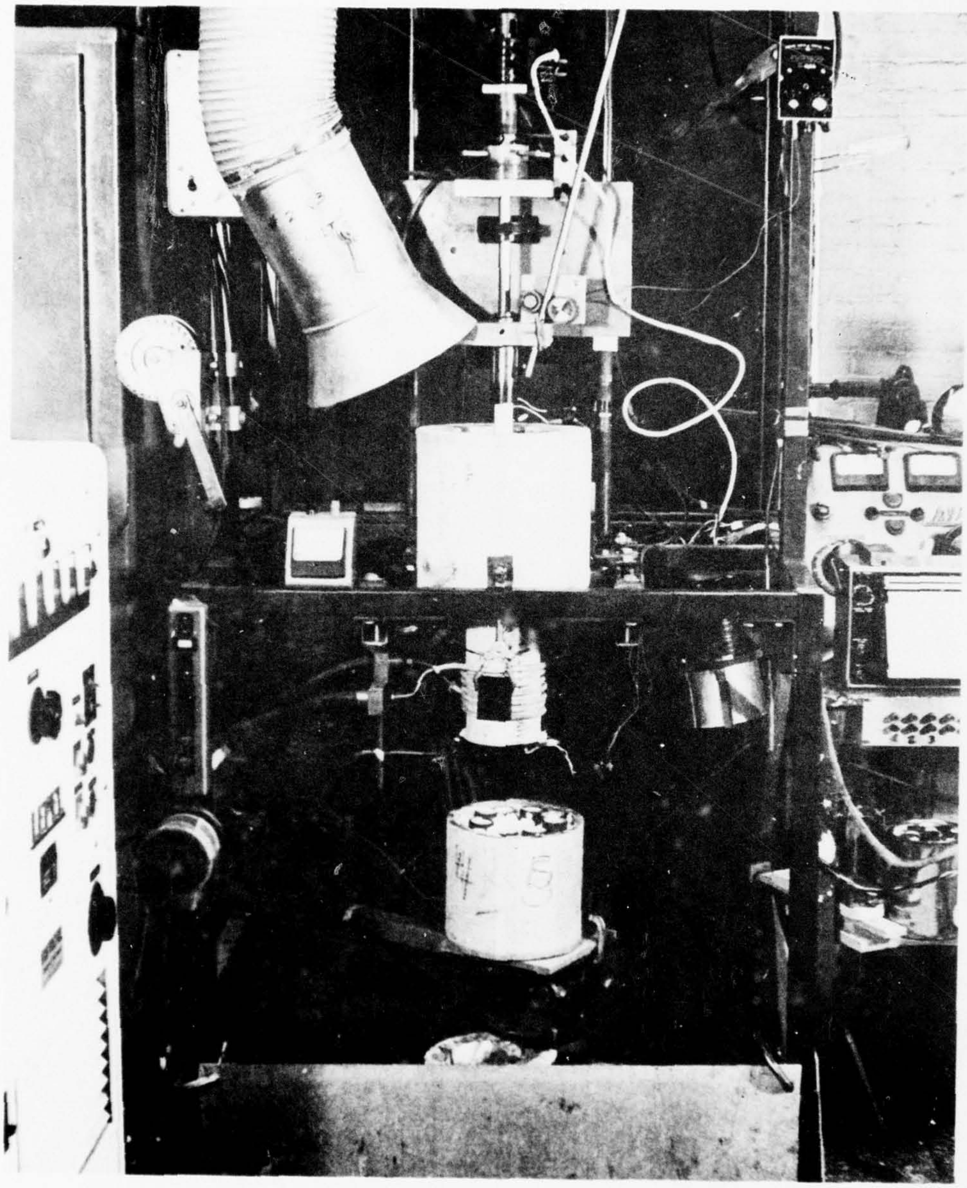


Figure 2: Overall view of the Continuous Rheocaster, set here for continuous ingot production.

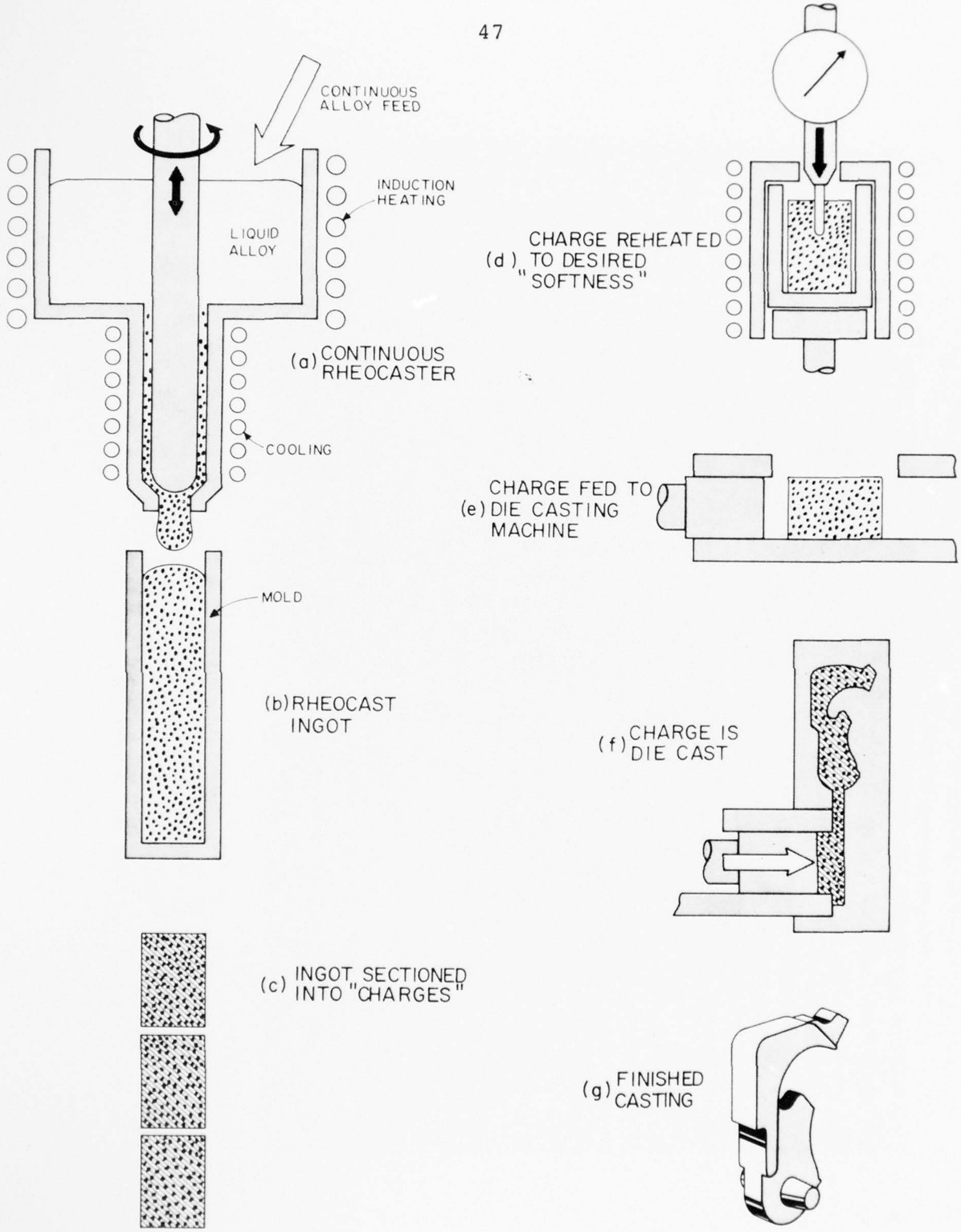



Figure 3: The Thixocasting process.

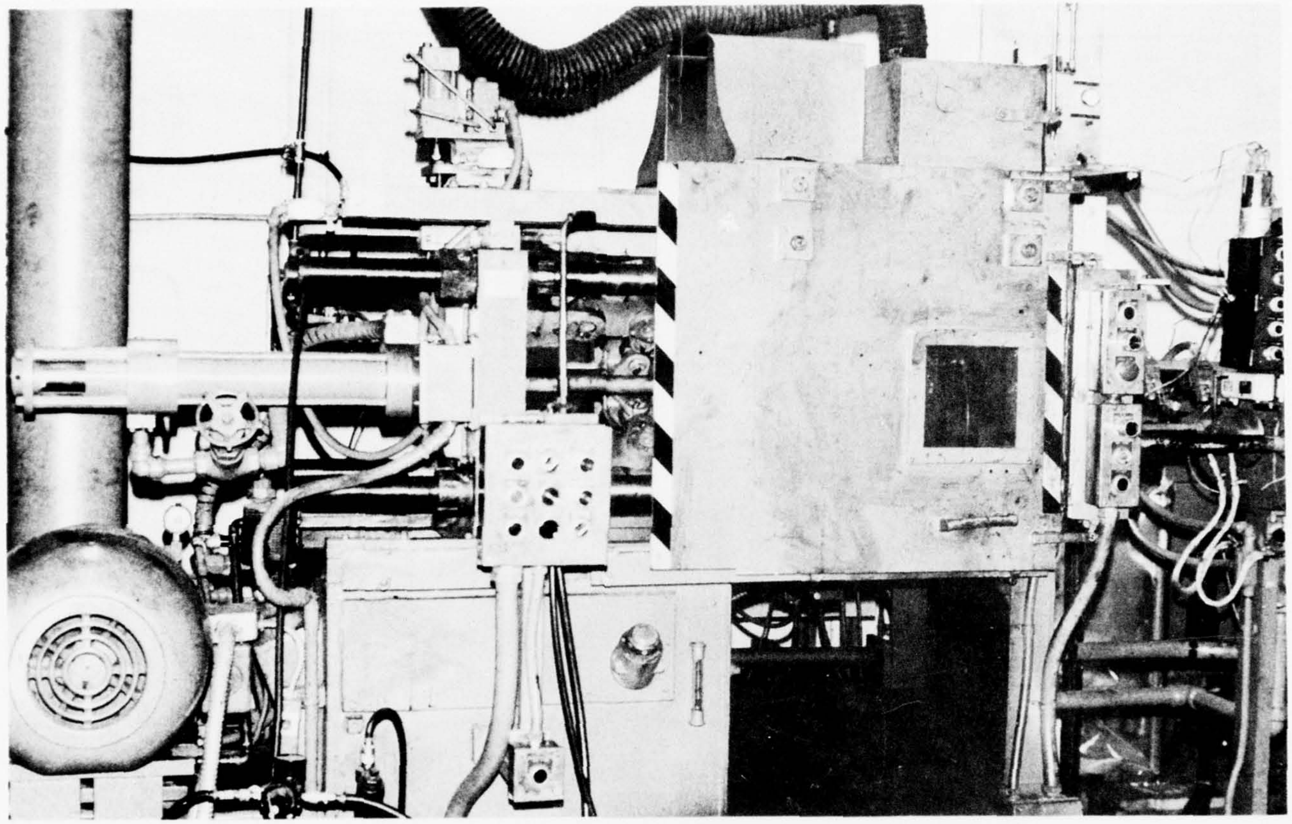


Figure 4: Photograph of the B&T Greenlee horizontal cold chamber die casting machine.

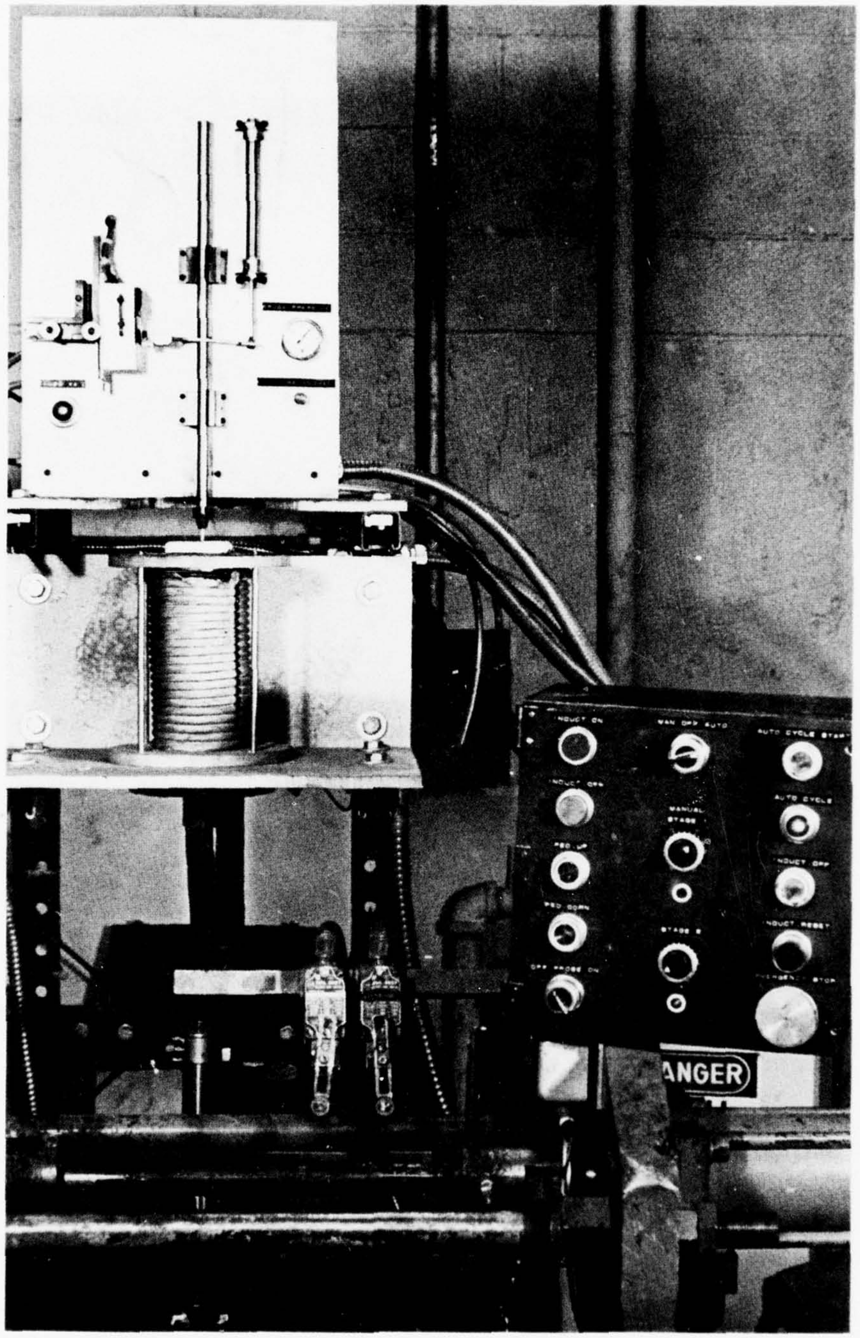


Figure 5: Overall view of the automated Thixocast reheating station.

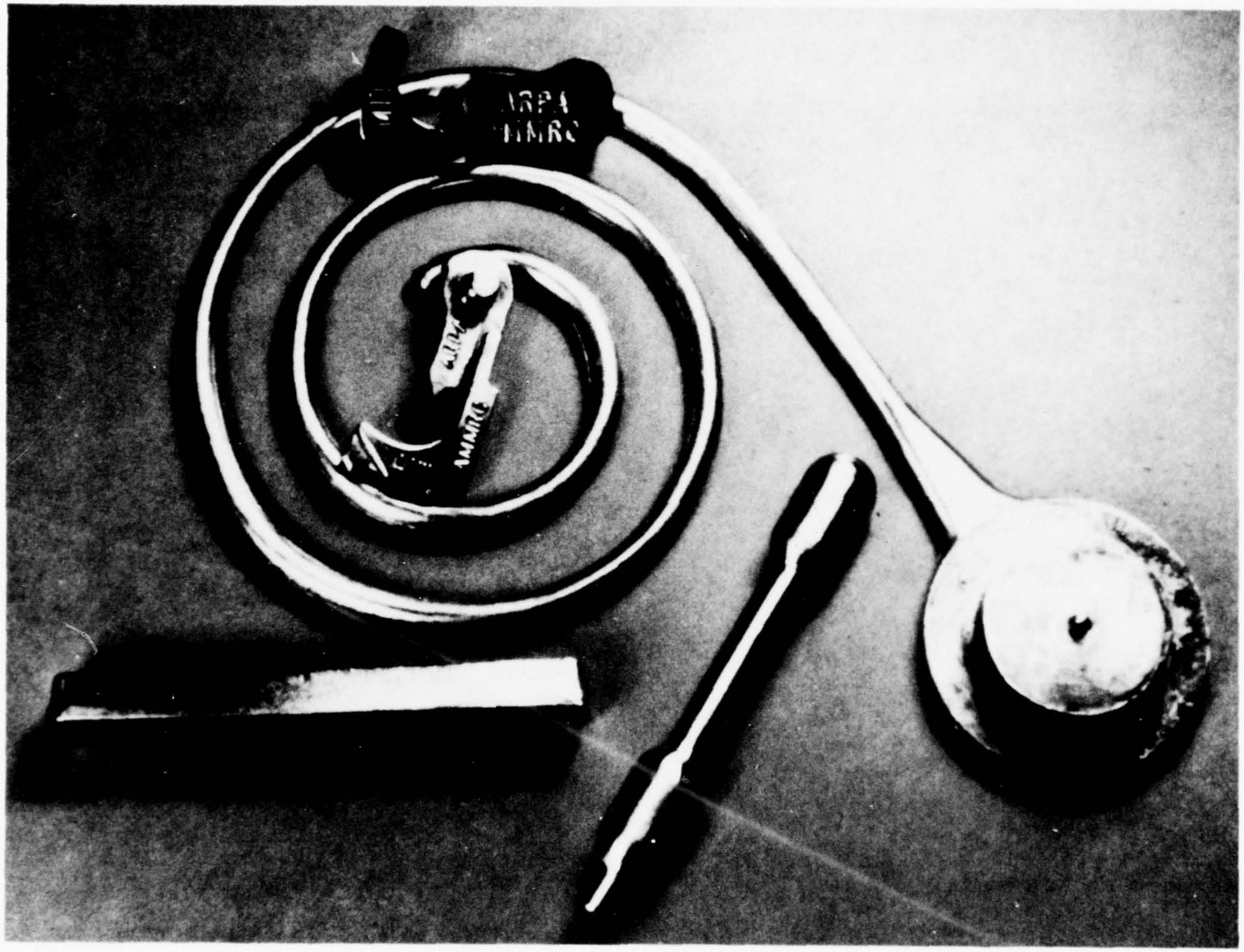


Figure 6: Various Thixocast parts.

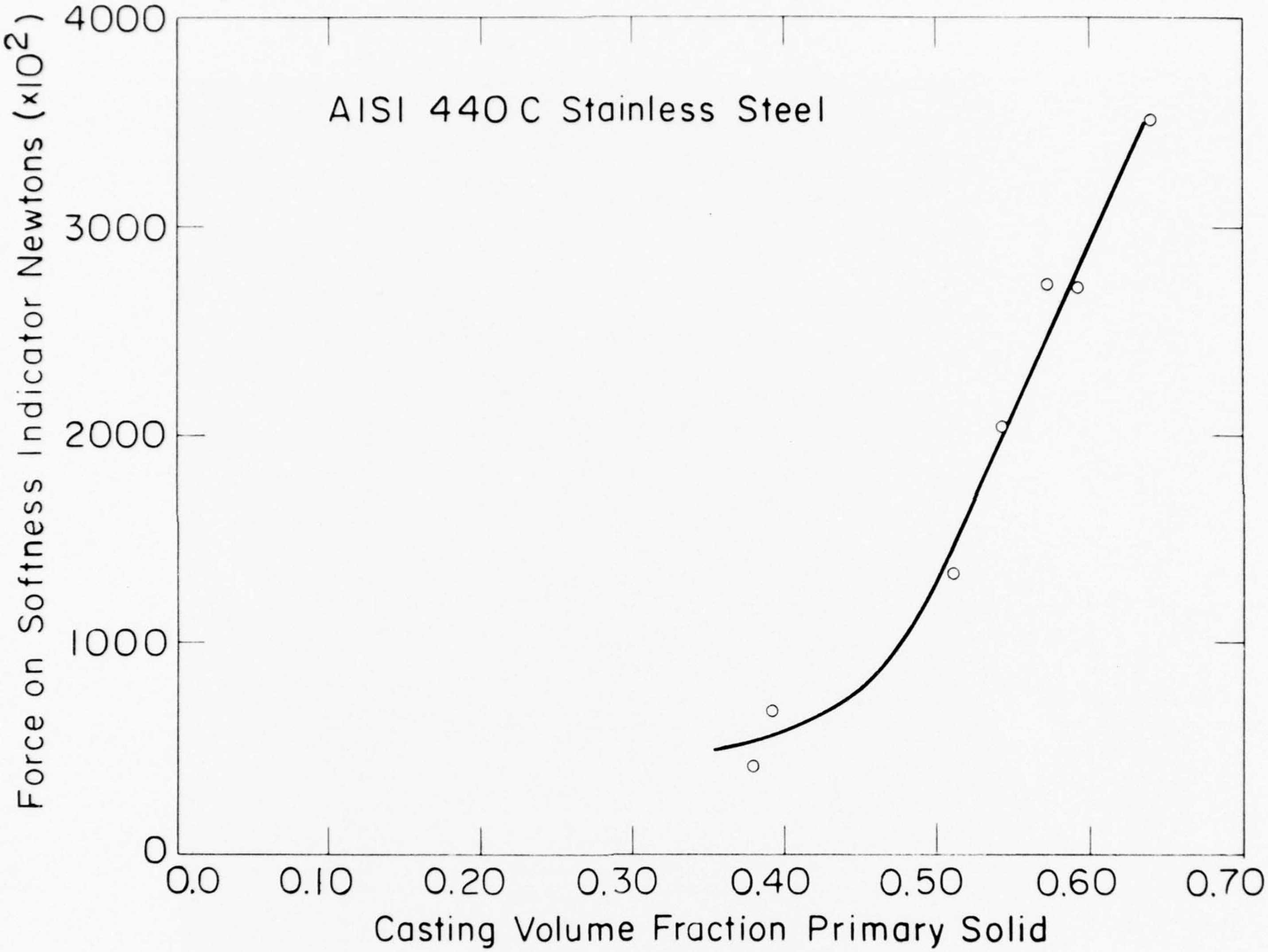



Figure 7: Operating curve for the softness indicator for AISI 440C stainless steel, using a 1/8" diameter flat bottom alumina probe with a 1/4" penetration distance.

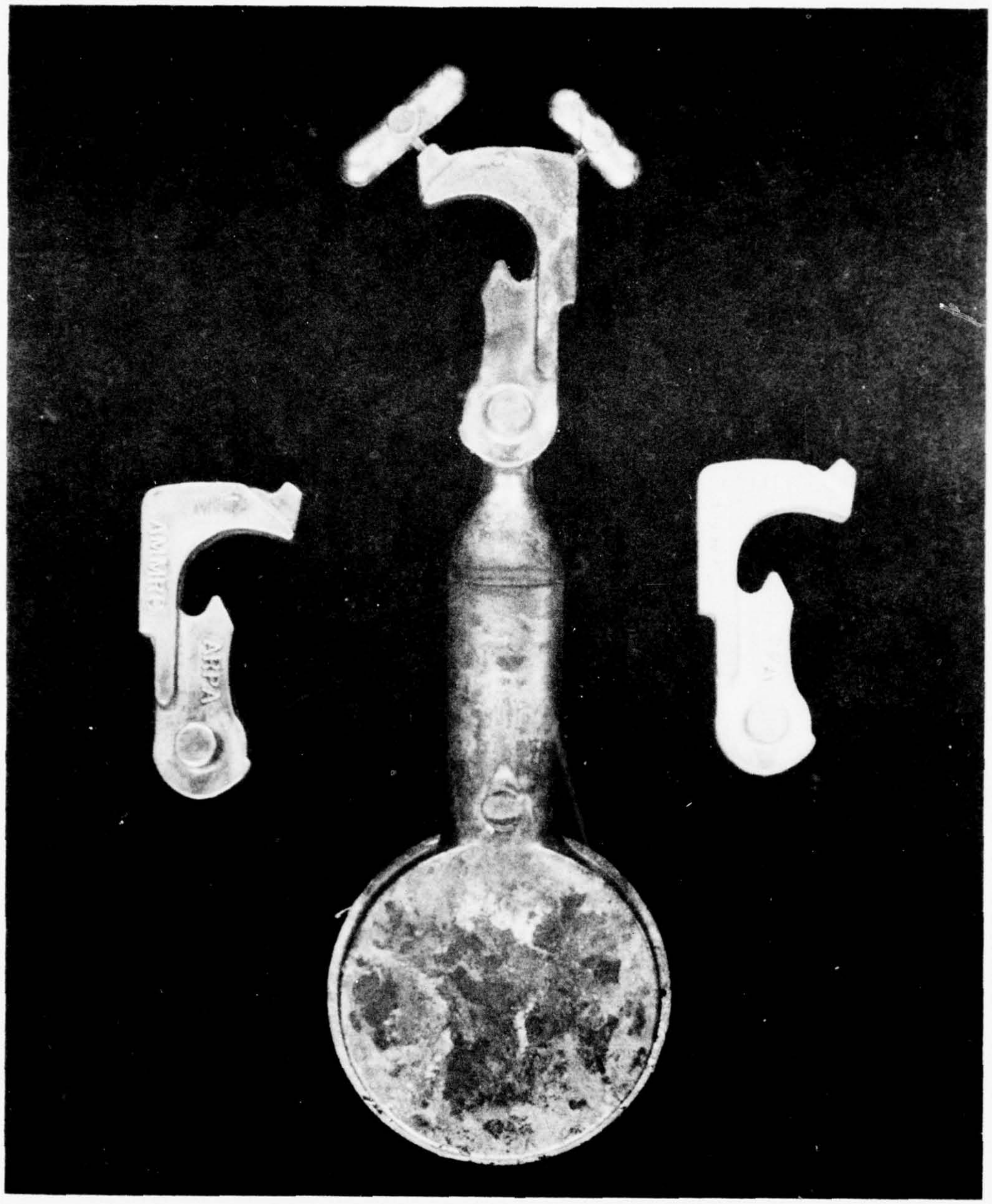



Figure 8: Photograph of the M-16 rifle hammer.

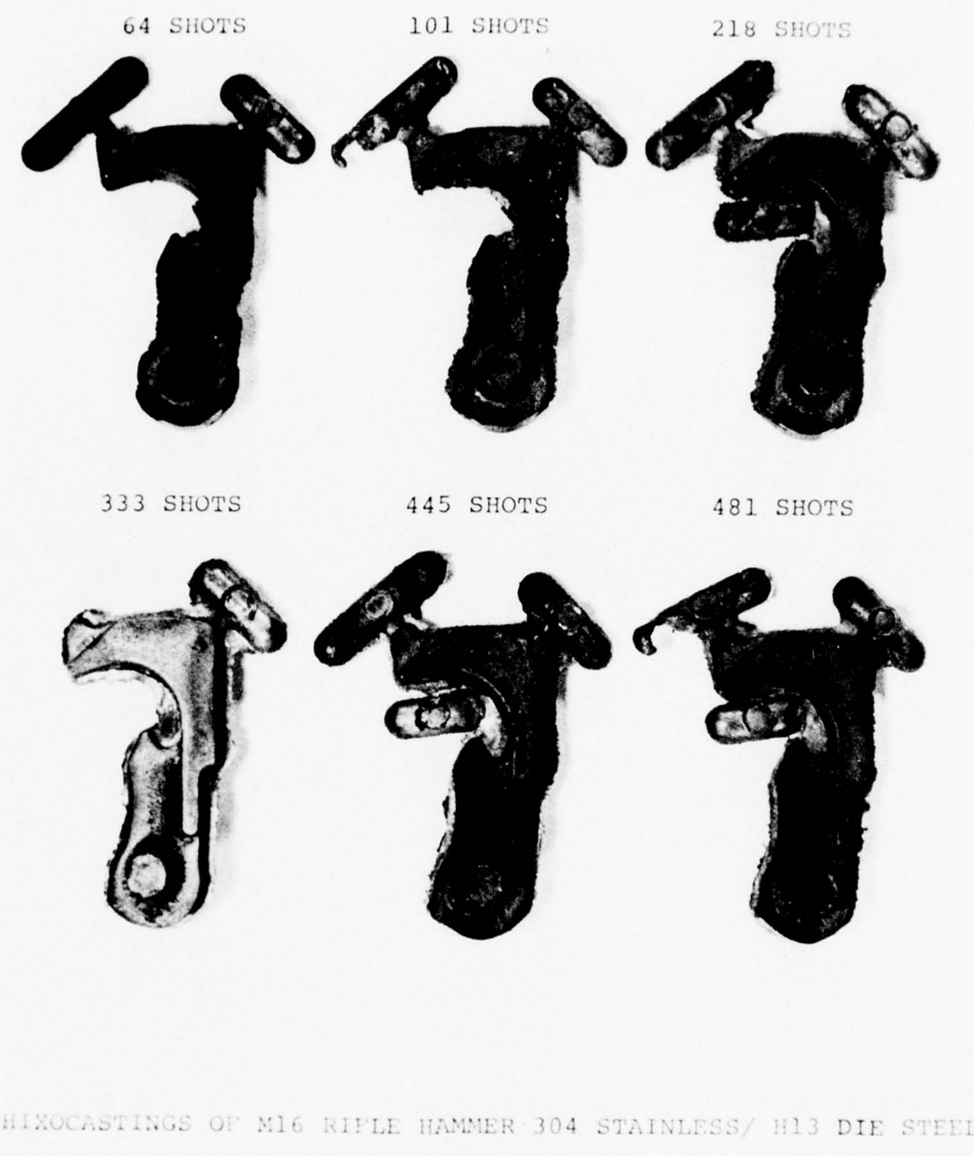



Figure 9: Sequence of 304 stainless steel Thixocastings produced at various intervals in the 500 shot die study in H-13 die steel.

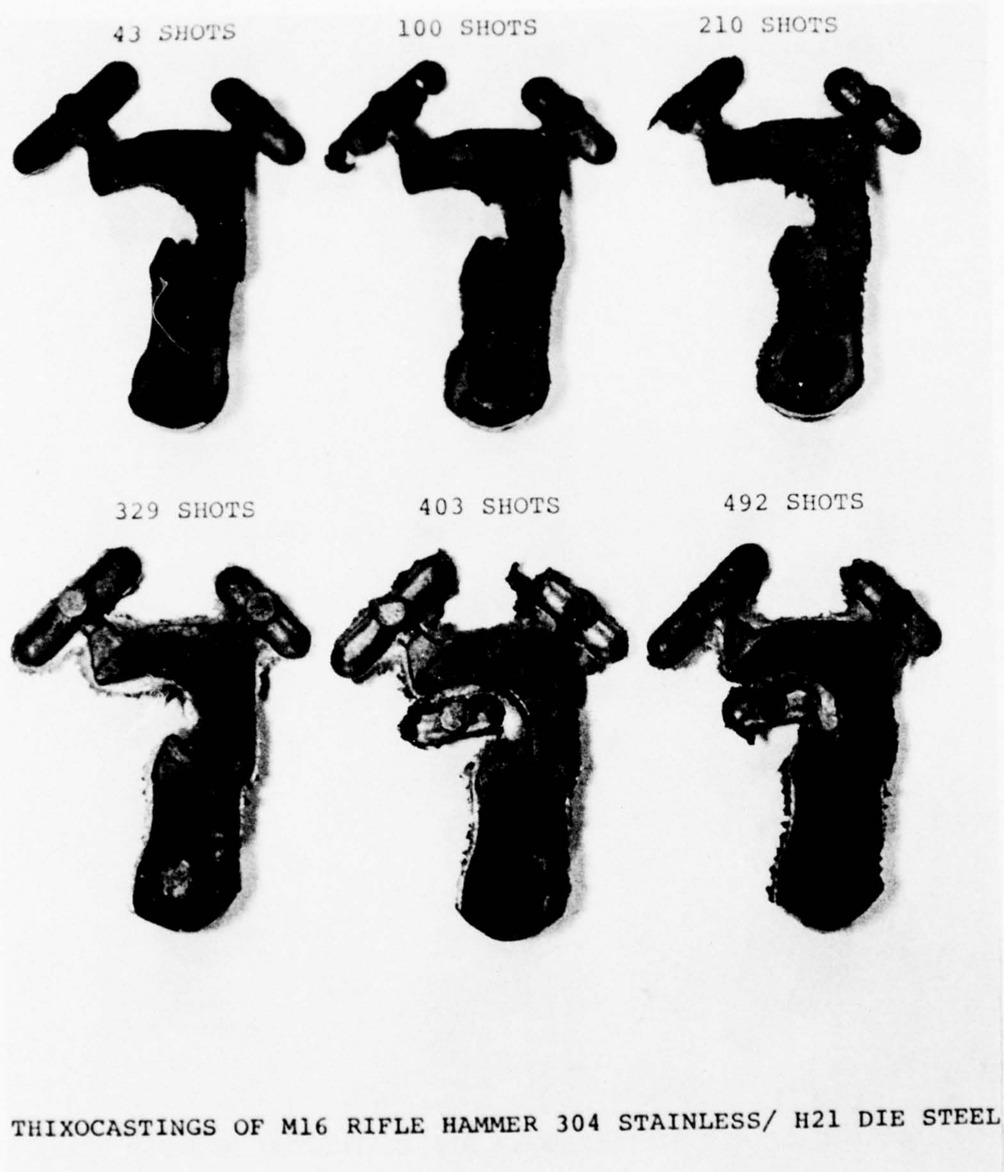



Figure 10: Sequence of 304 stainless steel Thixocastings produced at various intervals *in the* 500 shot die study in H-21 die steel.

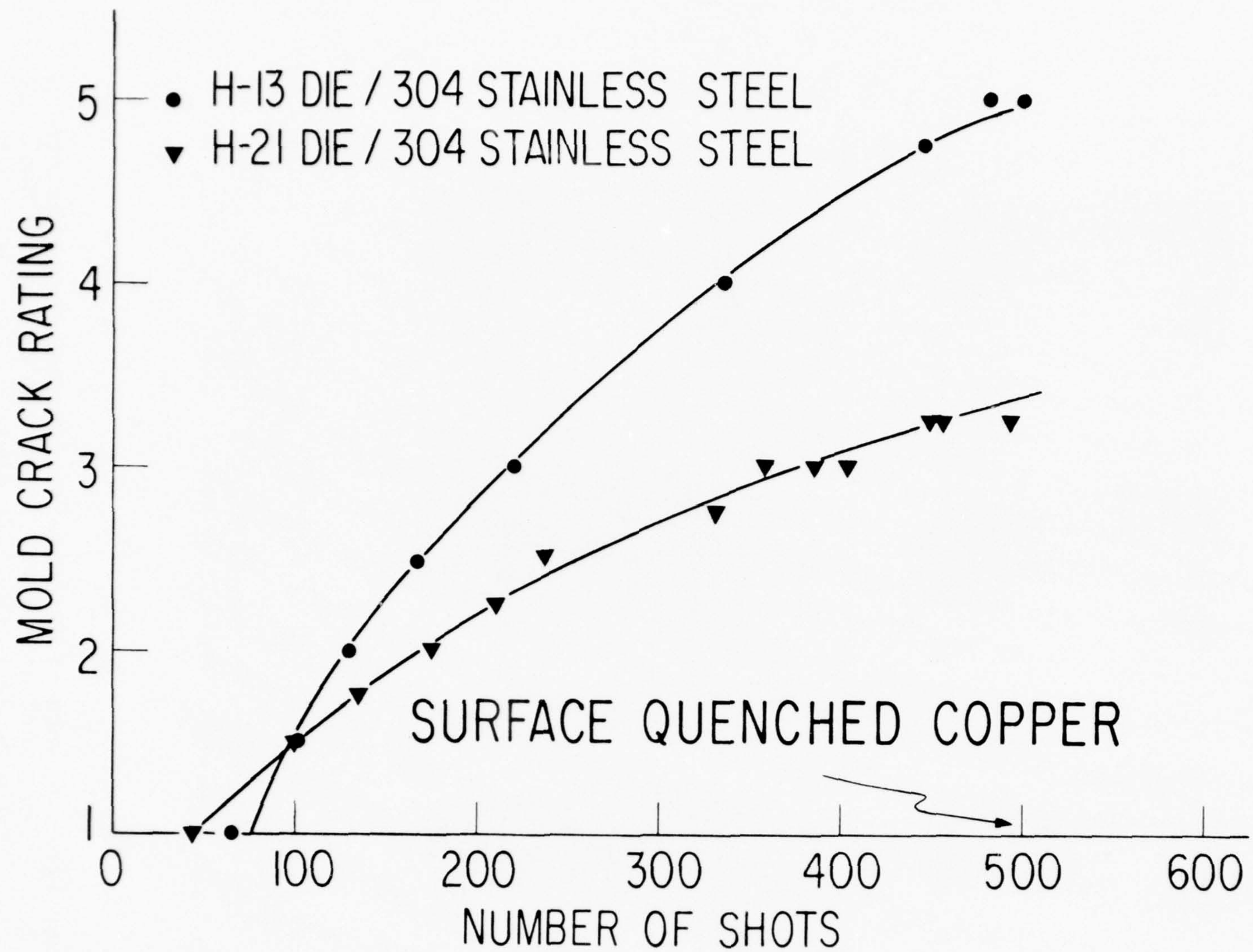



Figure 11: Die crack rating versus number of shots for Thixocasting AISI 304 stainless steel at 0.50 volume fraction solid into H-13 and H-21 steel dies.

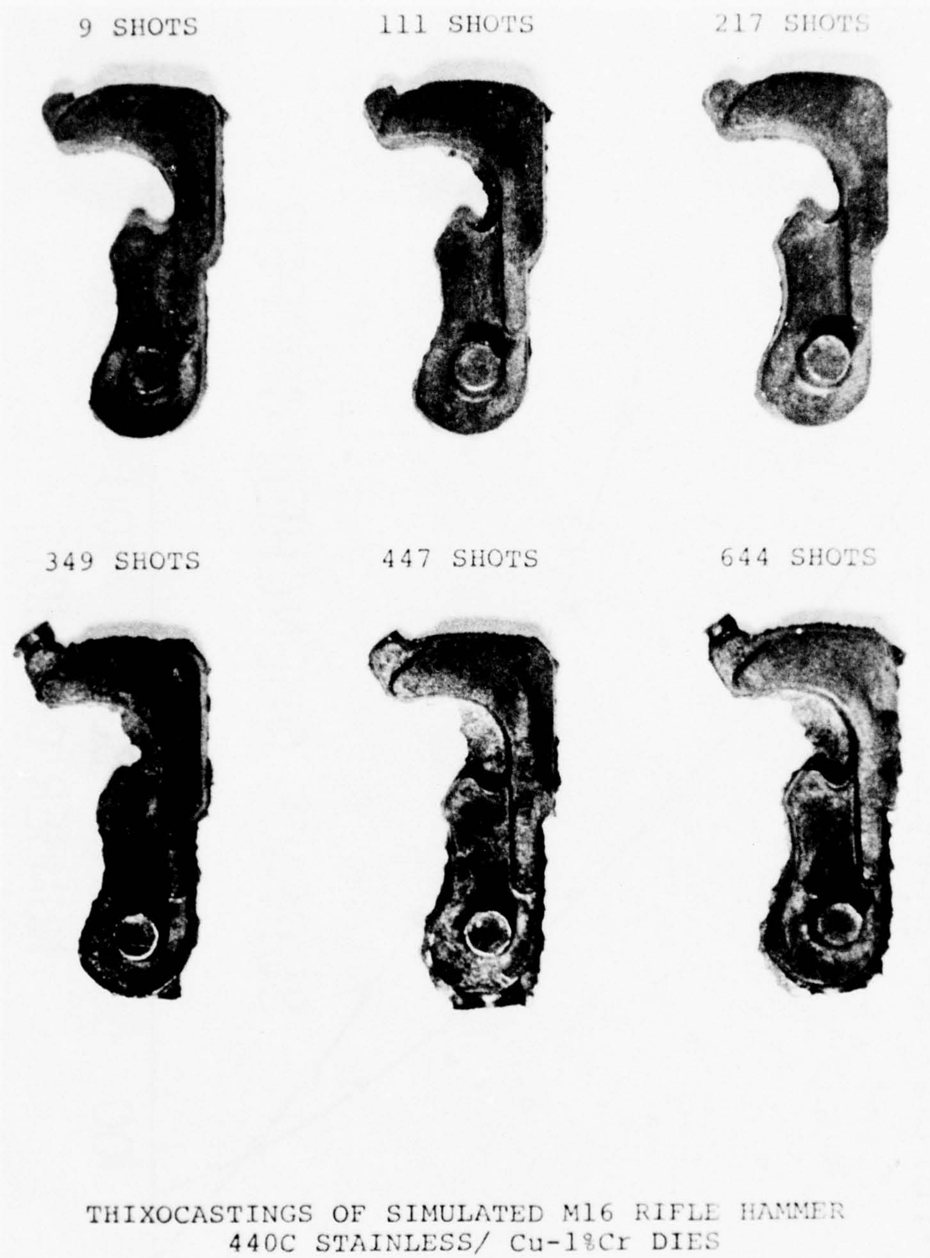



Figure 12: Sequence of 440C stainless steel Thixocastings produced at various intervals in the 600 shot die study in Cu-1% Cr dies.

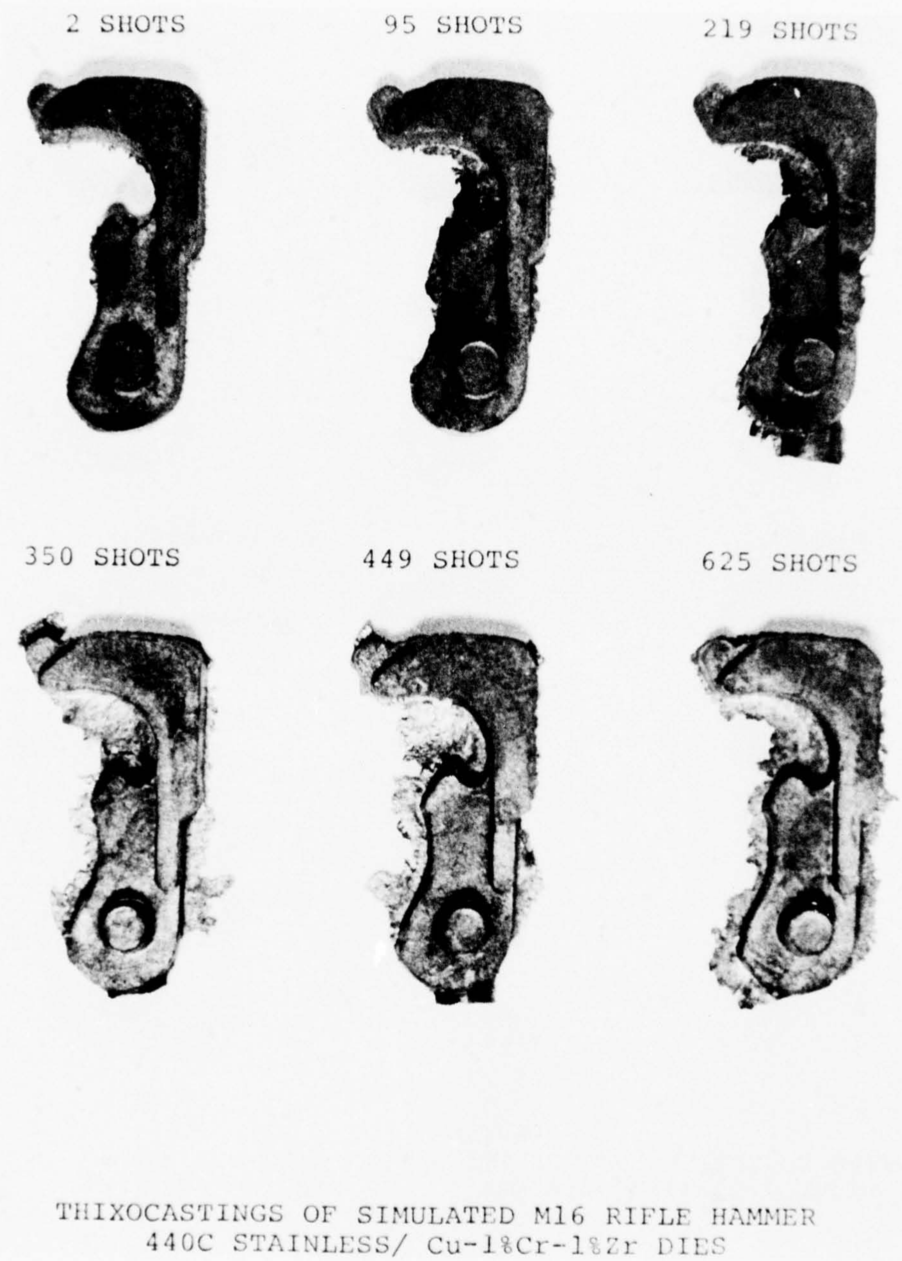
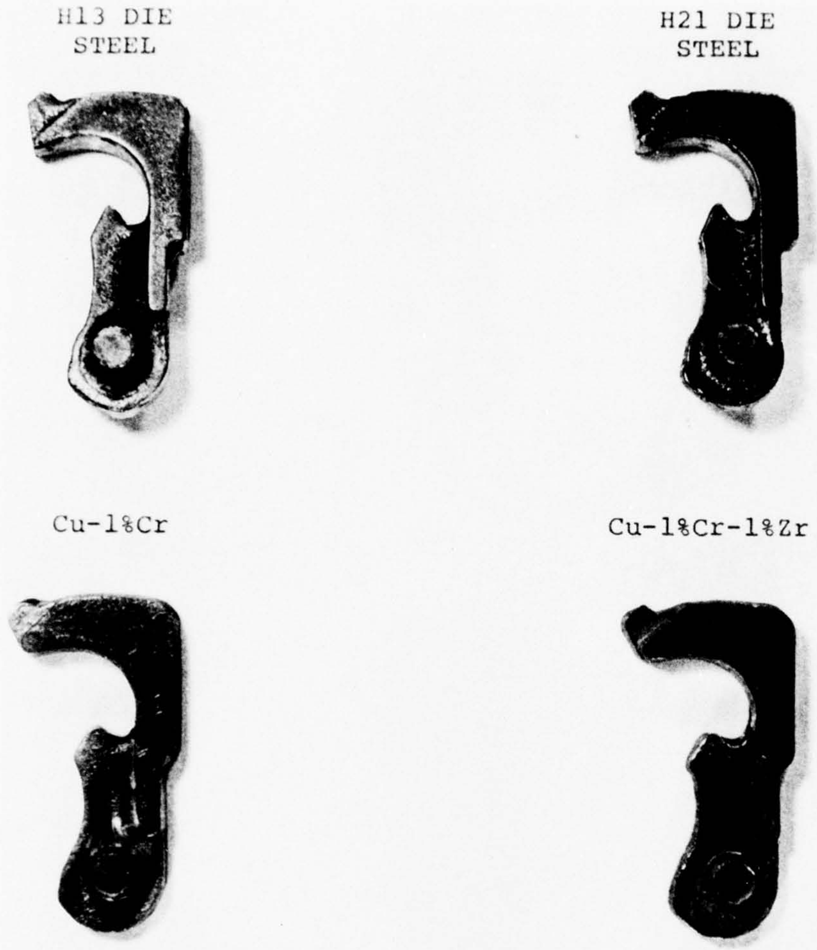



Figure 13: Sequence of 440C stainless steel Thixocastings produced at various intervals in the 600 shot die study in Cu-1% Cr-1% Zr dies.




FIVE HUNDREDTH SHOT OF THE ACTUAL (304 STAINLESS) OR SIMULATED (440C STAINLESS) M16 RIFLE HAMMER CAST IN VARIOUS DIE MATERIALS

Figure 14: The 500th Thixocasting produced in H-13 die steel, H-21 die steel, Cu-1% Cr dies, and Cu-1% Cr-1%Zr dies.

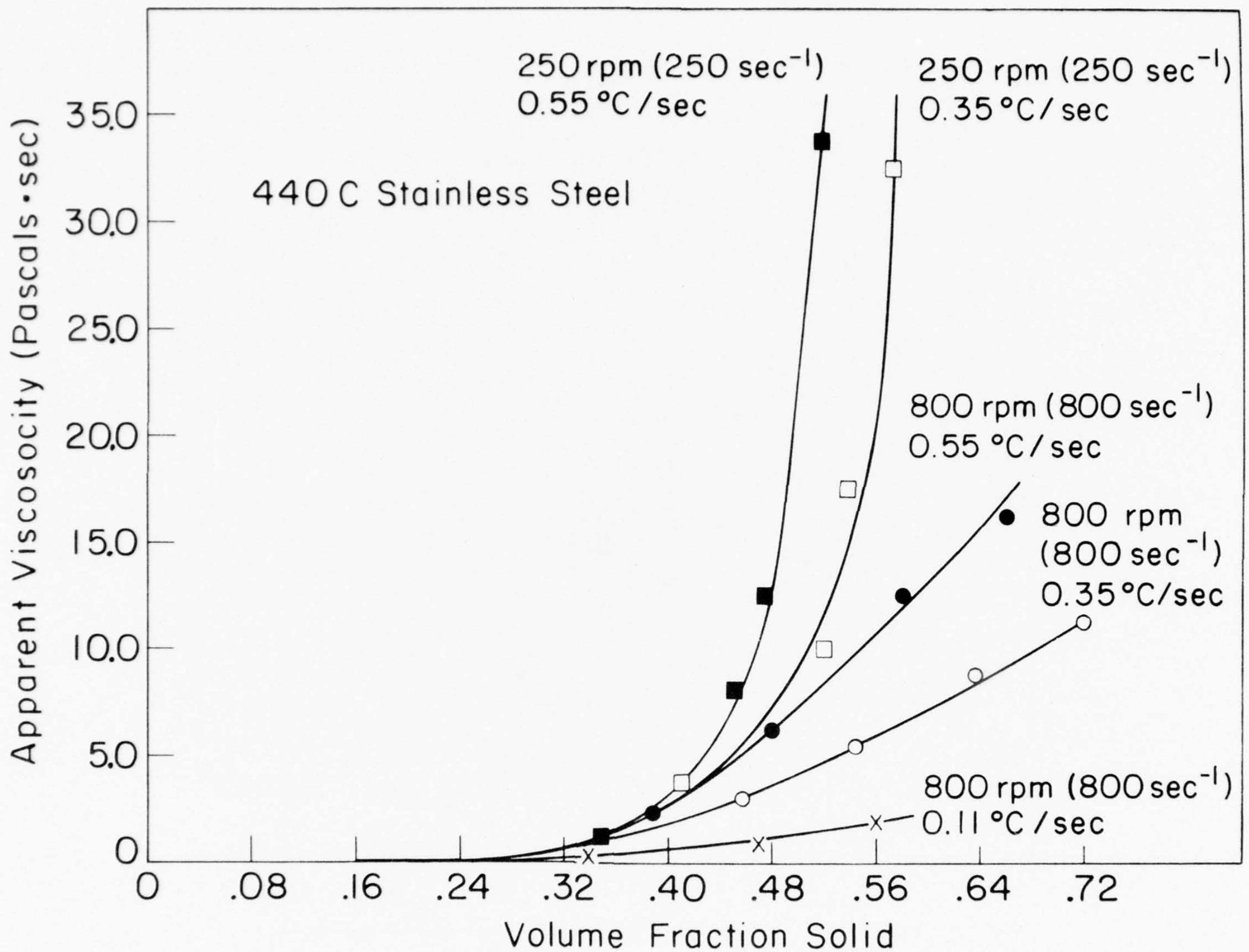



Figure 15: Approximate apparent viscosity versus volume fraction solid for AISI 440C stainless steel at different shear and cooling rates.

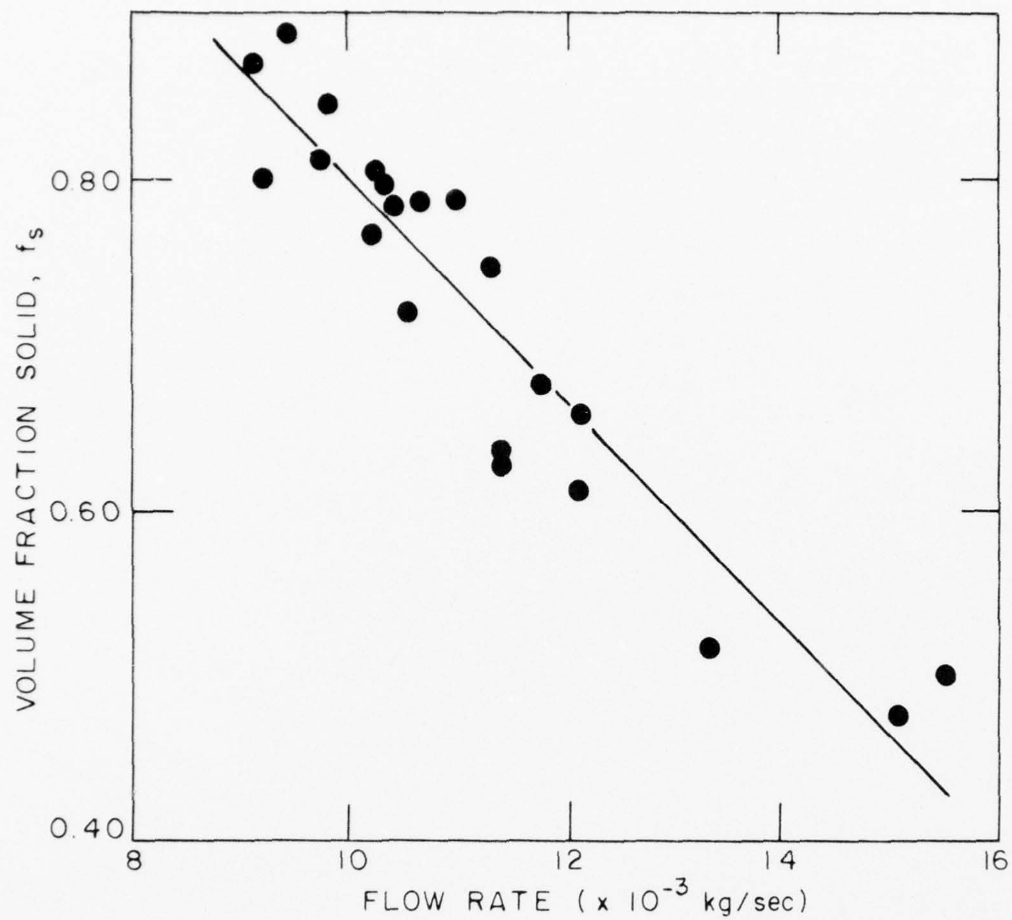



Figure 16: Effect of flow rate on volume fraction of primary solid particles, $f_s$.

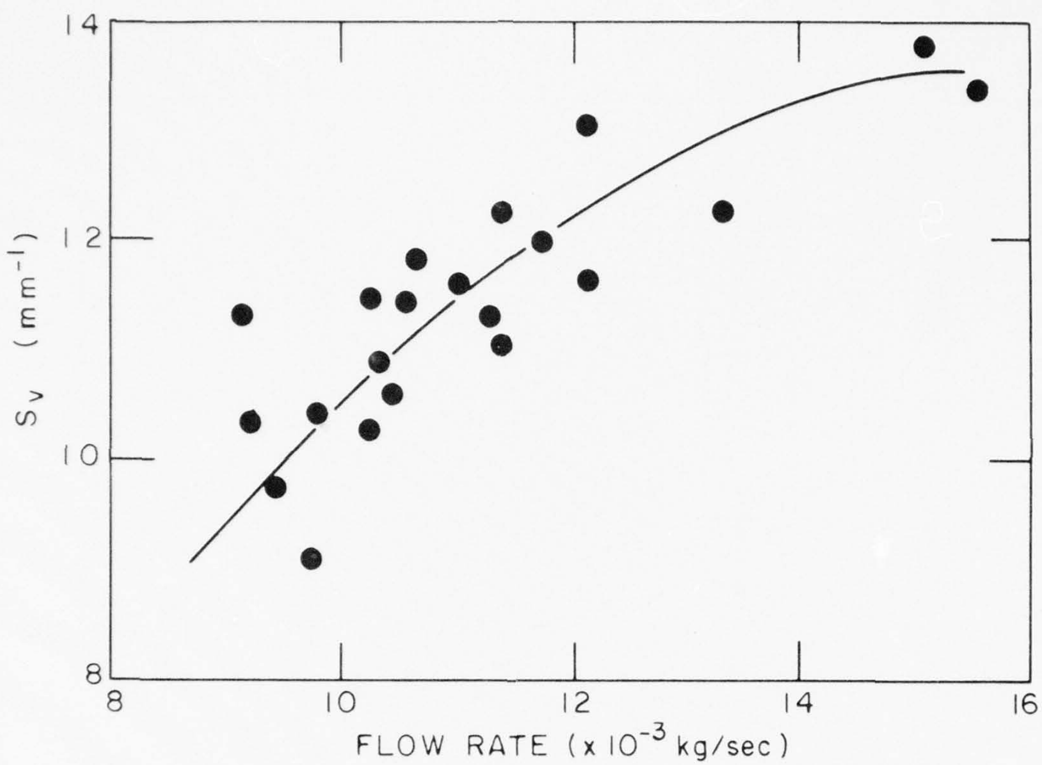



Figure 17: Effect of flow rate on the primary solid-liquid interface area per unit volume of the primary solid particles, $S_v$.

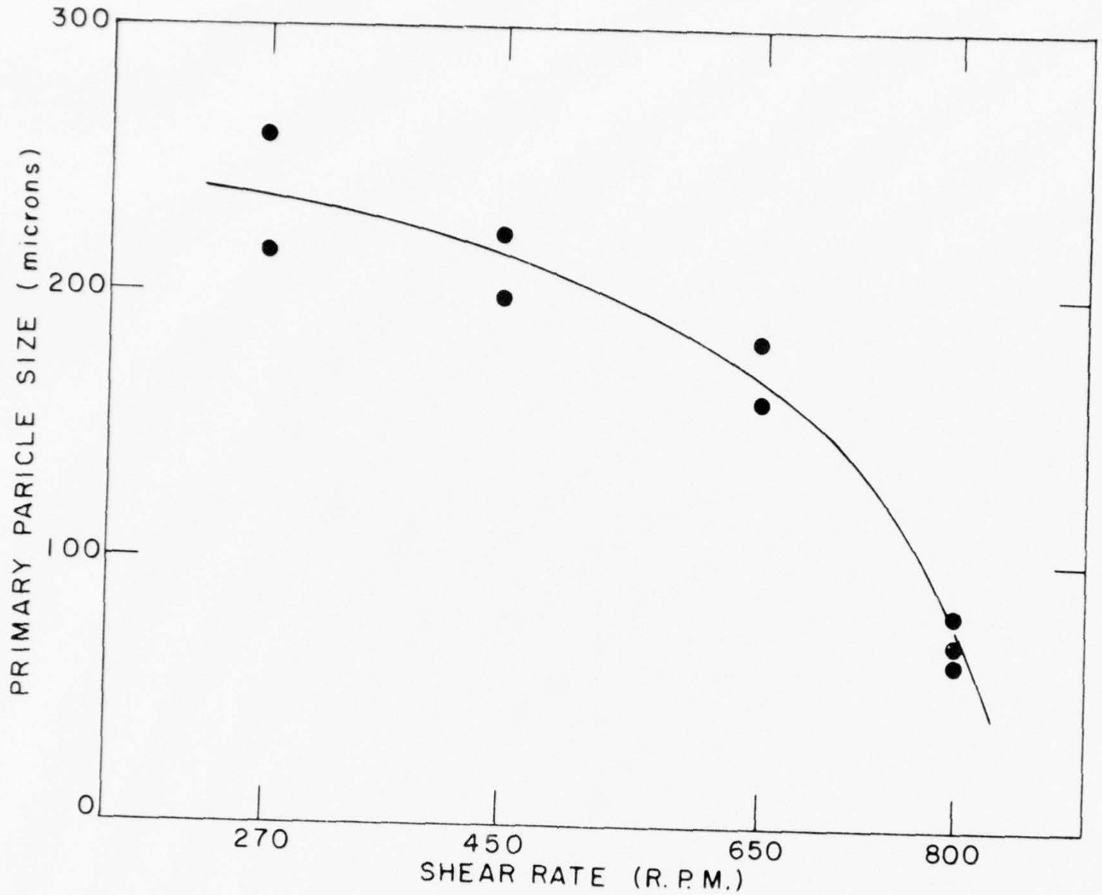



Figure 18: Effect of shear rate on average size of primary solid particles.

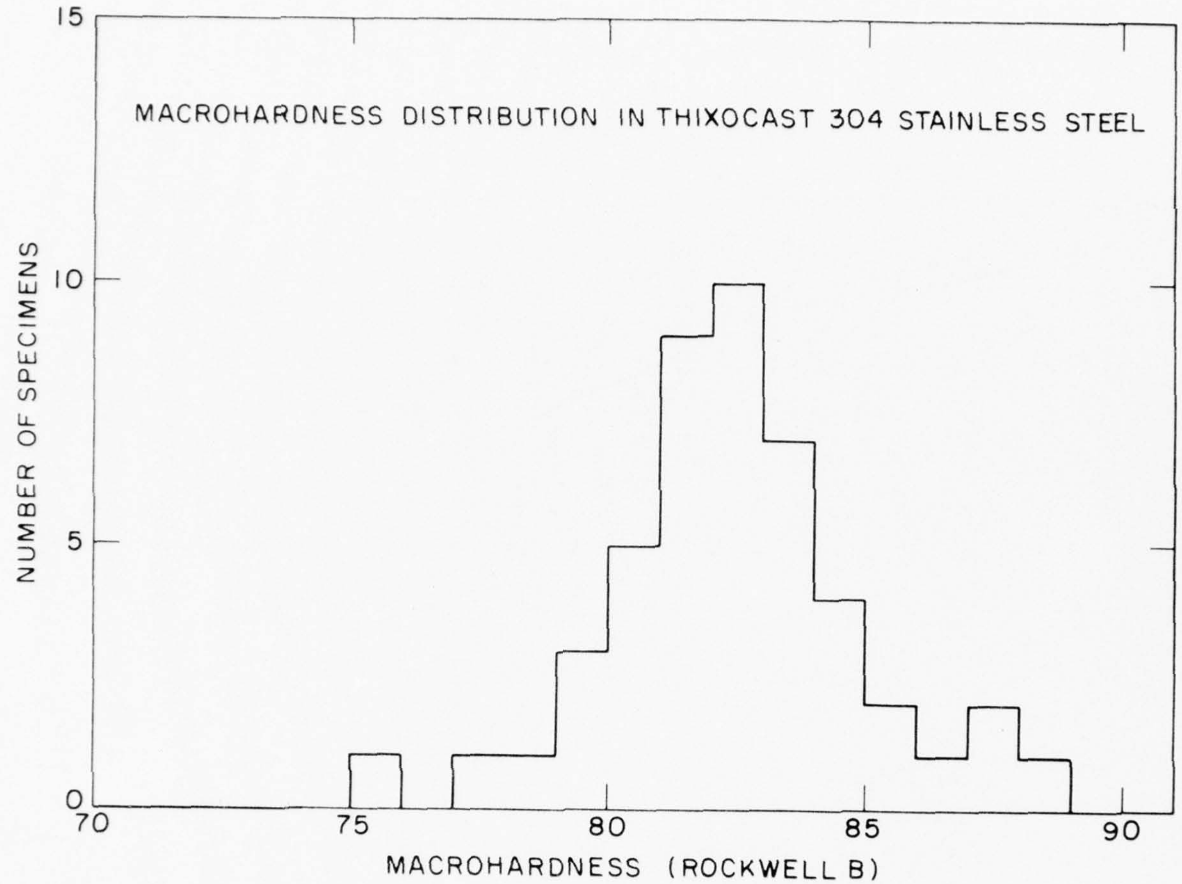



Figure 19: Histogram of Thixocast 304 stainless steel macrohardness values. Rockwell B scale, 100 kilogram load.

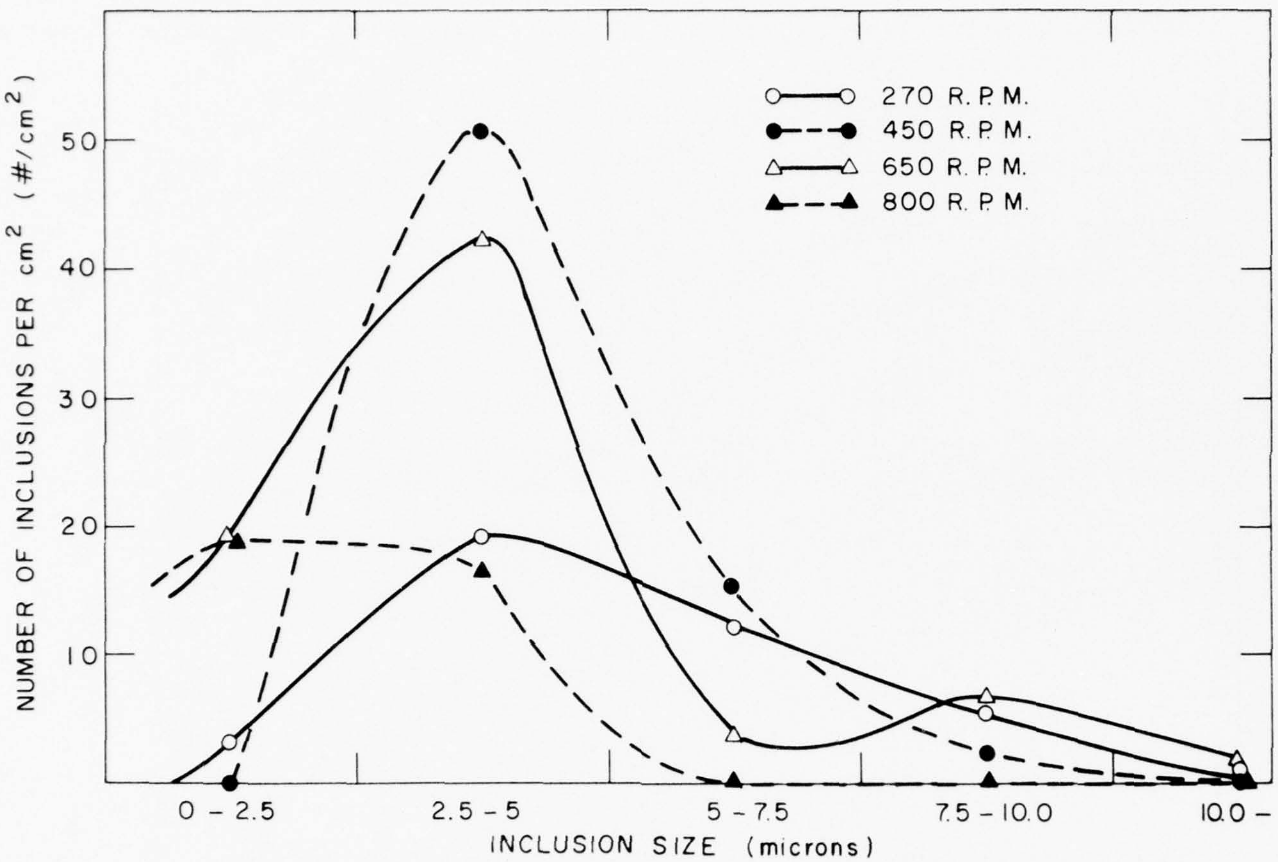



Figure 20: Effect of shear rate on the size distribution of oxide inclusions. Rheocast AISI 304 stainless steel.

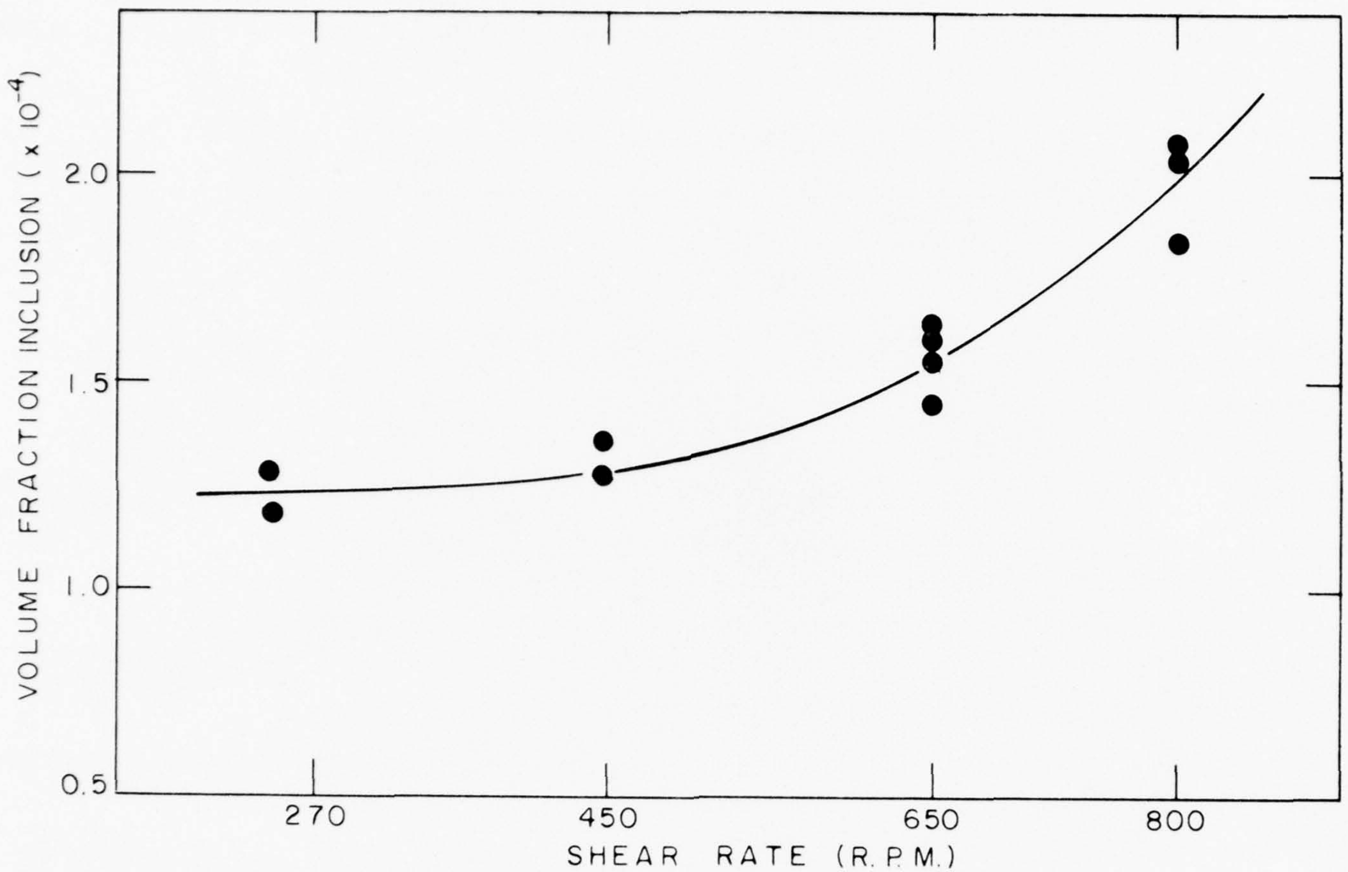



Figure 21: Effect of shear rate on the volume fraction of oxide inclusions, $f_i$. Rheocast AISI 304 stainless steel.

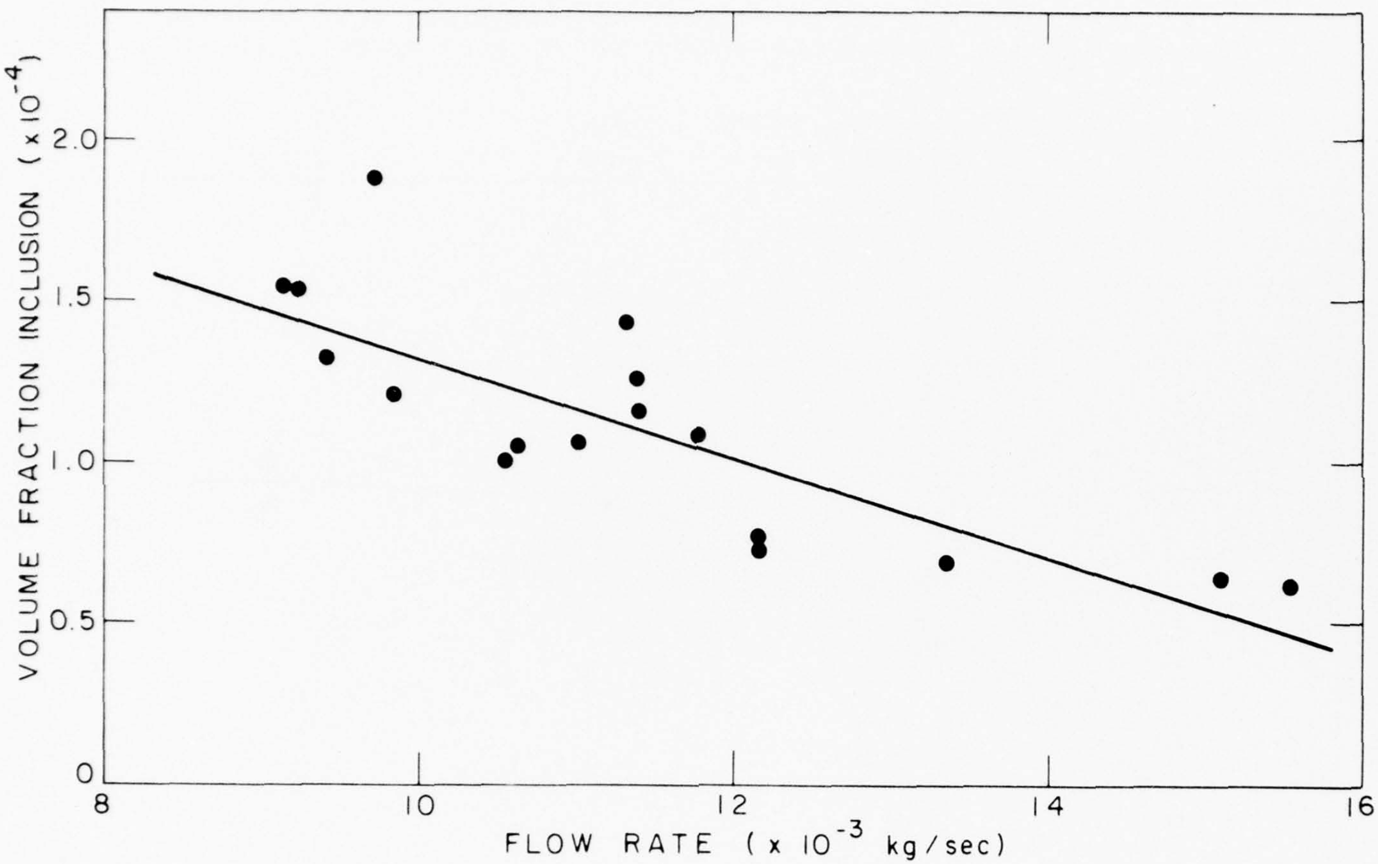



Figure 22: Effect of flow rate on the volume fraction of oxide inclusions, $f_i$. Rheocast AISI 304 stainless steel.

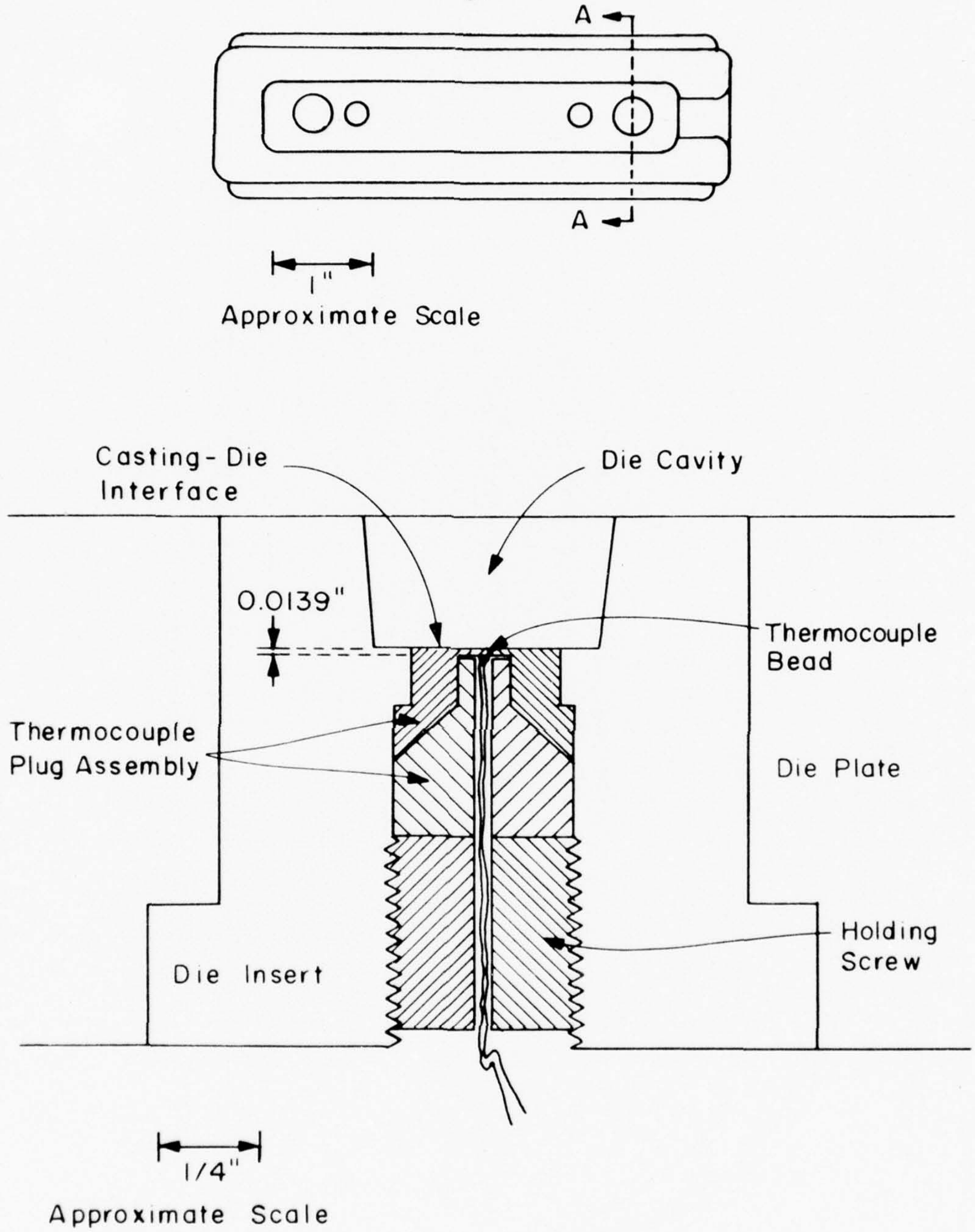



Figure 23: Schematic of die cavity used for thermal measurements. Top: Plan view of moving die-half insert. Bottom: Cut-away view at section A-A of above showing details of thermocouple assembly.

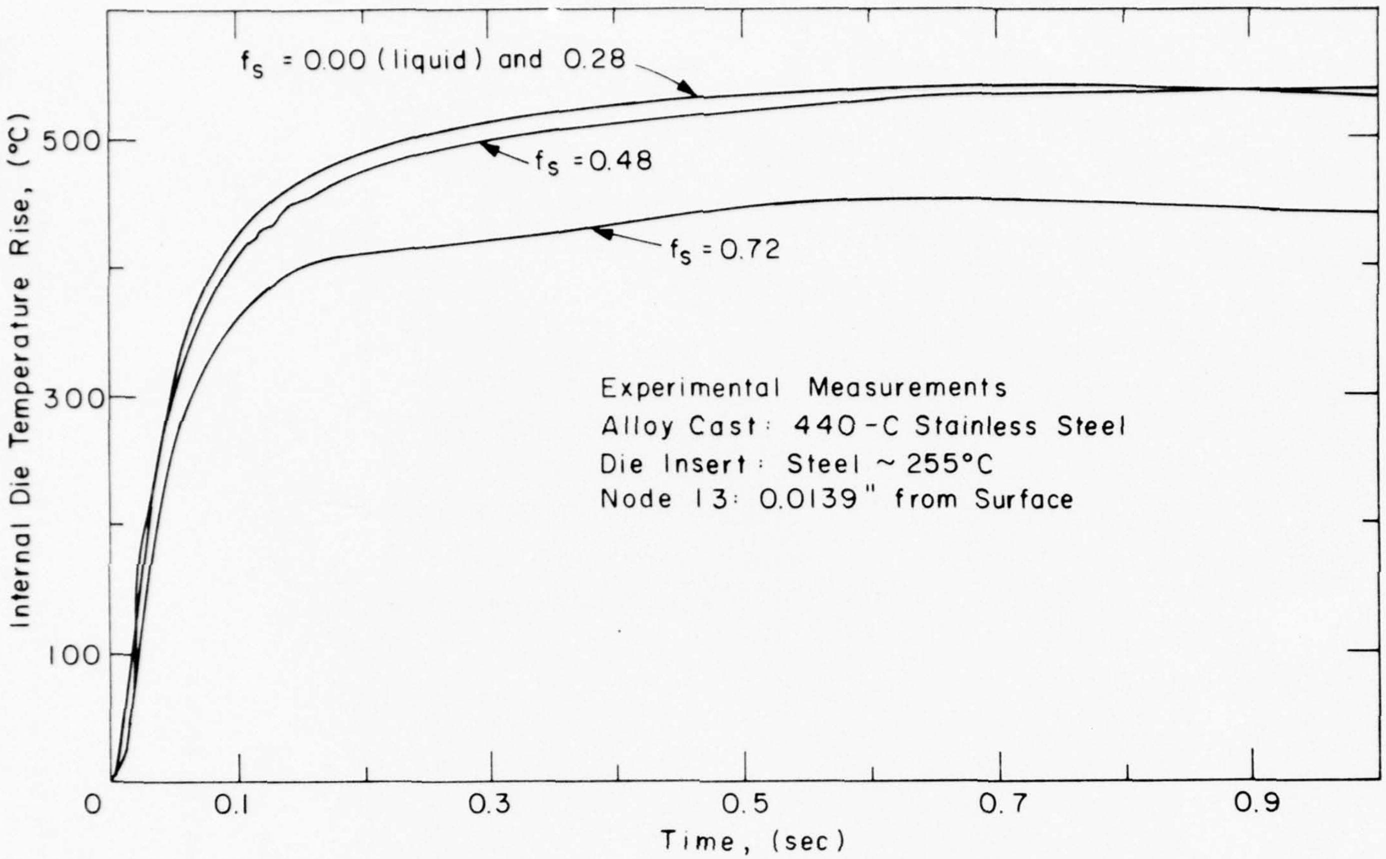



Figure 24: Measured internal die temperature rise when casting various volume fractions primary solid 440C stainless steel into plain carbon steel dies at 255°C. Thermocouple located 0.0139 inch from the casting-die interface.

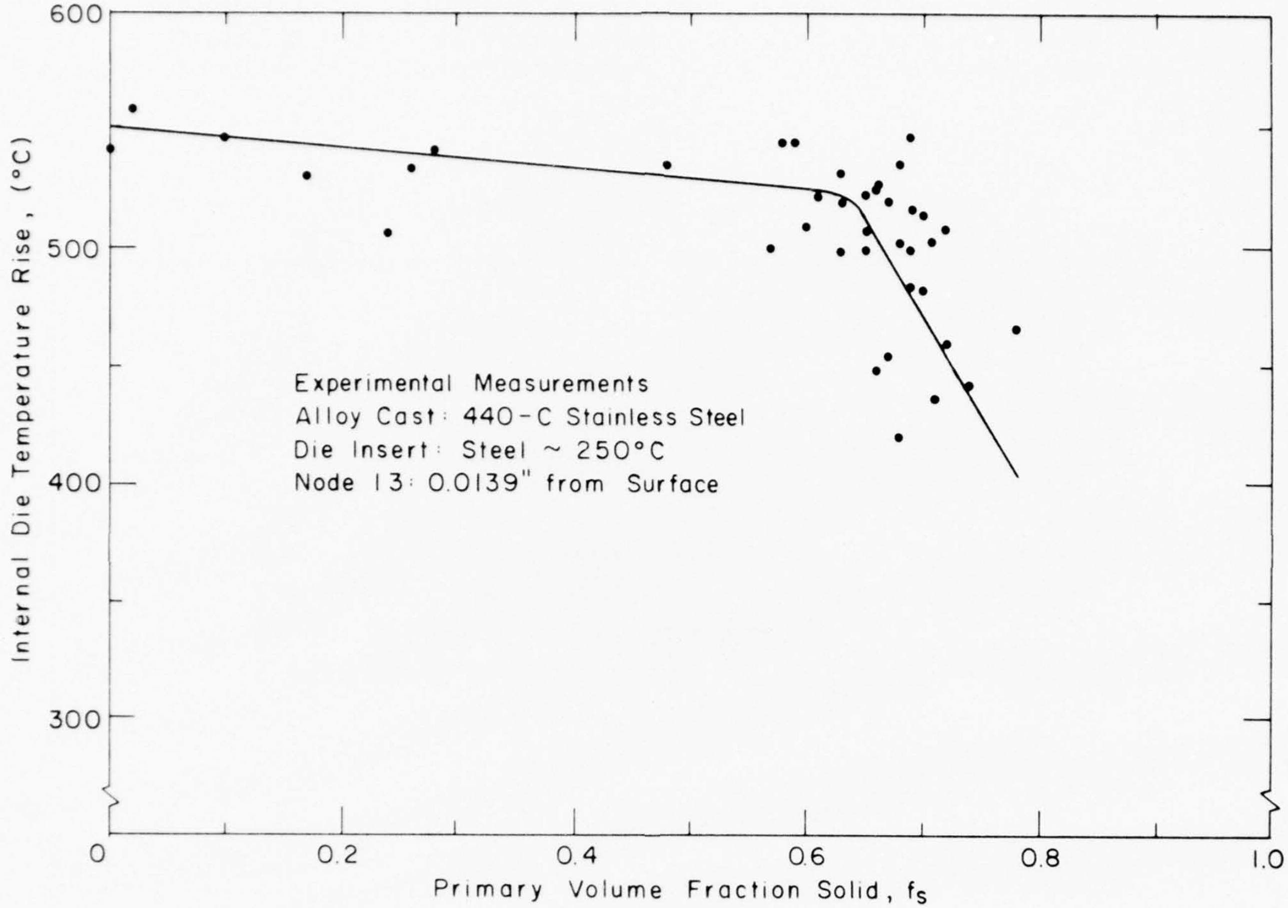



Figure 25: Measured relationship between maximum internal die temperature rise and primary volume fraction solid when casting 440C stainless steel into plain carbon steel dies at 250°C. Thermocouple located 0.0139 inch from the casting-die interface.

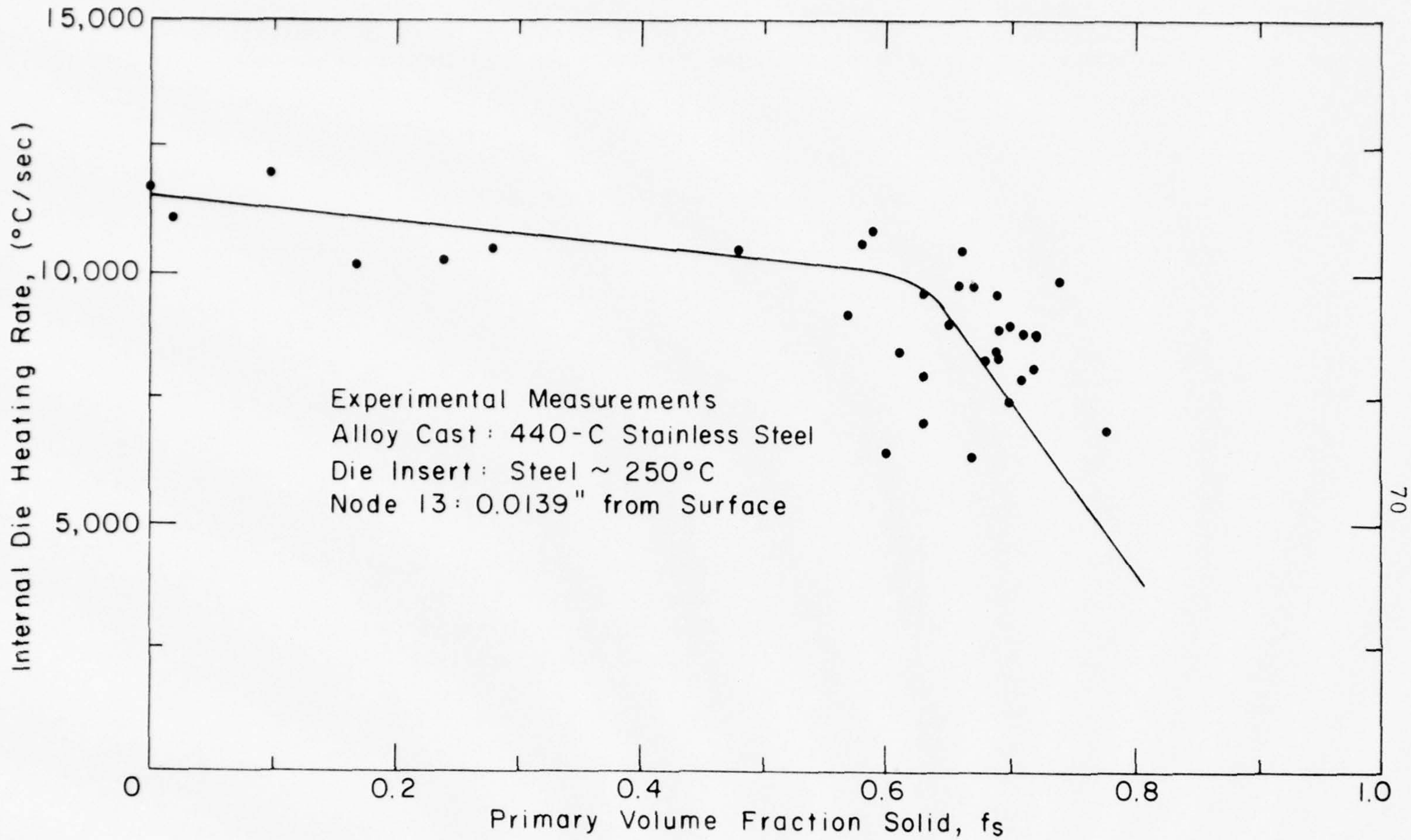



Figure 26: Measured relationship between internal die heating rate and primary volume fraction solid when casting 440C stainless steel into plain carbon steel dies at 250°C. Thermocouple located 0.0139 inch from the casting-die interface.

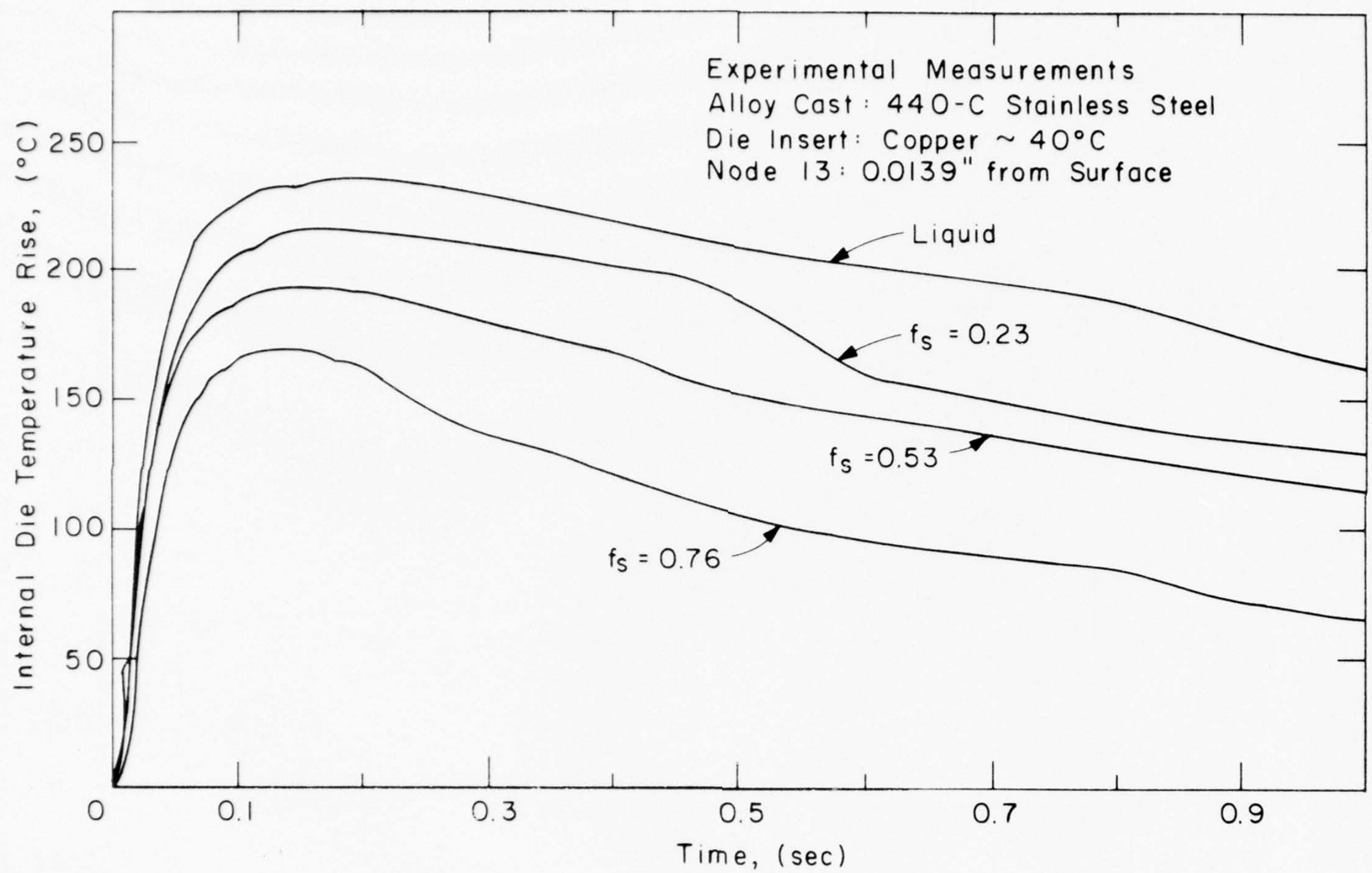



Figure 27: Measured internal die temperature rise when casting various volume fractions primary solid 440C stainless steel into high purity copper dies at 40°C. Thermocouple located 0.0139 inch from the casting-die interface.

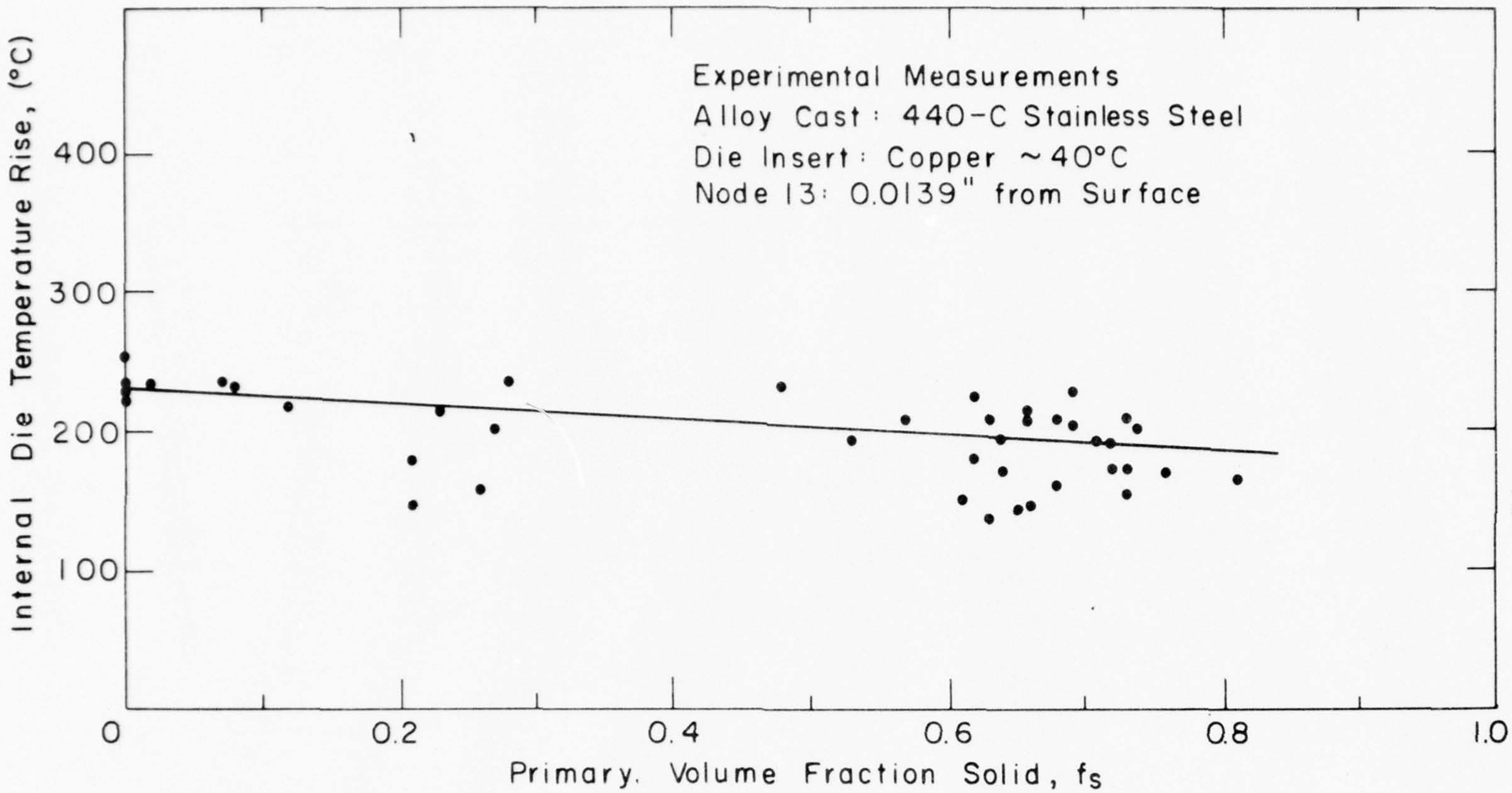





Figure 28: Measured relationship between maximum internal die temperature rise and primary volume fraction solid when casting 440C stainless steel into high purity copper dies at 40°C. Thermocouple located 0.0139 inch from the casting-die interface.

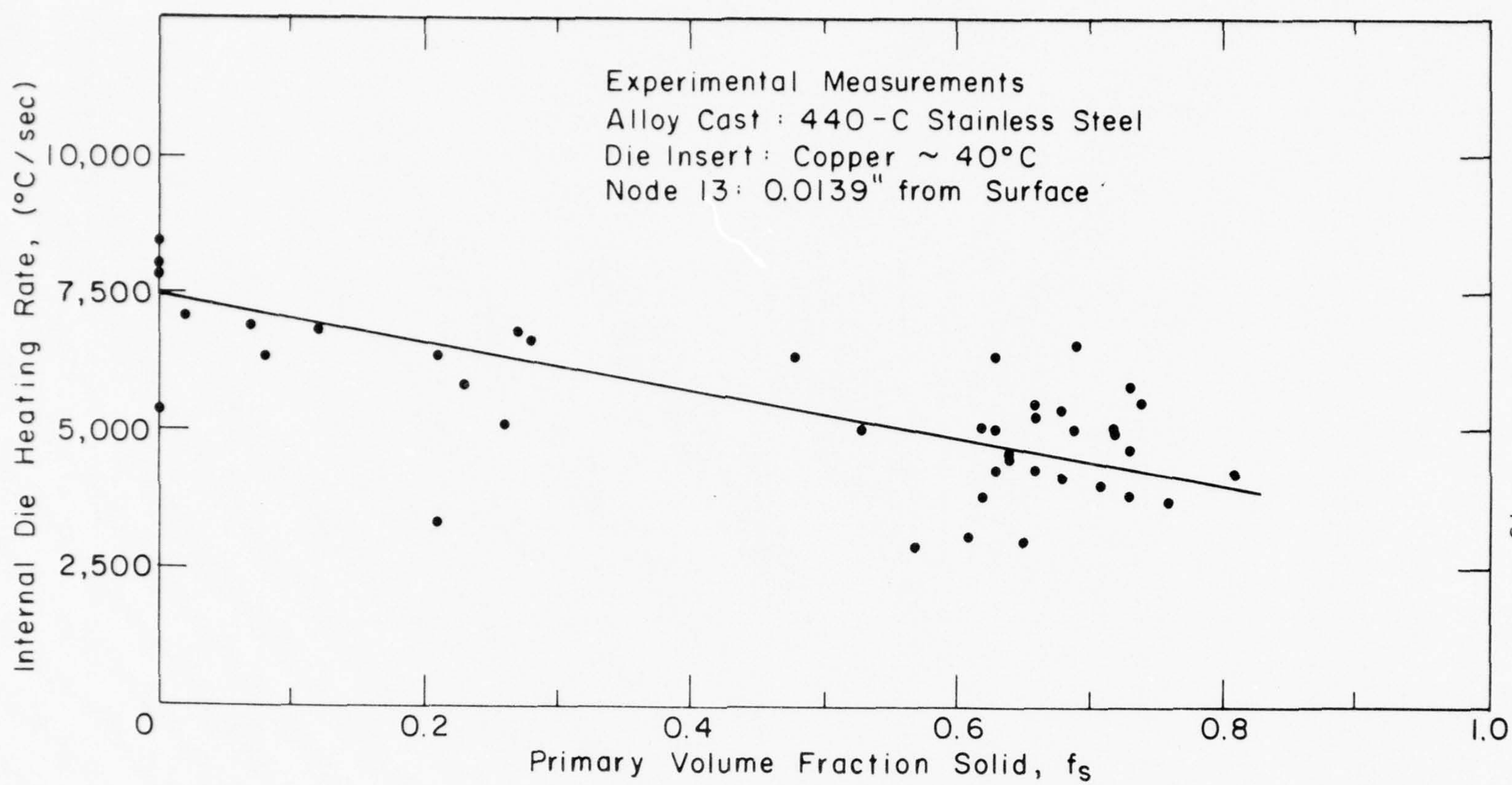



Figure 29: Measured relationship between internal die heating rate and primary volume fraction solid when casting 440C stainless steel into high purity copper dies at 40$^{O}$C. Thermocouple located 0.0139 inch from the casting-die interface.

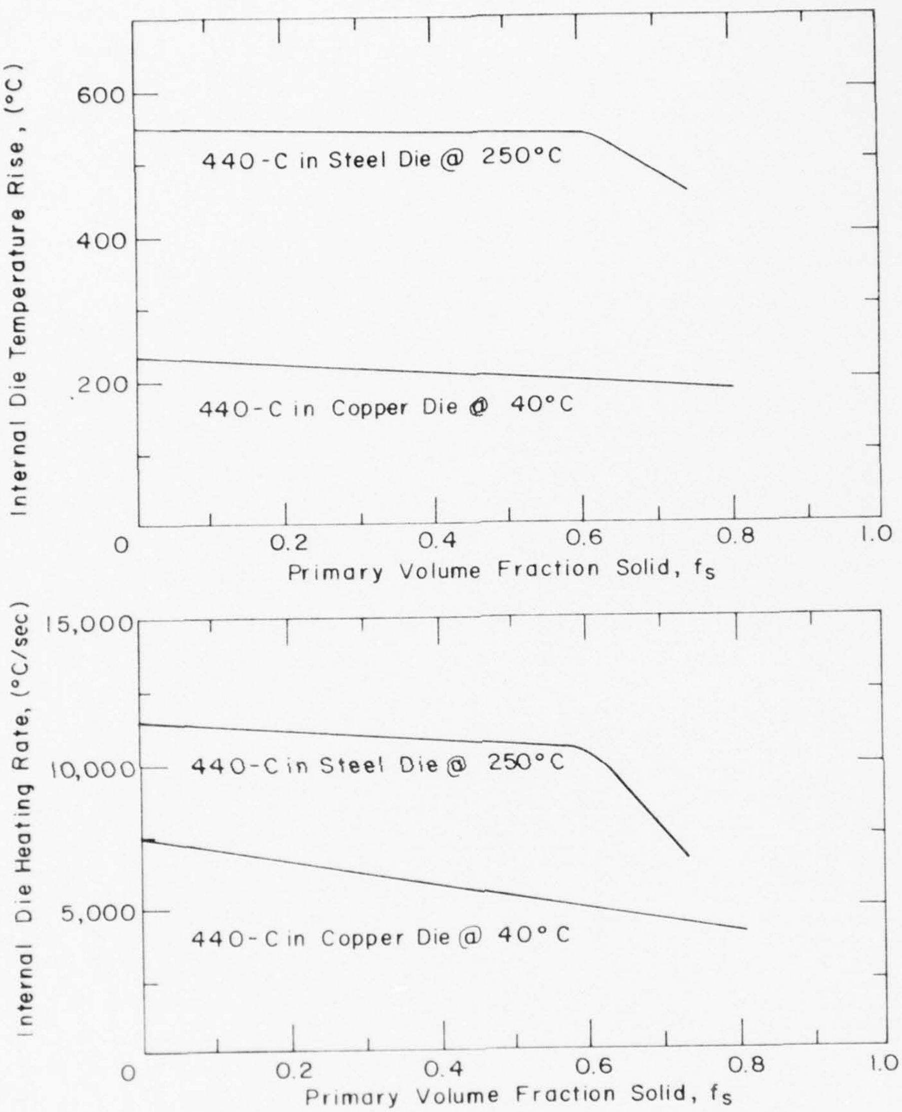



Figure 30: Comparison of die thermal response of plain carbon steel and high purity copper dies. Thermocouple located at 0.0139 inch from the casting-die interface. Steel dies were operated at 250°C; copper dies at 40°C. (a) Maximum temperature rise as a function of the primary volume fraction solid of 440C stainless steel charge material. (b) Measured heating rate as a function of the primary volume fraction solid of 440C stainless steel charge material.

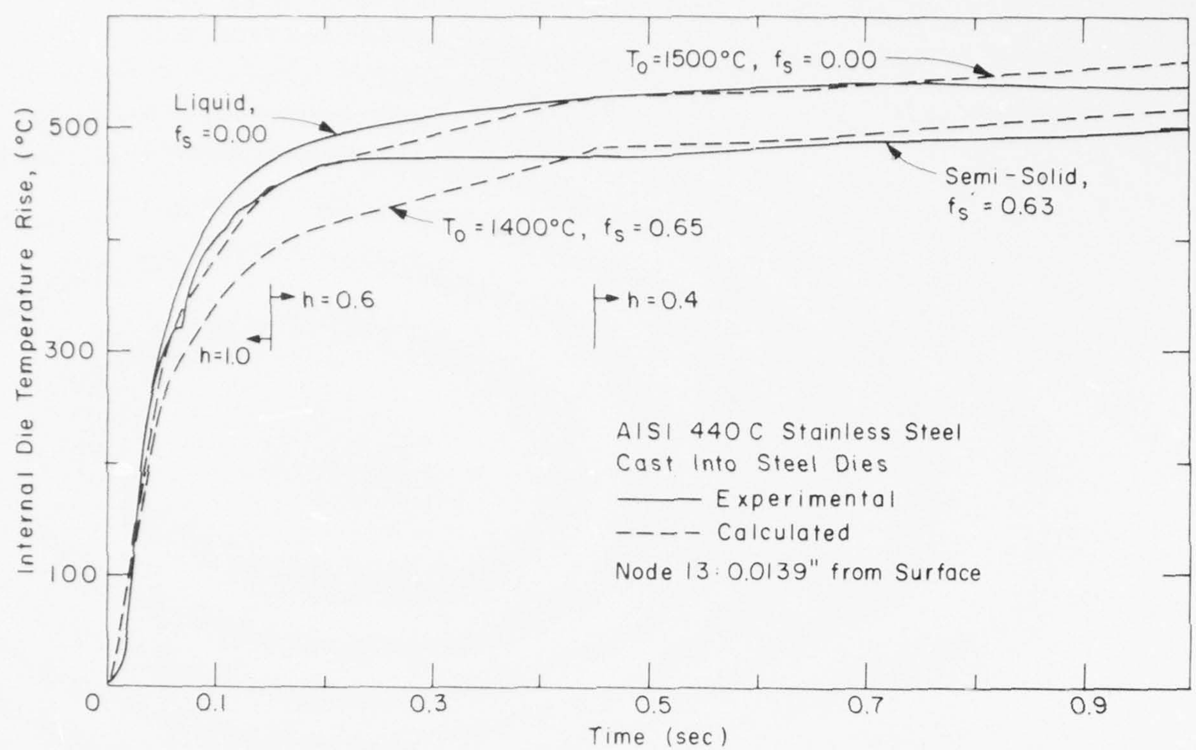



Figure 31: Increase in the internal die temperature when casting both liquid ($f_s$ = 0.00) and semi-solid ($f_s \simeq$ 0.65) 440C stainless steel into plain carbon steel dies. Die temperature was initially 250°C. Solid lines represent measured temperatures and dotted lines calculated temperatures from computer simulations. Thermocouple located at node 13, 0.0139 inch from the casting die interface. Changes in the interface coefficient, h, during computer simulation occur as noted.

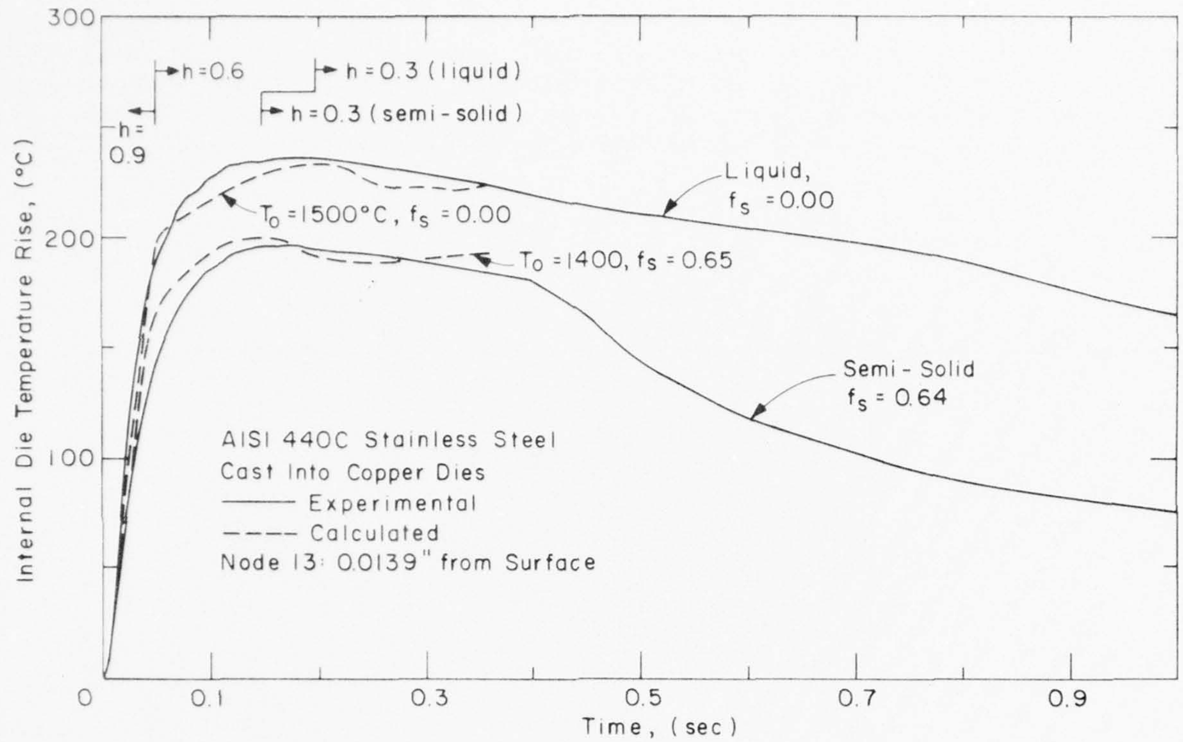



Figure 32: Increase in the internal die temperature when casting both liquid ($f_s = 0.00$) and semi-solid ($f_s \simeq 0.65$) 440C stainless steel into high purity copper dies. Die temperature was initially 40°C. Solid lines represent measured temperatures and dotted lines calculated temperatures from computer simulations. Thermocouple located at node 13, 0.0139 inch from the casting die interface. Changes in the interface coefficient, f, during computer simulation occur as noted.

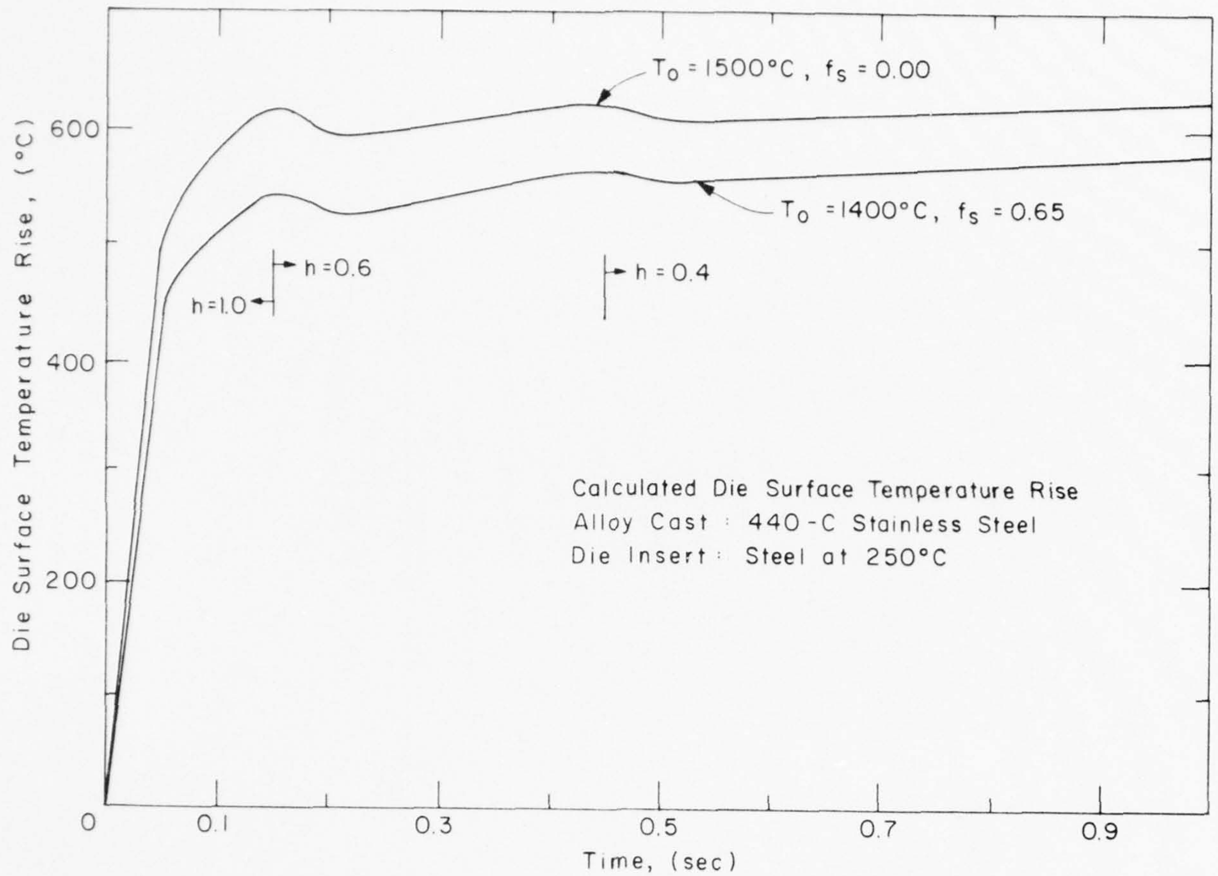



Figure 33: Computer simulated die surface temperature rise as a function of time for liquid and semi-solid 440C stainless steel cast into 250°C plain carbon steel dies. Changes in the interface coefficient, h, during simulation occur as noted.

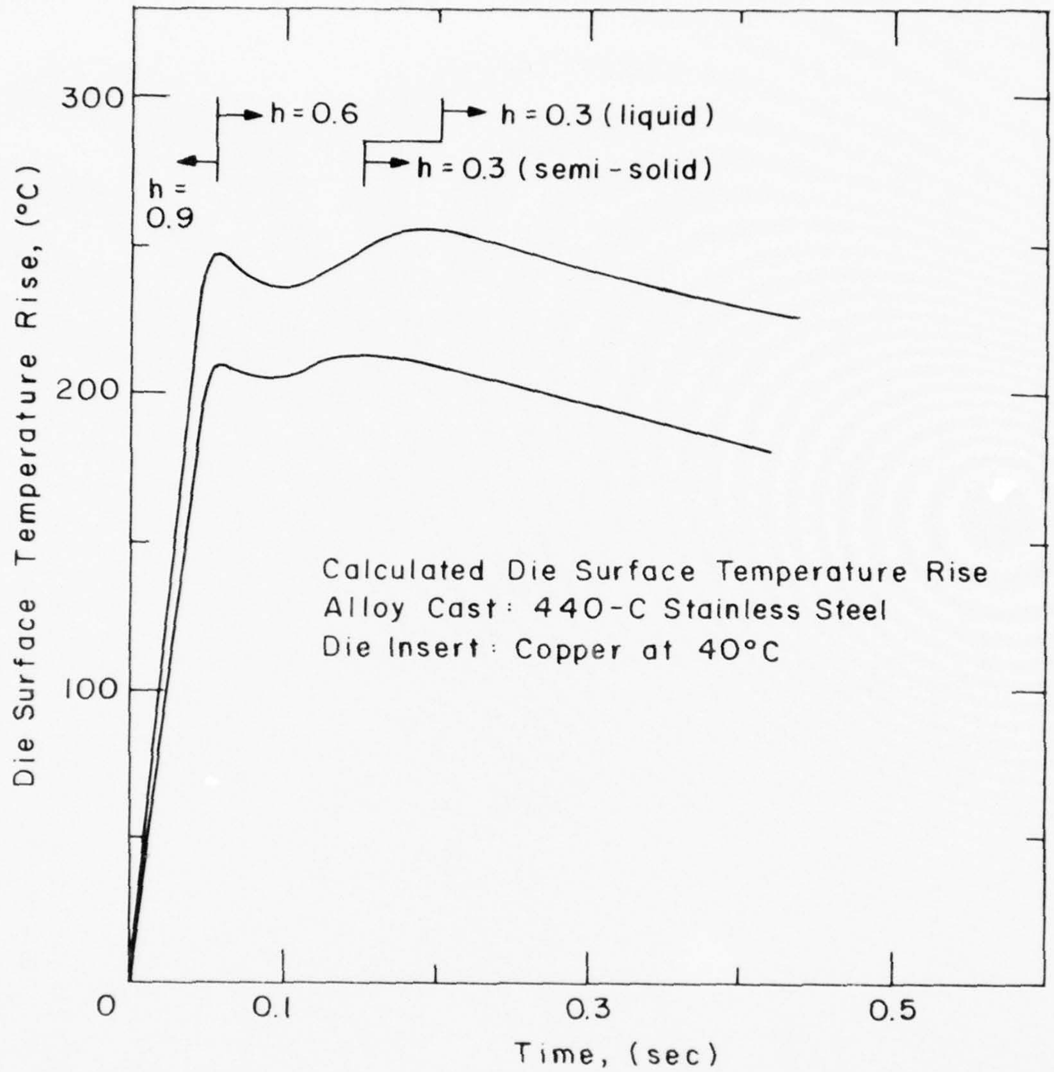



Figure 34: Computer simulated die surface temperature rise as a function of time for liquid and semi-solid 440C stainless steel cast into 40°C high purity copper dies. Changes in the interface coefficient, h, during simulation occur as noted.

# Appendix A

## List of Published Papers, Articles, Reports, Patents and Theses on Rheocasting

### Published Papers

1. D. B. Spencer, R. Mehrabian, M. C. Flemings, "Rheological Behavior of Sn-15% Pb in the Crystallization Range", Met. Trans., Vol. 3 (1972), pp. 1925-1932.

2. R. Mehrabian, M. C. Flemings, "Die Casting of Partially Solidified Alloys", Trans. A.F.S., Vol. 80 (1972), pp. 173-182. (Also Die Casting Engineer, July-August 1973, pp. 49-59.)

3. M. C. Flemings, R. Mehrabian, "Casting Semi-Solid Metals", Trans. International Foundry Congress, Moscow, A.F.S. Trans., Vol. 81 (1973), pp. 81-88.

4. E. F. Fascetta, R. G. Riek, R. Mehrabian, M. C. Flemings, "Die Casting Partially Solidified High Copper Content Alloys", Die Casting Engineer, September-October 1973, pp. 44-45. (Also, A.F.S. Cast Metals Research Journal, Vol. 9, No. 4 (1973), pp. 167-171; Trans. A.F.S., Vol. 81 (1973), pp. 95-100.)

5. R. Mehrabian, D. Geiger, M. C. Flemings, "Refining by Partial Solidification", Met. Trans., Vol. 5 (1974), pp. 785-787.

6. R. Mehrabian, R. G. Riek, M. C. Flemings, "Preparation and Casting of Metal-Particulate Non-Metal Composites", Met. Trans., Vol. 5 (1974), p. 1899.

7. M. C. Flemings, "Solidification Processing", Howe Memorial Lecture, Met. Trans., Vol. 5 (1974), pp. 2121-2134.

8. M. C. Flemings, "Solidification of Castings", Scientific American, Vol. 231, No. 6 (1974), pp. 88-95.

9. "Die Casting Semi-Solid Metals", Machinery and Production Engineering, 31 July 1974, pp. 146-150.

10. R. Mehrabian, M. C. Flemings, "Machine Casting of High Temperature Alloys", Proceedings of ASM Materials Science Seminar on New Trends in Materials Processing, October, 1974.

Published Papers (Continued)

11. "Die Casting Semi-Solid Copper Alloys", Machinery and Production Engineering (27 November 1974), pp. 594-597.

12. R. G. Riek, K. P. Young, N. Matsumoto, R. Mehrabian, M. C. Flemings, "Rheocasting of Ferrous Alloys", Paper No. G-T-75-153, Eight S.D.C.E. International Die Casting Exposition and Congress, Detroit Michigan (1975).

13. R. G. Riek, A. Vranchnos, K. P. Young, N. Matsumoto, R. Mehrabian, "Machine Casting of a Partially Solidified High Copper Content Alloy", Trans. A.F.S. (1975), pp. 25-30.

14. R. Mehrabian, A. Sato, M. C. Flemings, "Cast Composites of Aluminum Alloys", Light Metals, Vol. II (1975), pp. 175-193.

15. R. Mehrabian, M. C. Flemings, "Casting in the Liquid-Solid Region", New Trends in Materials Processing, ASM (1976), pp. 98-127.

16. M. C. Flemings, R. Mehrabian, "Casting Semi-Solid Aluminum Alloys", Proceedings of Sixth ILMT (Light Metals) Conference, Vienna, Austria (June 1975).

17. M. C. Flemings, R. G. Riek, K. P. Young, "Rheocasting Process", International Cast Metal Journal, Vol. 11 (1976), pp. 11-22.

18. M. C. Flemings, R. G. Riek, K. P. Young, "Rheocasting", Materials Science and Engineering, Vol. 25 (1976), pp. 103-117.

19. K. P. Young, R. G. Riek, J. F. Boylan, R. L. Bye, B. E. Bond, M. C. Flemings, "Thixocasting Copper Base Alloys", presented at the 80th A.F.S. Congress, Chicago, Illinois (1976). (Also, Die Casting Engineer (March-April 1976), pp. 46-52.)

20. K. P. Young, R. G. Riek, M. C. Flemings, "Thixocasting of Steel", Transactions S.D.C.E., Vol. 9 (1977), paper GT-77-092.

21. K. P. Young, R. G. Riek, M. C. Flemings, "Structure and Properties of Thixocast Steels", Proceedings of the Sheffield International Conference on Solidification and Casting, to be published by the Metals Society.

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22. M. C. Flemings, K. P. Young, "Rheocasting Development", Yearbook of Science and Technology, to be published by McGraw-Hill.

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1. G. X. Diamond, Assoc. Editor, "Rheocast Process: A New Metalcasting Discipline", Modern Casting (February 1972).

2. "Reports on Research", Massachusetts Institute of Technology, Vol. 2, No. 4 (December 1974).

3. "Die Casting Sharpens Its Edge", Special Report No. 670, American Machinist (November 25, 1975).

4. J. O'Connor, "MIT, Major Industries Join in R&D to Find New Steel Casting Methods", Metal Market.

## Theses

1. D. B. Spencer, Sc.D., "Rheology of Liquid-Solid Mixtures of Lead-Tin", Department of Materials Science and Engineering, Massachusetts Institute of Technology (June 1977).

2. D. R. Geiger, S.M., "Atomization and Refining of Metal Alloys Utilizing Partially Solid Partially Liquid Alloys", Department of Materials Science and Engineering, Massachusetts Institute of Technology (June 1972).

3. E. F. Fascetta, S.M., "Rheocasting of Copper and Iron Base Alloys", Department of Materials Science and Engineering, Massachusetts Institute of Technology (June 1973).

4. P. A. Joly, Ph.D., "Rheological Properties and Structure of a Semi-Solid Tin-Lead Alloy", Department of Materials Science and Engineering, Massachusetts Institute of Technology (June 1974).

5. F. S. Blackall, S.M., "The Delivery and Casting of Semi-Solid Metals", Department of Materials Science and Engineering, Massachusetts Institute of Technology (February 1975).

6. A. S. Vrachnos, S.M., "Machine Casting of a Partially Solidified High Copper Content Alloy", Department of Materials Science and Engineering, Massachusetts Institute of Technology (February 1975).

7. V. Laxmanan, S.M., "Rheocasting of Superalloys", Department of Materials Science and Engineering, Massachusetts Institute of Technology (June 1975).

8. B. E. Bond, S.M., "Machine Casting of Semi-Solid Bronze", Department of Materials Science and Engineering, Massachusetts Institute of Technology (September 1975).

9. D. G. Backman, Ph.D., "Machine Casting of High Temperature Alloys", Department of Materials Science and Engineering, Massachusetts Institute of Technology (September 1975).

10. F. E. Goodwin, S.M., "Structure and Properties of Thixocast High-Temperature Alloys", Department of Materials Science and Engineering, Massachusetts Institute of Technology (September 1976).

Theses (Continued)

11. M. L. Santor, S.M., "Structure Characterization of Continuously Rheocast AISI 304 Stainless Steel", Department of Materials Science and Engineering, Massachusetts Institute of Technology (June 1977).

12. A. Shibutani, S.M., "Microstructure and Inclusions in Rheocast Stainless Steel", Department of Materials Science and Engineering, Massachusetts Institute of Technology (June 1977).

Reports

1. M. C. Flemings, et al., "Machine Casting of Ferrous Alloys", Interim Technical Report. AMMRC CTR 74-27, ARPA Contract DAAG46-73-C-0110, 1 January - 30 December 1973, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts.

2. M. C. Flemings, et al., "Machine Casting of Ferrous Alloys", Interim Technical Report. AMMRC CTR 74-55, ARPA Contract DAAG46-73-C-0110, 1 January - 30 June 1974, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts.

3. M. C. Flemings, et al., "Machine Casting of Ferrous Alloys", Technical Report. AMMRC CTR 75-22, ARPA Contract DAAG46-73-C-0110, 1 July 1974 - 30 June 1975, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts.

4. M. C. Flemings, K. P. Young, R. G. Riek, "Machine Casting of Ferrous Alloys", Interim Technical Report. AMMRC CTR 76-15, ARPA Contract DAAG46-73-C-0110, 1 July - 31 December 1975, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts.

5. M. C. Flemings, K. P. Young, R. G. Riek, J. F. Boylan, R. L. Bye, "Machine Casting of Ferrous Alloys" Interim Technical Report. AMMRC CTR 76-39, ARPA Contract DAAG46-73-C-0110, 1 January - 30 June 1976, prepared for Army Materials and Mechanics Research Center, Watertown, Massachusetts.

## U.S. Patents Issued

1. U.S. Patent No. 3,840,364, issued October 8, 1974, "Methods of Refining Metal Alloys", M. C. Flemings, R. Mehrabian, D. R. Geiger.

2. U.S. Patent No. 3,902,544, issued September 2, 1975, "Continuous Process for Forming an Alloy Containing Non-Dendritic Primary Solids", M. C. Flemings, R. Mehrabian, R. G. Riek.

3. U.S. Patent No. 3,951,651, issued April 20, 1976, "Metal Composition and Method for Preparing Liquid-Solid Alloy Metal Composition and for Casting the Metal Composition", M. C. Flemings, R. Mehrabian.

4. U.S. Patent No. 3,948,650, issued April 6, 1976, "Composition and Methods for Preparing Liquid-Solid Alloys for Casting and Casting Methods Employing the Liquid-Solid Alloys", M. C. Flemings, R. Mehrabian, D. B. Spencer.

5. U.S. Patent No. 3,936,298, issued February 3, 1976, "Metal Composition and Methods for Preparing Liquid-Solid Alloy Metal Composition and for Casting the Metal Composition", M. C. Flemings, R. Mehrabian.

6. U.S. Patent No. 3,954,455, issued May 4, 1976, "Composition and Methods for Preparing Liquid-Solid Alloys for Casting and Casting Methods Employing the Liquid-Solid Alloys", M. C. Flemings, R. Mehrabian, D. B. Spencer.

7. U.S. Patent No. 4,011,901, issued March 15, 1977, "Method for Determining the Suitability of Metal Compositions for Casting", M. C. Flemings, K. P. Young.

## Foreign Patents Issued

1. Canadian Patent No. 957,180, issued November 5, 1974, "Method of and Apparatus for Preparing Liquid-Solid Alloys for Casting and Casting Methods Employing the Liquid".

2. British Patent No. 1400624, issued June 16, 1972, as above.

3. Italian Patent No. 992,859, issued September 30, 1975, "Metal Composition and Methods for Preparing Liquid-Solid Alloy Metal Composition and for Casting the Metal Compositions", R. Mehrabian, M. C. Flemings.

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MACHINE CASTING OF FERROUS ALLOYS
M. C. Flemings, K. P. Young, J. F. Boylan,
R. L. Bye, M. L. Santor, B. E. Bond,
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Cambridge, Massachusetts 02139

Technical Report DAAG46-73-C-0110, June 1977, 86 pp -
illus - tables, Contract DAAG46-73-C-0110
ARPA Order No. 2267, Program Code 7Y10
Final Report, 30 June 1976 - 30 June 1977

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Die Casting
Solidification
Rheocasting
Thixocasting

This is the sixth and final report describing research conducted at the Massachusetts Institute of Technology as part of a joint university-industry research program on machine casting of ferrous alloys. It covers the period of the 42nd month to the 54th, the final one year research of the overall 4-1/2 year program.

During this year the basic Rheocasting system, which was fully operational at the beginning of the year, was improved in various ways to increase reliability and productivity. Specific improvements were the addition of a reducing gas in the melting chamber, a shield gas extension nozzle and graphite inserts at the bottom of the Rheocaster to eliminate "hot spots". Large quantities of 304 and 440C stainless steel alloys were cast during this period (approximately 800 pounds of 304 and 2000 pounds of 440C) and smaller quantities of other materials were also Rheocast including M2 tool steel, and HS 31 Cobalt base superalloy.

Improvements in details and automation of the Thixocasting process were also made during this period. Work subsequently concentrated on casting large quantities of stainless steel into various die materials in order to determine die life and to optimize that die life.

Trials previously reported on H-13 dies were completed and similar work then conducted on H-21 dies. This latter die material showed significant improvement in performance over H-13. Also dramatic improved performance was found by using copper dies and dies of copper-chromium and copper-chromium-zirconium alloy. Special die quenching methods were employed to lengthen die life. In the Cu-Cr-Zr die, over six hundred shots of a casting were made no mold cracking and only slight parting line erosion.

Computer and experimental study of heat flow in Thixocasting continued to aid in optimizing die life. Significant differences have been found depending on metal, die material, fraction solid, and mold treatment. Specifically, results show that copper dies heat to a much less extent and much less rapidly than do steel dies when metal is cast.

Detailed studies have been made on the structure of Rheocastings and Thixocasting, including solidification structure, and oxide inclusions. These have been related to operating variables of the continuous Rheocasting unit.

Army Materials and Mechanics Research Center,
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MACHINE CASTING OF FERROUS ALLOYS
M. C. Flemings, K. P. Young, J. F. Boylan,
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Trials previously reported on H-13 dies were completed and similar work then conducted on H-21 dies. This latter die material showed significant improvement in performance over H-13. Also dramatic improved performance was found by using copper dies and dies of copper-chromium and copper-chromium-zirconium alloy. Special die quenching methods were employed to lengthen die life. In the Cu-Cr-Zr die, over six hundred shots of a casting were made no mold cracking and only slight parting line erosion.

Computer and experimental study of heat flow in Thixocasting continued to aid in optimizing die life. Significant differences have been found depending on metal, die material, fraction solid, and mold treatment. Specifically, results show that copper dies heat to a much less extent and much less rapidly than do steel dies when metal is cast.

Detailed studies have been made on the structure of Rheocastings and Thixocasting, including solidification structure, and oxide inclusions. These have been related to operating variables of the continuous Rheocasting unit.

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MACHINE CASTING OF FERROUS ALLOYS
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