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MACHINE CASTING OF FERROUS ALLOYS

November 1976

by M.C. Flemings, K.P. Young, R.G. Riek, J.F. Boylan, R.L. Bye

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Interim Technical Report

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ABSTRACT

This is the fifth interim 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 thirty-sixth to the forty-second month of this four-year program.

The basic system for Thixocasting ferrous alloys is fully and reliably operational. The Continuous Rheocaster works dependably in production runs in which typically up to 500 pounds of steel is produced at a rate of about 80 pounds per hour. Much longer runs could be produced if desired.

The Thixocast reheating process is completely automated. The two stage heating cycle employed delivers steel charges suitable for Thixocasting with a maximum temperature variation in the charge of $\pm 3^{o}C$. Work has been primary on 304 and 440C stainless steel.

Emphasis during this period has been on the production of a large amount of Rheocast stainless steel and the initiation of large scale Thixocasting runs to test actual die life. More than 3000 pounds of Rheocast stainless steel have been produced to date. Five hundred stainless steel Thixocastings have been produced in a hardened H-13 steel die with die life superior to results reported for H-13 dies used for liquid cast steel. The castings produced showed consistently good internal soundness. This Thixocasting work has been primarily on 304 stainless steel; additional work is planned on 440C.

Mechanical property evaluation of Thixocast 304 stainless steel indicates it possesses strength superior to the conventionally cast alloy with somewhat less ductility.

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,[1-4] 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[1-4] summarize the program through the first three years of activity (period ending December 31, 1975). At that point in the program the major thrust of effort had been on the development of a pilot plant scale system for Thixocasting ferrous alloys. This report summarizes the 6 month period January 1, to June 30, 1976 in which the system has been operated in essentially final form, and the emphasis has been placed on (1) the preparation of a large amount of Rheocast steel for large scale Thixocasting runs to test actual die life in a variety of die materials, and (2) the initiation of those runs. The first such die study run has been completed in this period with encouraging results, both in terms of die life and casting quality.

Work has also continued during this period on the development of new forming processes utilizing a modified version of the Pb-Sn model alloy Continuous Rheocaster. Also, experimental and theoretical analysis of heat transfer in die casting is continuing.

Continuous Rheocaster

During this report period, the design of the Continuous Rheocaster for stainless steel production has been finalized. In total more than 3000 pounds of stainless steel have been produced together with smaller quantities of other alloys in runs of up to 500 pounds. Total production is detailed in Table 1.

A larger crucible size has been implemented. It is essentially similar to the previous design except that the upper chamber ferrous alloy capacity has been increased from 17 pounds to 40 pounds. A schematic of the larger furnace is shown in Figure 1. A high density alumina sheath has been incorporated outside the agitation zone to improve heat extraction efficiency. With this design the maximum AISI 304 stainless steel slurry output rate is about 300 pounds hour^{-1} at about 0.5 volume fraction solid. In actual operation such high output is limited by the capacity of the upper reservoir chamber to intermittent bursts of about 40 pounds. During normal operation output and melting rate are balanced to give continuous uninterrupted production at a rate of about 80 pounds hour^{-1}. Typical runs now produce from 250 to 500 pounds. Furnace life is usually limited to 2 runs, but could be much greater. At the present time furnace life is dictated by failure of the internal alumina nozzle which has been traced to flaws in the as-received pieces. Erosion of the ceramics at nozzle failure is otherwise slight. Slag attack on the alumina components in the area of the slurry output nozzle has been eliminated by the incorporation of an Argon-4% Hydrogen protective gas shroud as shown in Figure 1.

Control of the Continuous Rheocaster is now almost exclusively by monitoring the amperage needed to drive the rotor in the agitation zone at constant speed. Thermocouples in the reservoir and stirring rotor remain for start up purposes but, save for monitoring reservoir chamber superheat, are not utilized in production. Continuous output of slurry of essentially constant fraction solid is achieved simply by regulating flow rate to stabilize the rotor drive amperage indication.

Considerable effort has also been developed to characterization of Continuously Rheocast AISI 304 stainless steel. A typical water quenched microstructure is shown in Figure 2. This shows the duplex structure of the primary solid particles consisting of δ ferrite partially transformed by peritectic reaction to austenite. The solute segregation throughout the microstructure of water quenched samples of the 304 stainless steel slurries has been determined by microprobe analysis. Figure 3 shows the typical measured variation in Fe, Cr, Ni, and Mn across a primary solid particle. The effect of heat treatment on the microsegregation in these structures is being investigated.

A program is also underway to characterize the inclusions found in Rheocast stainless steel.

Thixocasting

During this report period, the Thixocasting process for die casting partially solidified slurries of high temperature alloys has been radically improved by the introduction of a fully automatic reheat station (Figure 4). The new system incorporates a fully insulated induction furnace which has improved coil design to minimize end losses. This is coupled to a redesigned Softness Indicator[4], which shuts off power to the induction coil and ejects the charge from the furnace when it has reached the desired casting condition (typically .45 to .55 fraction solid). The Softness Indicator now utilizes an adjustable air cylinder drive, while the actual probe has been changed to 1/8 inch diameter, flat bottom alumina rod which performs better at the higher operating temperatures experienced during the reheating of stainless steels. This system has the capacity for two stage heating, the initial stage being a high heating rate (typical 40 KW) step to quickly bring the charge up the alloy solidus temperature, while the second step reduces the heat input to a predetermined level which minimizes any temperature gradients through the ingot during final heating. This procedure has been refined to permit heating of 304 stainless steel charges to the liquid-solid region with a maximum measured temperature variation in the charge of $\pm 3^{\circ}C$. The resulting reheat cycles for both 440C and 304 stainless steel have been reduced to approximately ninety seconds. Further reductions could of course be effected with relatively simple, but time consuming modifications.

Die life studies for Thixocast stainless steel has continued through this report period using a variety of die materials. Identical die inserts for the casting of the MI6 rifle hammer have been machined in H-13 and H-21 die steels and hardened according to recommended industrial practices. To date, over 500 shots have been made into one set of hardened H-13 inserts operated at 275°C. No welding has been experienced, and die failure has been limited to fatigue cracking at localized hot spots on the die surface. A history of part finish is shown in Figure 5. This is a significant improvement over previously reported works on H-13 die life for casting steels[5,6].

These parts were cast at about 0.5 volume fraction solid and a sample of 291 castings were rated radiographically for internal soundness according to a previously adopted scale[3]. The results are shown in Figure 6 and because of the excellent internal soundness of the majority of the castings a new, stricter standard was adopted as illustrated in Figure 7. The histogram of Figure 8 shows the radiographic rating of the same sample of 291 castings according to this new scale.

Approximately 100 shots of Thixocast stainless steel have been made under the same conditions into the identical shape in H-21 die inserts. While results are still not complete at this time, the trend shows a marked improvement in die life for H-21 over that of H-13.

In addition to die life studies, work investigating the mechanical properties of Thixocast parts has been conducted[7]. Tensile specimens were die cast in performed shapes under identical conditions, machined to final shape and tested. As Table II indicates, typical results for Thixocast 304 stainless steel show a significant improvement in strength over the conventionally cast alloy, with somewhat less ductility.

As part of some complimentary research done in the area of formability and mechanical property evaluation of Rheocast 304 stainless steel, ITT Harper Company has tested the mechanical properties of Rheocast ingots subsequently extruded[8].

Rheocast ingots, supplied by M.I.T. were hydrostatically extruded (at 900-950^{o}C, extrusion ratio 4.6:1), machined and tensile tested. The results, as shown in Figure 9, indicate that the tensile properties of extruded Rheocast 304 stainless steel are at least equivalent to extruded wrought material and superior to conventionally cold worked 304 stainless steel.

Summary Conclusions

1. The design of the Continuous Rheocaster has been finalized. It has produced stainless steel slurries at a continuous production rate of 80 pounds hour^{-1} in runs as large as 500 pounds.
2. More than 3000 pounds of Rheocast stainless steel ingots have been produced, most of which will be used for large scale Thixocasting runs to study actual die life.
3. The reheating system for Thixocasting has been completely automated. Charges of stainless steel can be reheated for Thixocasting in 90 seconds with a maximum temperature variation within the charge of $\pm 3^{0}$C. Casting rate for stainless steel is 40 shots hour^{-1} in the Thixocasting system.
4. A die life study in which 500 304 stainless steel Thixocastings have been made in a hardened H-13 die steel die indicates die life superior to that reported for H-13 dies when used for liquid cast steel. The castings from this study show consistently good internal soundness.
5. Initial mechanical property evaluation indicates that Thixocast 304 stainless steel is superior in strength to the conventionally cast alloy, with somewhat less ductility. In limited testing Extruded Rheocast 304 stainless steel possessed mechanical properties at least equivalent to those obtained for extruded wrought 304 stainless steel.

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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 AMMRC, Watertown, Mass.

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6. A. B. Draper, E. E. Klans, J. H. Hoke, J. M. Samuels, G. Scholl, "Casting Ferrous Metals into Refractory Metal Dies," Final Report to The Pennsylvania Science and Engineering Foundation, August 1975.

7. F. E. Goodwin, "Structure and Properties of Thixocast High Temperature Alloys," S.M. Thesis, M.I.T., September 1976.

8. H. L. Andrews, J. S. Orlando, I.T.T. Harper Inc., Research and Development Case Report No. RD-7304-2.

TABLE I

TOTAL PRODUCTION OF CONTINUOUSLY RHEOCAST ALLOYS

Alloy	Pounds Produced
Copper Alloy 905	1050
AISI 440 C Stainless Steel	1080
AISI 304 Stainless Steel	1950
H.S. 31 Cobalt Base Superalloy	250

TABLE II

INITIAL MECHANICAL PROPERTY EVALUATION OF THIXOCAST 304 STAINLESS STEEL AT M.I.T.

	Ultimate Tensile Strength psi	0.2% Offset (Yield) Stress psi	% Elongation at Rupture
Typical Thixocast	91,000	41,000	25
Typical Investment Cast	70-80,000	35-40,000	30-40

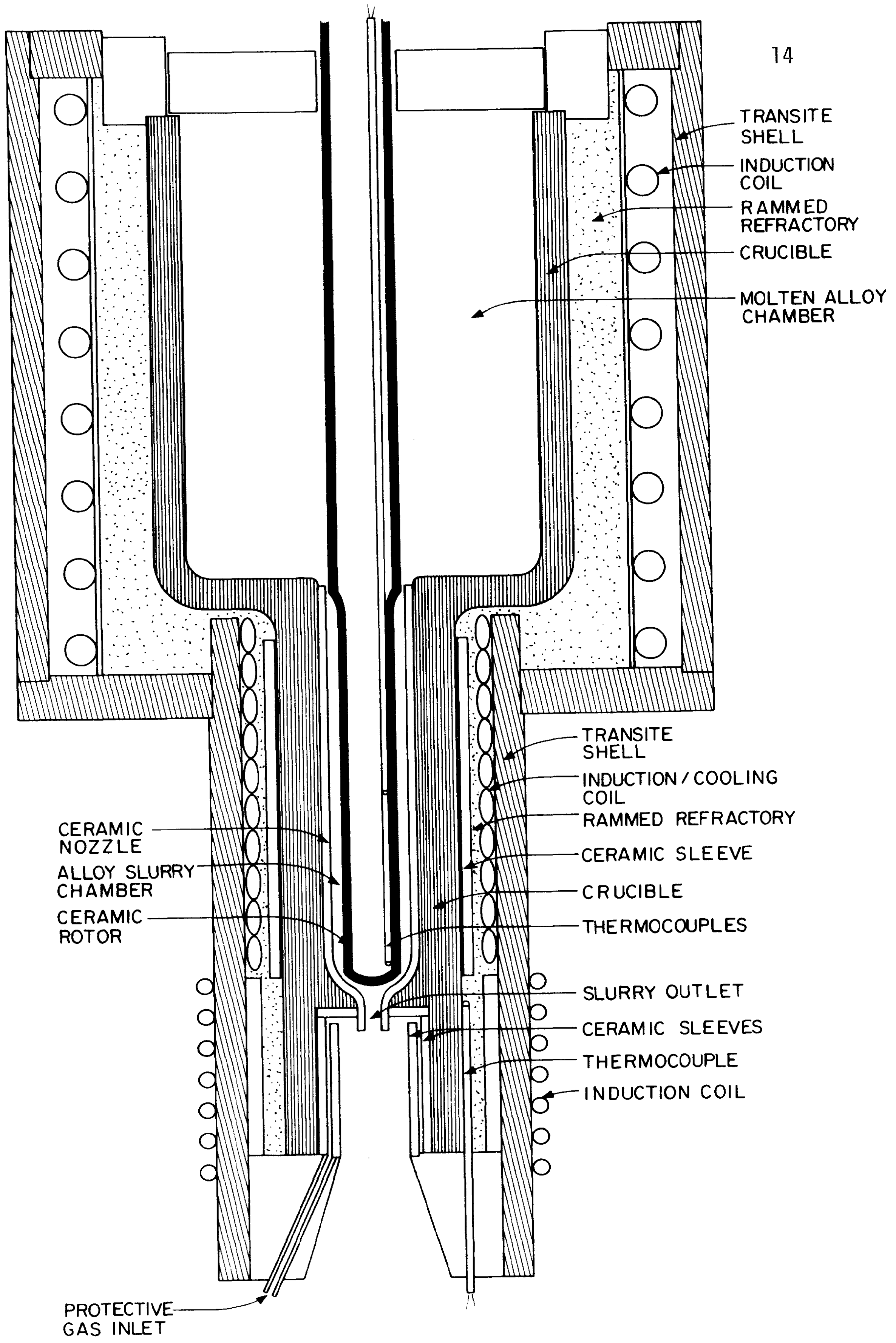
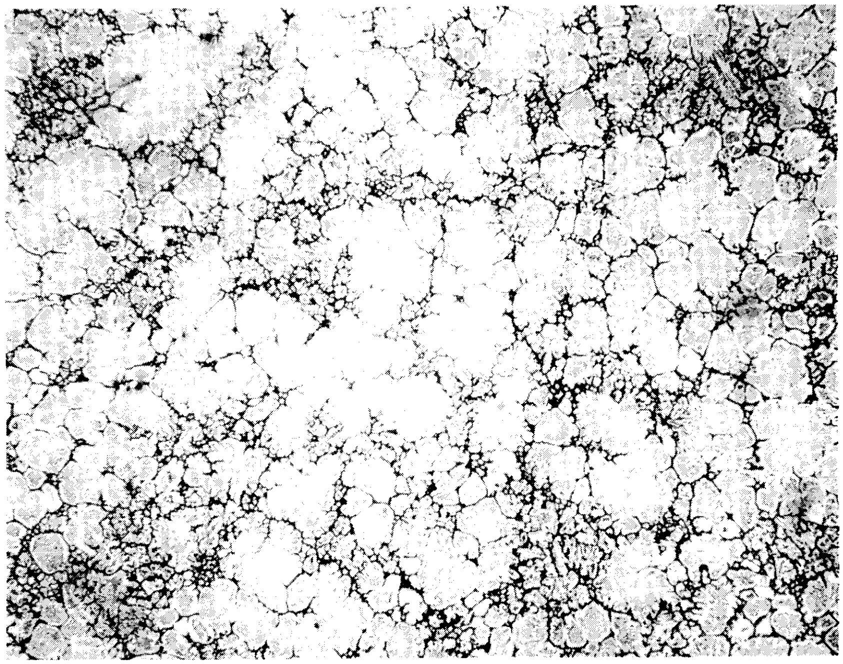
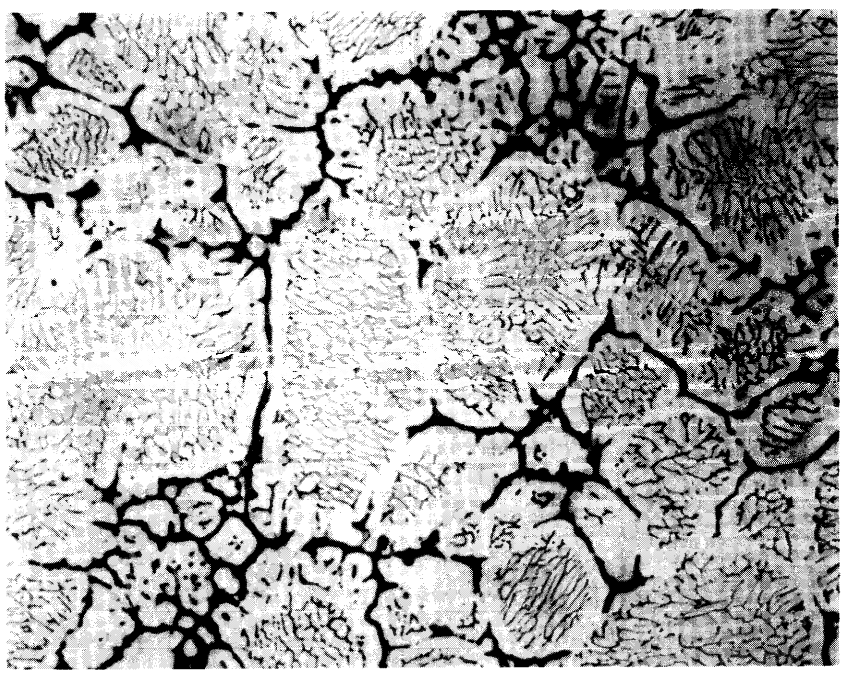


Figure 1: Schematic cross section of the Continuous Rheocasting furnace which has an upper chamber steel capacity of 40 pounds. Overall furnace height is 20-1/2 inches.



(a)



(b)

Figure 2: Photomicrographs of Continuously Rheocast AISI 304 stainless steel. KOH electrolytic etch. (a) 50X; (b) 200X.

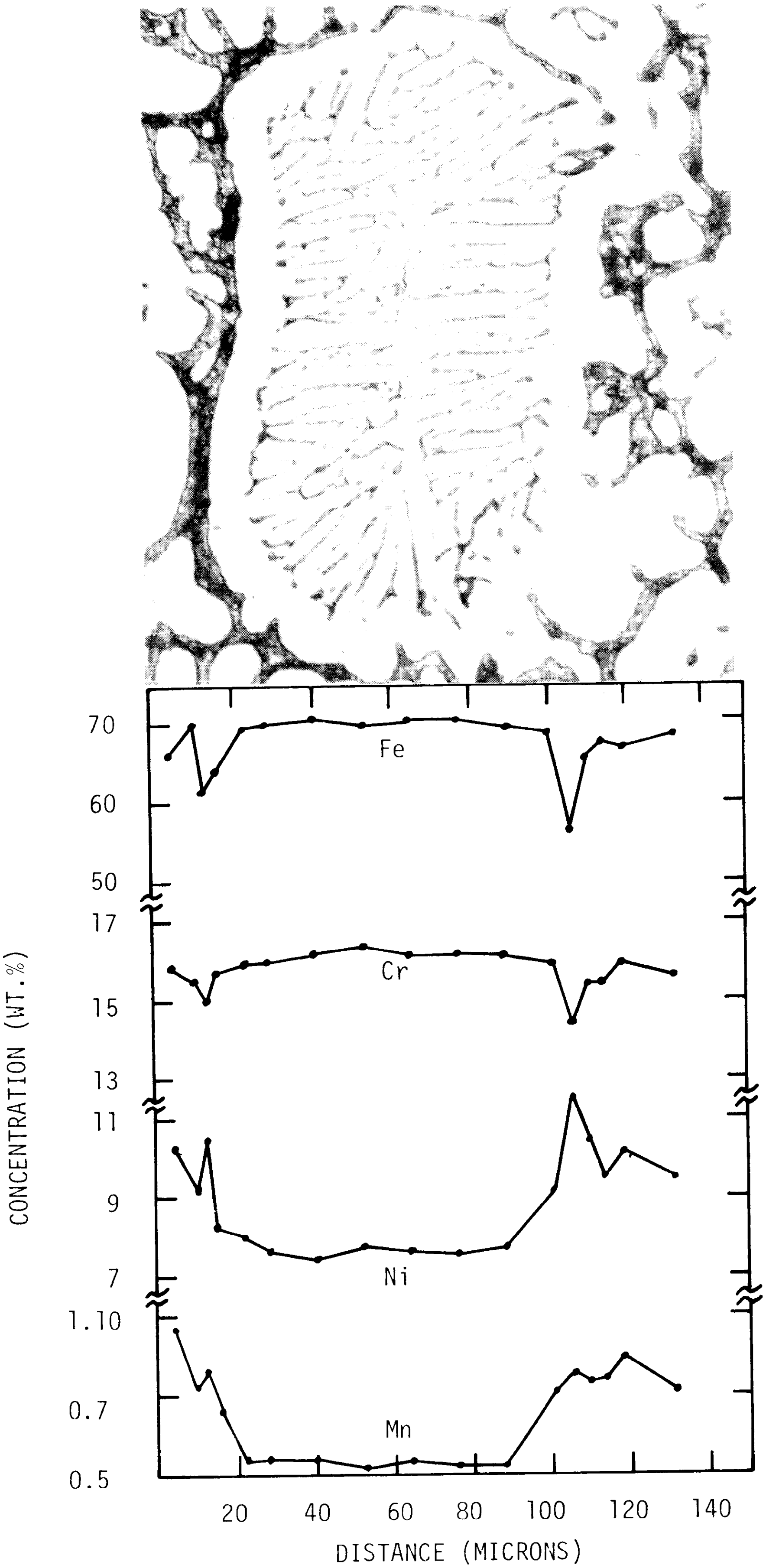


Figure 3: Microprobe data showing typical composition variations in AISI 304 stainless steel slurry. Sample was direct water quenched on removal from the Continuous Rheocaster.

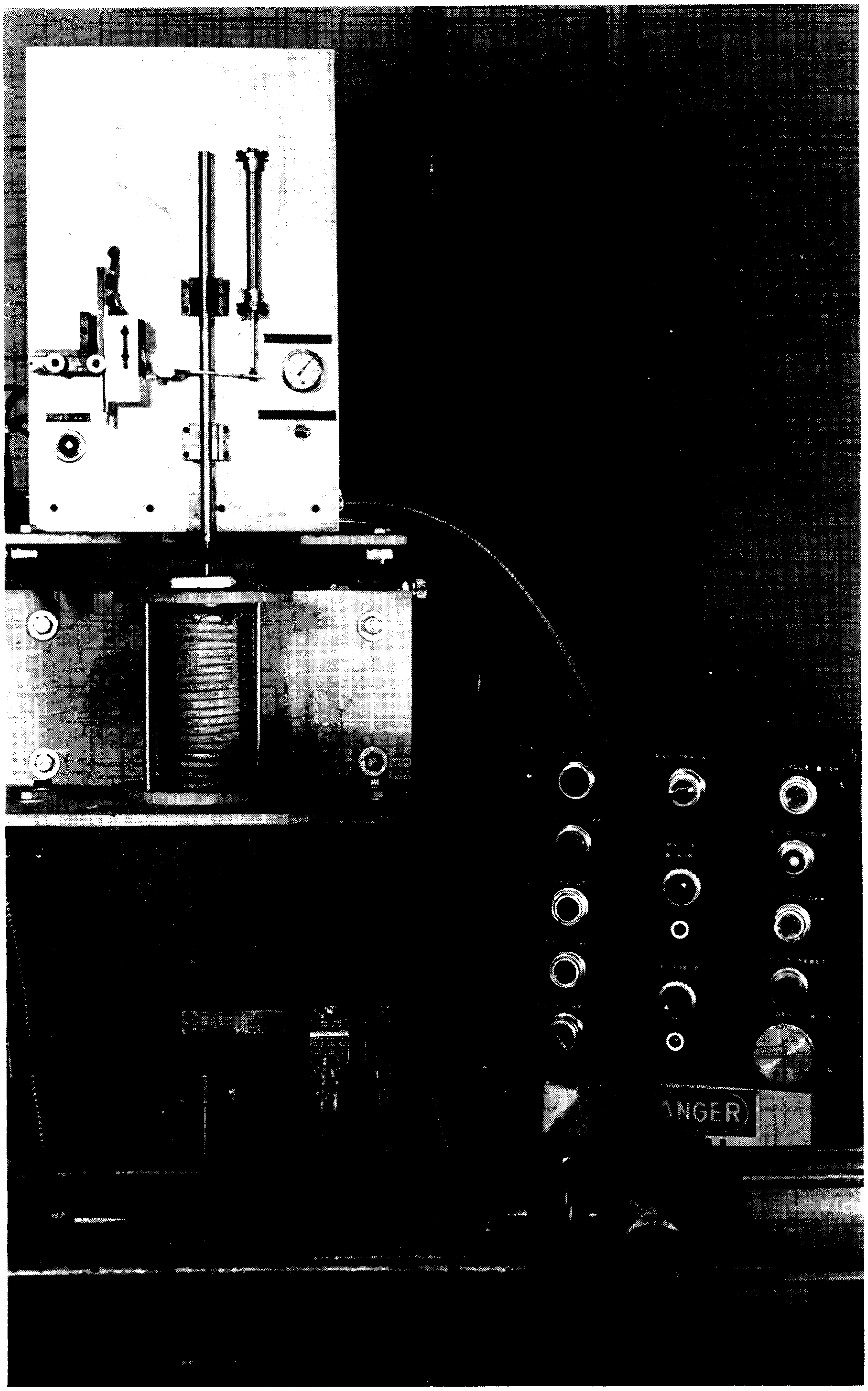
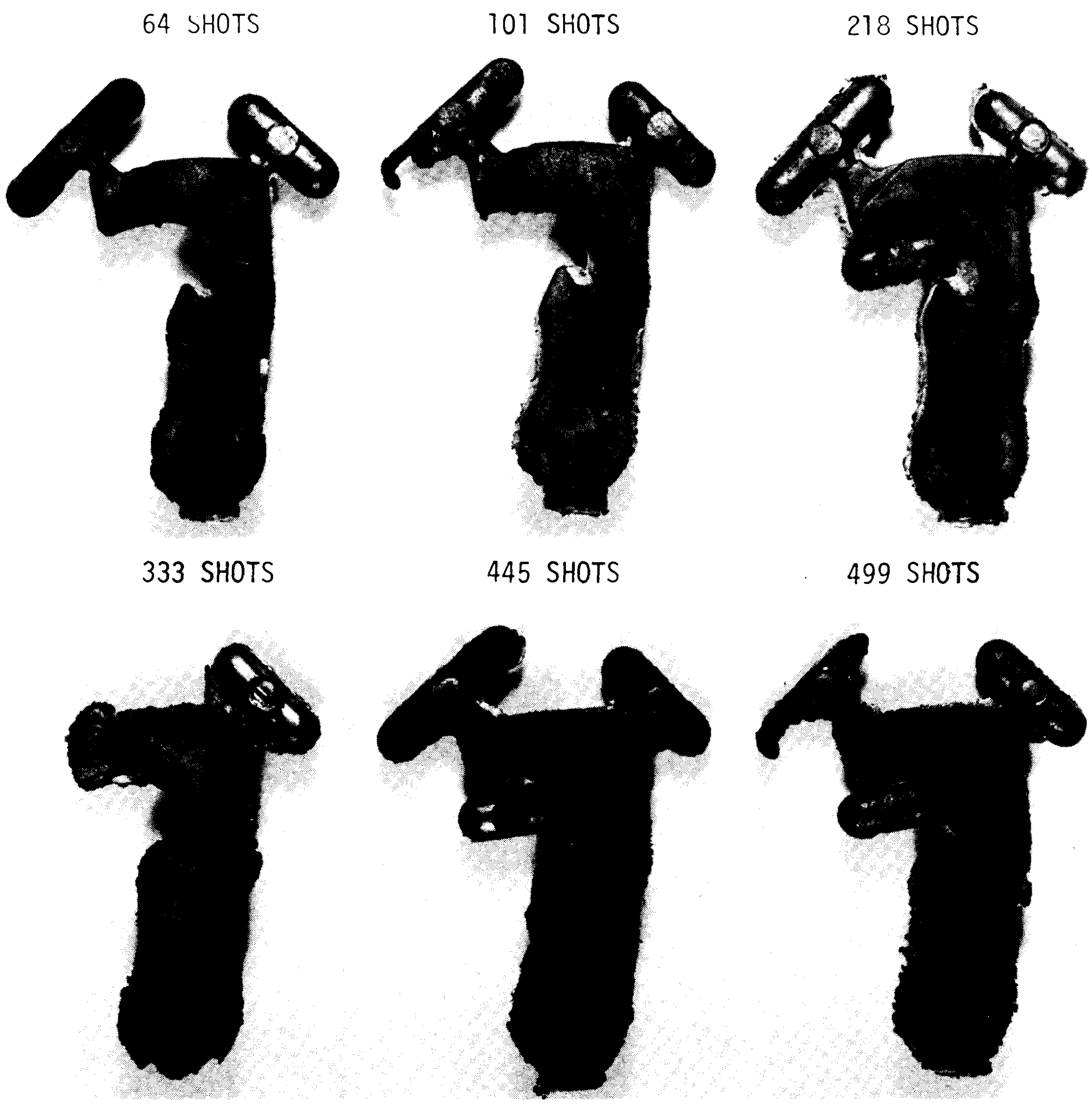


Figure 4: Overall view of the automated Thixocast reheating station.



THIXOCASTINGS OF M16 RIFLE HAMMER 304 STAINLESS/ H13 DIE STEEL

Figure 5: Sequence of 304 stainless steel Thixocastings produced at various intervals in the 500 shot die study run in H-13 die steel. 1X.

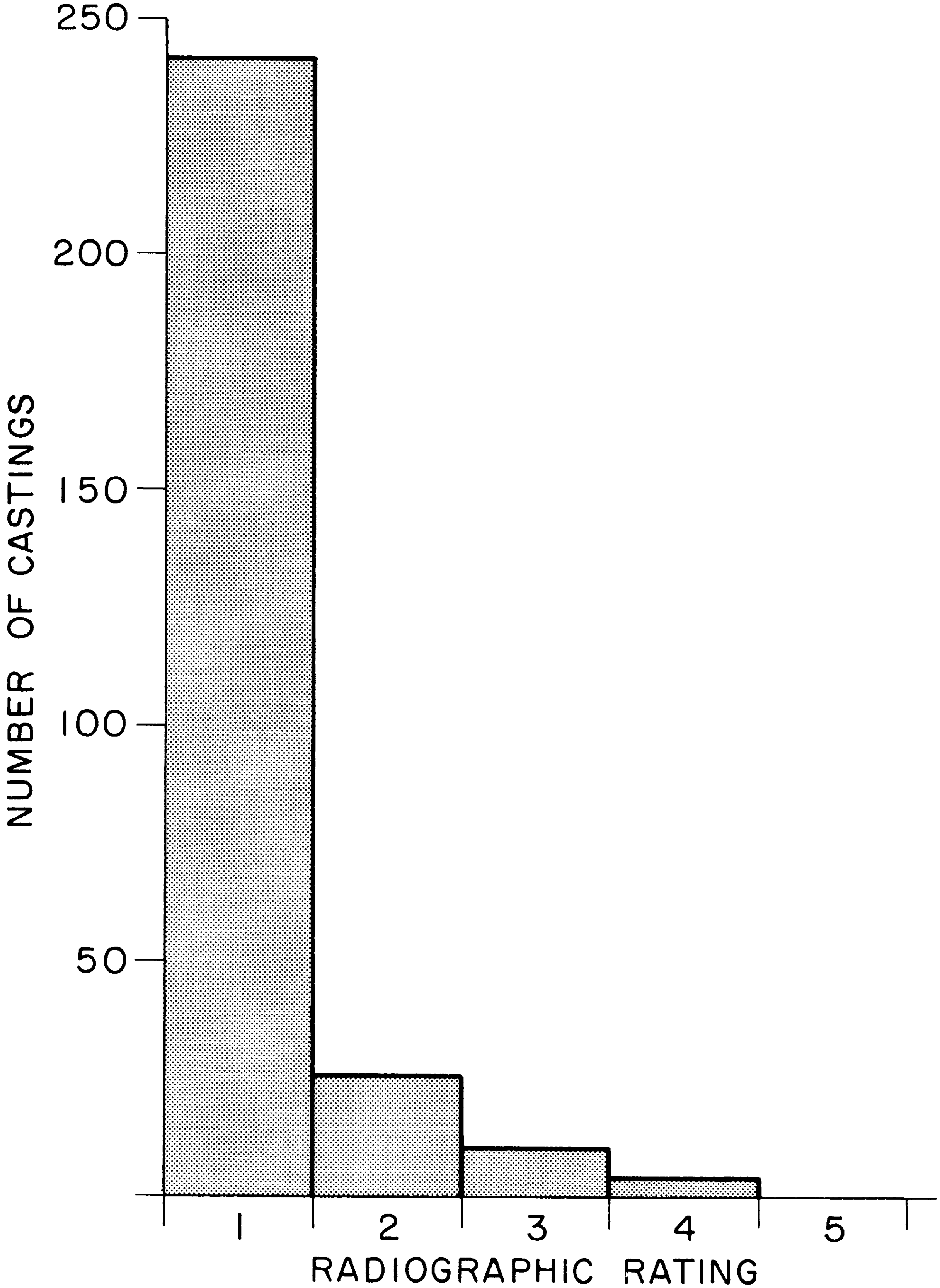
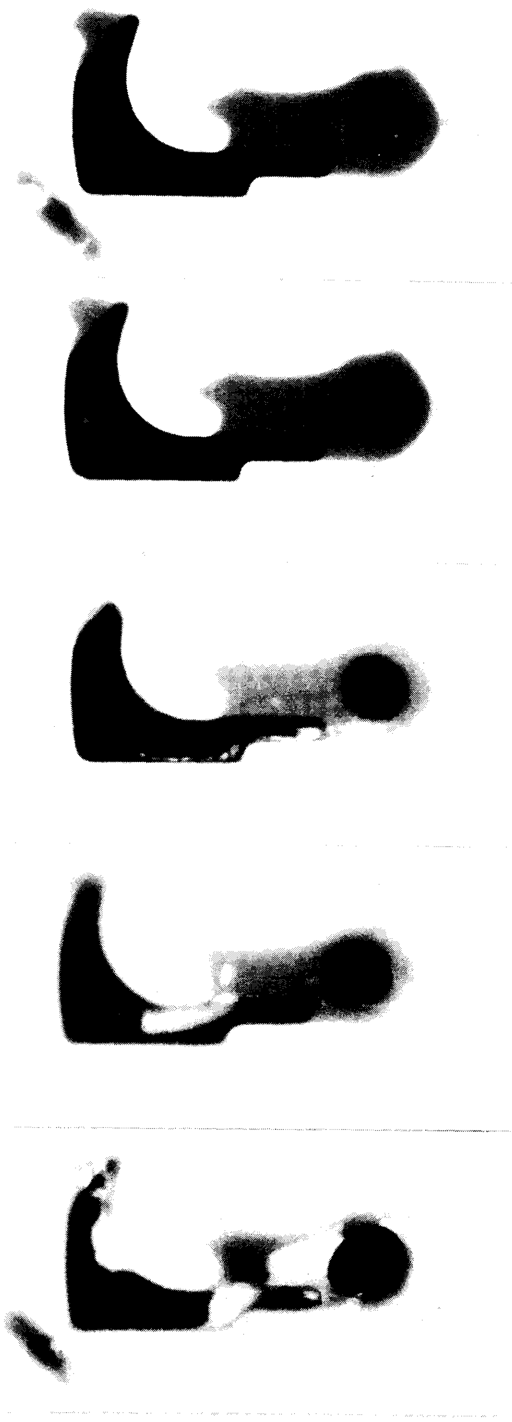


Figure 6: Distribution of radiographic ratings according to a previously adopted scale[3] in a sample of 290 Thixocastings of 304 stainless steel. Castings were made at 0.5 volume fraction solid into a hardened H-13 steel die.



Rating 1

Rating 2

Rating 3

Rating 4

Rating 5

Figure 7: Examples of revised radiographic rating system.

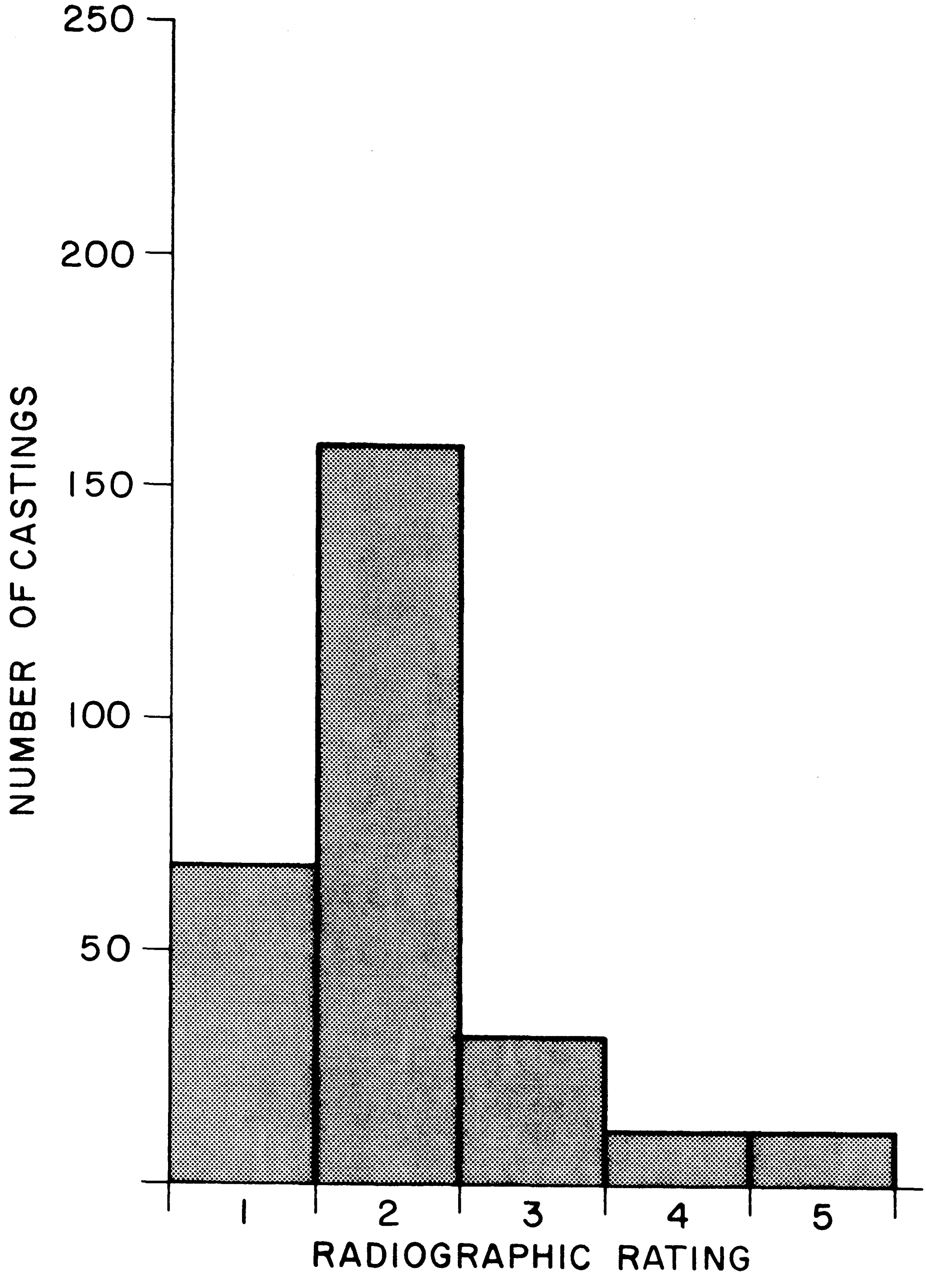


Figure 8: Distribution of radiographic ratings of the 291 Thixocastings of 304 stainless steel from Figure 6 according to the revised scale of Figure 7.

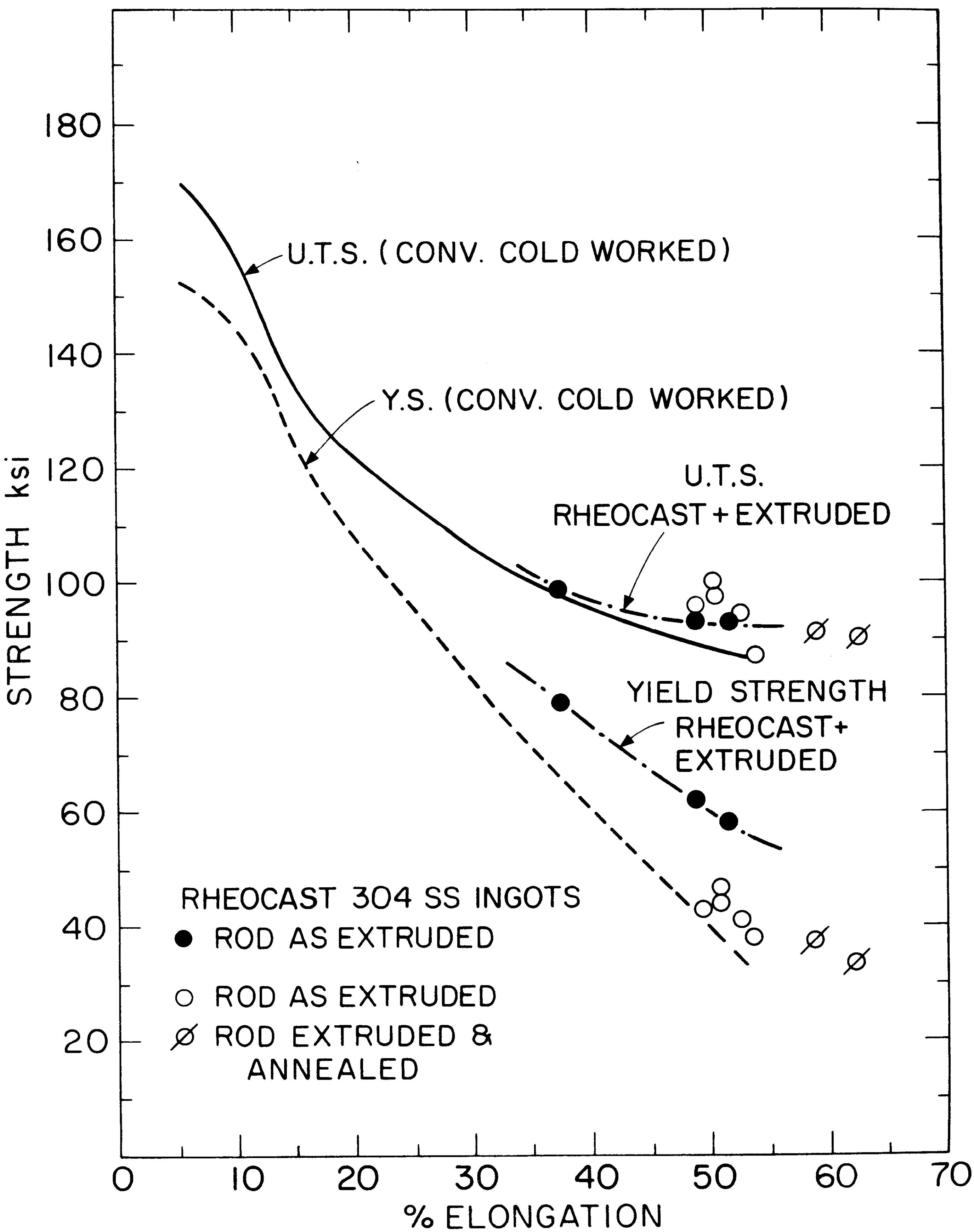


Figure 9: Mechanical properties of hydrostatically extruded Rheocast 304 stainless steel compared with the conventionally cold worked material and hydrostatically extruded wrought 304 stainless steel (open circles).

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Rheocasting
Thixocasting

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This is the fifth interim 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 thirty-sixth to the forty-second month of this four-year program.

The basic system for Thixocasting ferrous alloys is fully and reliably

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered) operational. The Continuous Rheocaster works dependably in production runs in which typically up to 500 pounds of steel is produced at a rate of about 80 pounds per hour. Much longer runs could be produced if desired.

The Thixocast reheating process is completely automated. The two stage heating cycle employed delivers steel charges suitable for Thixocasting with a maximum temperature variation in the charge of $\pm 3^{o}C$. Work has been primarily on 304 and 440C stainless steel.

Emphasis during this period has been on the production of a large amount of Rheocast stainless steel and the initiation of large scale Thixocasting runs to test actual die life. More than 3000 pounds of Rheocast stainless steel have been produced to date. Five hundred stainless steel Thixocastings have been produced in a hardened H-13 steel die with die life superior to results reported for H-13 dies used for liquid cast steel. The castings produced showed consistently good internal soundness. This Thixocasting work has been primarily on 304 stainless steel; additional work is planned on 440C.

Mechanical property evaluation of Thixocast 304 stainless steel indicates it possesses strength superior to the conventionally cast alloy with somewhat less ductility.