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# Characterization of Modified 9 Cr-1 Mo Steel Sand Castings

V. K. Sikka

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METALS AND CERAMICS DIVISION

# CHARACTERIZATION OF MODIFIED 9 Cr-1 Mo STEEL SAND CASTINGS

V. K. Sikka

NOTICE: This document contains information of a preliminary nature. It is subject to revision or correction and therefore does not represent a final report.

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# CHARACTERIZATION OF MODIFIED 9 Cr-1 Mo STEEL SAND CASTINGS*

V. K. Sikka

## ABSTRACT

Experience with the sand casting of modified 9 Cr-1 Mo steel at several foundries is presented. The castings included simple blocks, elbows, valve bodies, and a steam chest. Castings were characterized by tensile and Charpy impact tests, for the effects of thermal aging on Charpy impact properties and hardness, and by creep, fatigue, and microstructure. Properties of the castings were compared with those observed for wrought material. In general, mechanical properties of castings were slightly lower than those of the wrought material.

## INTRODUCTION

A modified 9 Cr-1 Mo alloy with high-temperature strength exceeding that of type 304 stainless steel up to 600°C has been developed by ORNL in conjunction with Combustion Engineering, Chattanooga, Tennessee (see Table 1 for specifications). The alloy has been melted and fabricated into wrought products both in the United States and abroad. The alloy specifications for the tubing and plate have been approved in the ASTM, and Code Case 1943 for the use of this alloy in Section I of ASME Code has been approved and published.

Although a significant amount of research and development has been done on the wrought products, the sand castings and their properties have not been studied extensively. The purpose of this section is to present the casting experience with this alloy and the mechanical properties of the sand castings.

*Work performed under DOE/BTP AF 15 40 10 3, Task OR-1.7, Advanced Alloy Technology.

## CASTING EXPERIENCE

The very first casting of the modified 9 Cr-1 Mo alloy was a valve body cast at Quaker Foundry during November 1978 (Fig. 1). The casting was about 70 mm thick, it weighed nearly a ton and was free of any defects. The casting's chemical analysis is given in Table 1. Its nitrogen content was below the specified range. The Quaker casting was subjected to tensile, Charpy impact, and creep testing.

The next set of castings was made at Atlas Foundry and Machine Company. This company melted three AOD heats of modified 9 Cr-1 Mo steel for sand casting into a steam chest and two elbows. The steam chest was from a pattern supplied by Transamerican Delaval, Inc., and the elbow dimensions were specified by Babcock and Wilcox. The chemical analyses of the three heats melted by Atlas are listed in Table 1. The heat used for the steam

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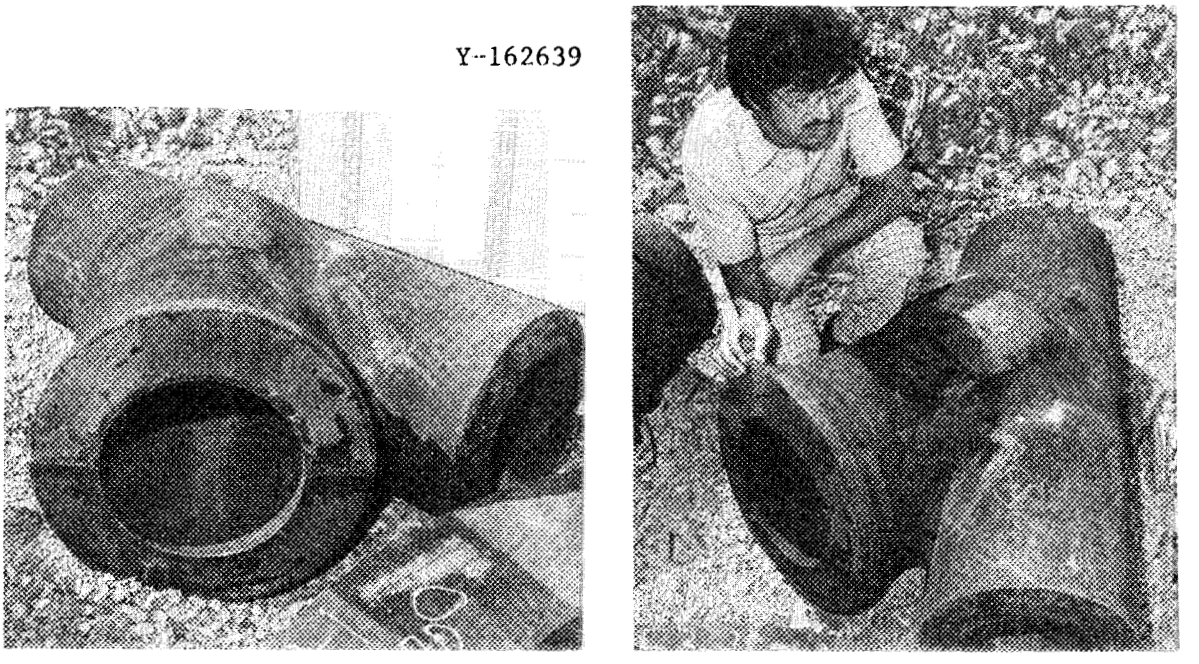

(*a*) (*b*)

Fig. 1. Valve body cast from the modified 9 Cr-1 Mo steel (Quaker heat F5349). (*a*) Front. (*b*) Top.

Table 1. Chemical analyses of commercial heats tested for producing modified 9 Cr-1 Mo steel sand castings

| Element | Specified | Vendor analysis (wt %) | | | | |
|---|---|---|---|---|---|---|
| | | Atlas Foundry | | | Quaker Foundry, valve (heat F5349V) | IHI, Japan, cast blocks (heat 1279) |
| | | Steam chest (heat 450682) | Elbow 1 (heat 452282) | Elbow 2 (heat 456582) | | |
| Carbon | 0.08–0.12 | 0.094 | 0.145[a] | 0.119 | 0.10 | 0.12 |
| Manganese | 0.30–0.60 | 0.43 | 0.48 | 0.42 | 0.39 | 0.51 |
| Phosphorus | 0.020 maximum | 0.014 | 0.013 | 0.006 | 0.007 | 0.016 |
| Sulfur | 0.010 maximum | 0.004 | 0.018[a] | <0.001 | 0.015 | 0.006 |
| Silicon | 0.20–0.50 | 0.35 | 0.40 | 0.46 | 0.35 | 0.36 |
| Chromium | 8.00–9.50 | 8.81 | 9.41 | 8.77 | 8.80 | 9.06 |
| Molybdenum | 0.85–1.05 | 0.92 | 1.02 | 0.98 | 0.94 | 0.93 |
| Nickel | 0.40 maximum | 0.20 | 0.32[b] | 0.21 | 0.10 | |
| Vanadium | 0.18–0.25 | 0.212 | 0.239 | 0.212 | 0.205 | 0.22 |
| Niobium | 0.06–0.10 | 0.074 | 0.087 | 0.073 | 0.060 | 0.10 |
| Nitrogen | 0.03–0.07 | 0.009[a] | 0.032 | 0.032 | 0.011 | 0.03 |
| Aluminum | 0.04 maximum | 0.001 | 0.056[a] | 0.030 | <0.001 | 0.011 |

[a]Outside the specified range.

[b]Amounts higher than desired with the melting technique used but still within the specified range.

chest was within the specified range except for nitrogen. The heat (452282) used for the first elbow casting was out of the specified range for C, Ni, and Al. Atlas melted an additional heat (456582) which was within chemical specification and produced a second elbow casting.

Two different views of the steam chest are shown in Fig. 2. This casting is very complex, with some very thick sections and holes. The maximum thickness in the casting was 203 mm. To provide experience in repair welding, an area between two holes was removed and welded as shown in Fig. 3. The vendor-supplied tensile properties of the steam chest exceeded the room-temperature specified properties for this alloy in the wrought condition. The vendor also reported a room-temperature Charpy impact energy for this casting of 97 J (71 ft-lb). Tensile, Charpy impact, and creep tests conducted on this casting at ORNL are reported in a later section.

The elbows from the two heats are shown in Figs. 4 and 5. They had an outer diameter of 572 mm and an inner diameter of 419 mm. The vendor-supplied tensile properties of both elbows exceeded the minimum specified values for the wrought modified alloy. Elbow 1 was not tested because its composition was out of the specified range. Elbow 2 was subjected to tensile and creep tests to be reported later.

Several observations from the sand-casting exercise at Atlas are listed below.

1. Atlas can make the modified 9 Cr-1 Mo heats within the specifications.

2. Complex shapes can be sand cast from this alloy.

3. Fine porosity was observed near the surface of the sand castings. This porosity appeared to be related to the nitrogen content of the material. Lowering the nitrogen content to below 0.01% minimized the porosity. The Quaker casting, which had a nitrogen content of 0.011%, showed no porosity. The Japanese casting experience, to be described below, showed no porosity problems, even with 0.03% N. From this experience, we recommend that additional castings be made at Atlas to confirm the nitrogen effect on porosity.

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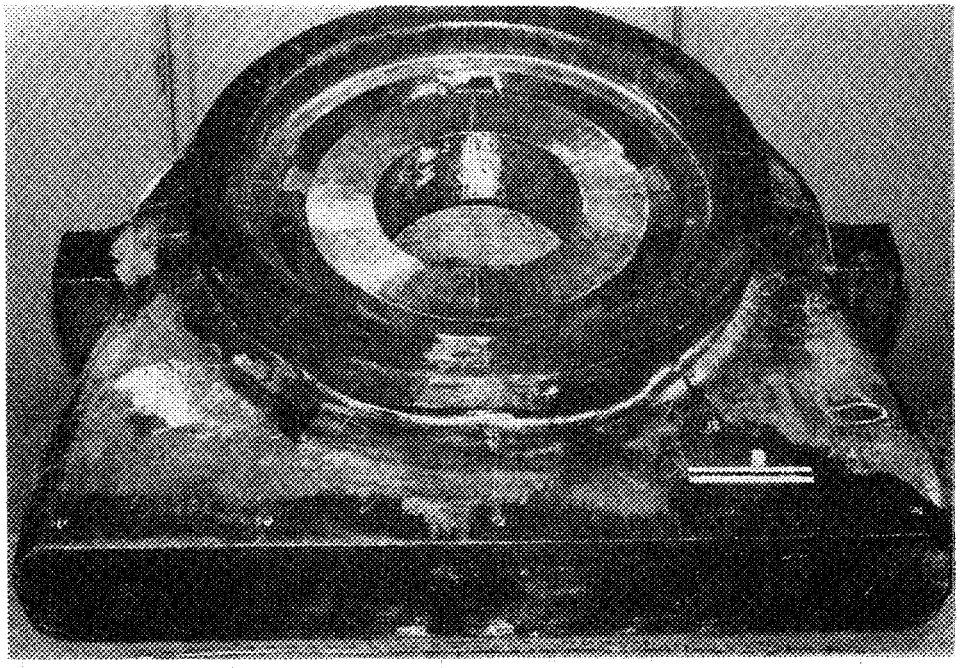

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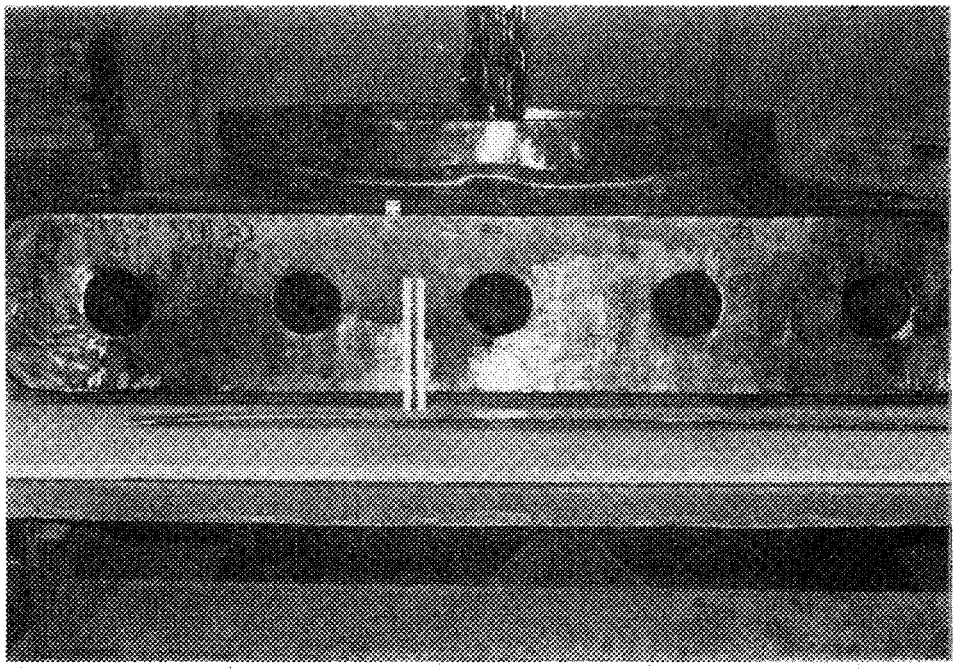

100 mm

Fig. 2. Two views of a steam chest of modified 9 Cr-1 Mo steel sand cast by Atlas Foundry and Machine Company.

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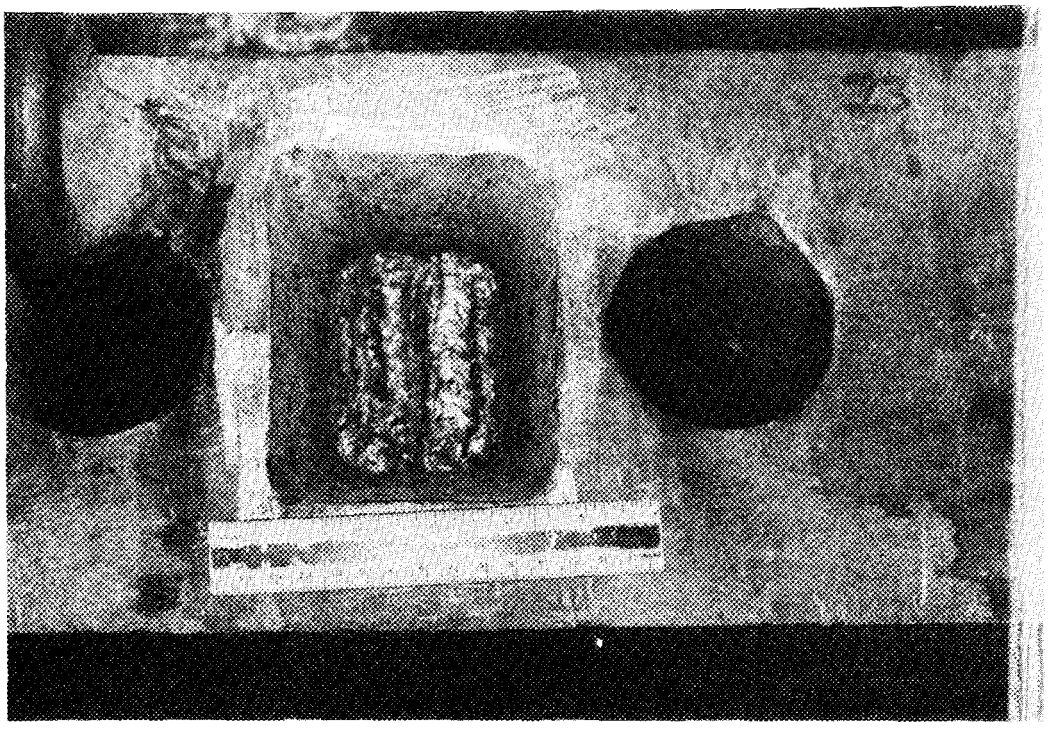

50 mm

Fig. 3. Weld-repaired section in the sand-cast steam chest of modified 9 Cr-1 Mo steel.

The Ishikawajima-Harima Heavy Industries Co., Limited (IHI) of Japan has been very interested in sand-cast components of modified 9 Cr-1 Mo steel. They recently sand cast blocks and a full-size gate valve of this material. The blocks are shown in Fig. 6 and the valve body in Fig. 7. The chemical analyses of the heat used in making these castings fully met the specified chemistry (Table 1). The dye penetrant results showed that the valve body casting (152-mm inside bore diameter) was free of any macroscopic porosity. The IHI is conducting a detailed mechanical property characterization program on these castings. At ORNL, we have conducted tensile and Charpy impact tests on the IHI sand-cast blocks. The results of these tests are presented below. Some of the results from the IHI test program are also included.

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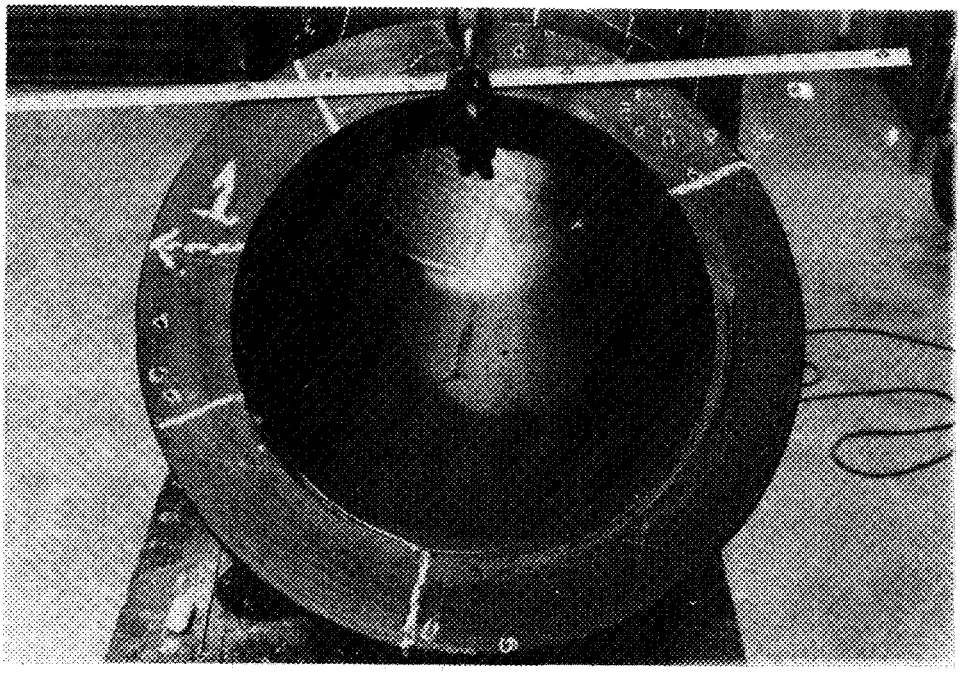

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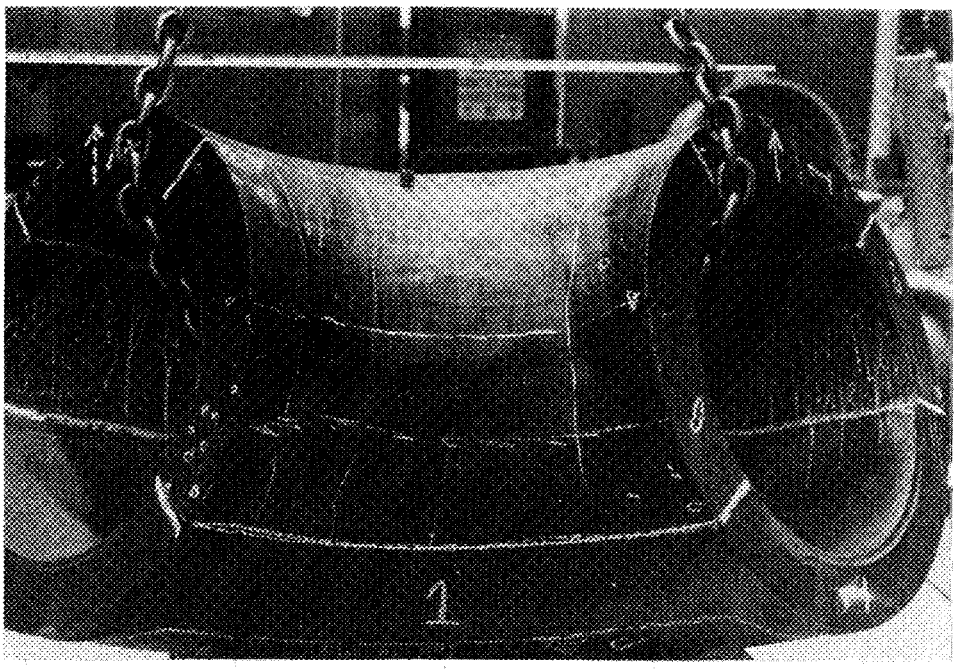

100 mm

Fig. 4. Elbow of modified 9 Cr-1 Mo steel from heat 452282 by Atlas Foundry and Machine Company.

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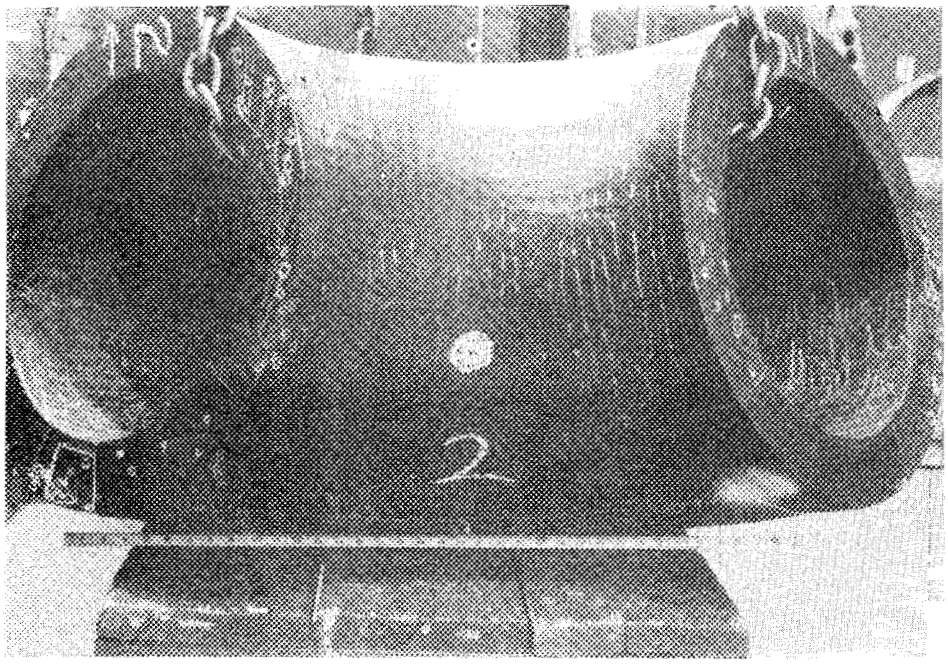


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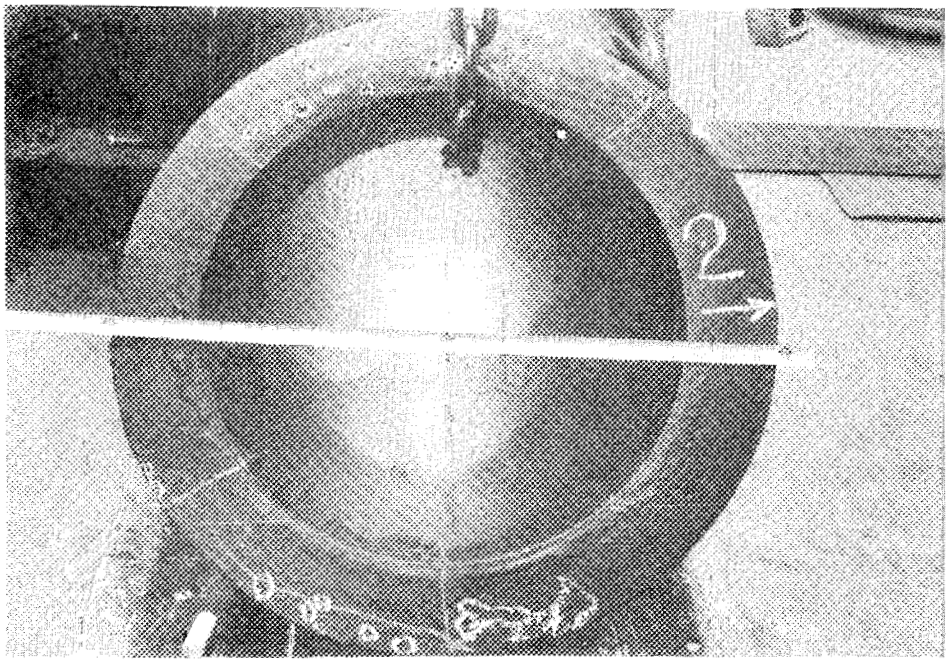


100 mm

Fig. 5. Elbow of modified 9 Cr-1 Mo steel from heat 456582 by Atlas Foundry and Machine Company.

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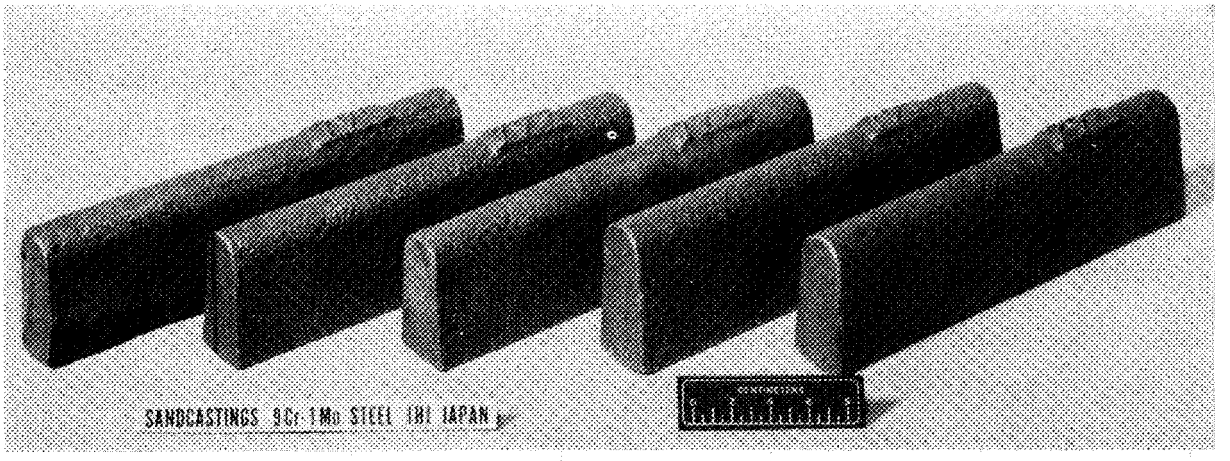


Fig. 6. Blocks of modified 9 Cr-1 Mo steel sand cast at Ishikawajima-Harima Heavy Industries Company, Limited, Japan. These blocks were received at ORNL for testing and evaluation.

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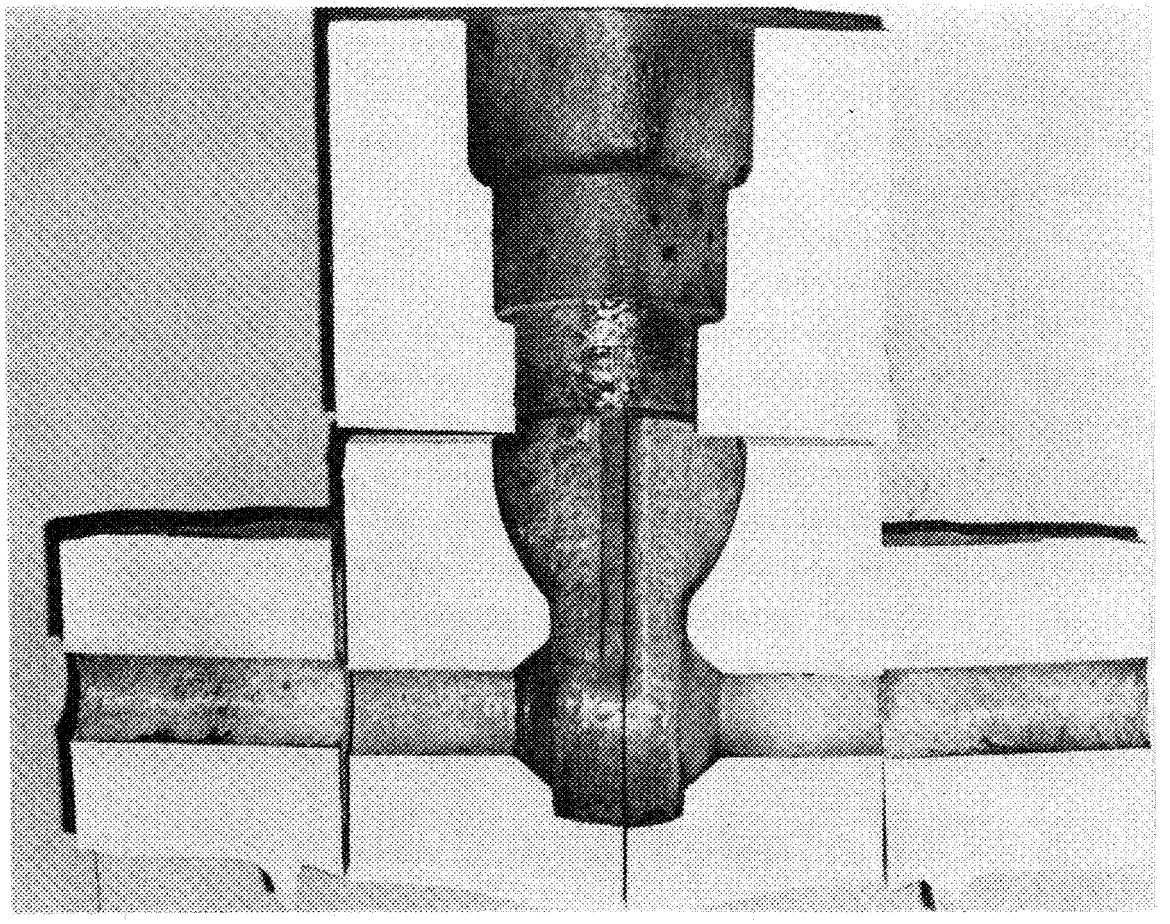

Fig. 7. Gate valve of modified 9 Cr-1 Mo steel sand cast at Ishikawajima-Harima Heavy Industries Company, Limited, Japan.

## TENSILE PROPERTIES

Tensile data on various sand castings are included in Tables 2 through 5 and plotted in Figs. 8 through 11. The average and average − 1.65 SEE* curves for the wrought material are included in these figures for comparison. The following observations are derived from the data in these figures.

1. Considerable scatter is evident in the yield strength data on various castings. Some data approach the average for the wrought material and some fall slightly below the average − 1.65 SEE curve for the wrought material. We believe that the scatter is caused by the quality of various castings and possibly also by the slight differences in heat treatment used by various vendors. The Quaker casting, which was sound and was heat treated at ORNL, provided the best yield strength.

2. Ultimate tensile strength data showed less scatter than did yield strength data. Also, ultimate tensile strength values for some castings fell slightly below the average − 1.65 SEE curve for the wrought material. Castings with the lower yield strengths also showed the lower ultimate tensile strengths.

3. Total elongation data for the castings were well represented by the average and average − 1.65 SEE curves for the wrought material.

4. The castings showed reduction of area values below the average − 1.65 SEE curve for the wrought material. Because the elongation values for the castings were similar to those of the wrought material, we believe that porosity in the necked area of the specimen may be responsible for the lower reduction of area values. Even so, the reduction of area for most castings exceeded 55% for the entire test temperature range.

5. The minimum specified values for the wrought material of yield, ultimate, total elongation, and reduction of area at room temperature describe the properties of all castings at room temperature. However, the yield and ultimate tensile strengths and reduction of area may fall below

---

*SEE = standard error of estimate. It defines a more accurate value of standard deviation.

Table 2. Tensile properties of sand-cast valve body of modified 9 Cr-1 Mo steel (heat F5349V). The casting was made at Quaker Foundry and was normalized at 1040°C and tempered at 760°C at ORNL

| Temperature (°C) | Strength (MPa) | | Elongation (%) | Reduction of area (%) |
|---|---|---|---|---|
| | 0.2% yield | Ultimate tensile | | |
| | | **Longitudinal specimens** | | |
| Room | 547 | 672 | 21.40 | 67.43 |
| 93 | 524 | 636 | 22.51 | 62.80 |
| 204 | 509 | 602 | 15.80 | 62.80 |
| 316 | 490 | 576 | 20.95 | 67.46 |
| 427 | 462 | 529 | 24.45 | 69.32 |
| 538 | 373 | 407 | 34.15 | 85.20 |
| 649 | 193 | 221 | 43.80 | 93.96 |
| 760 | 80 | 94 | 54.80 | 96.59 |
| | | **Transverse specimens** | | |
| Room | 549 | 673 | 24.70 | 65.67 |
| 93 | 530 | 639 | 21.70 | 66.12 |
| 204 | 511 | 604 | 20.00 | 66.85 |
| 316 | 492 | 578 | 18.55 | 60.75 |
| 427 | 463 | 525 | 21.35 | 67.97 |
| 538 | 403 | 429 | 28.60 | 81.72 |
| 649 | 193 | 228 | 38.13 | 91.12 |
| 760 | 77 | 91 | 60.30 | 97.18 |

Table 3. Tensile properties of sand-cast steam chest of modified 9 Cr-1 Mo steel (heat 450682). The casting was received from Atlas Foundry after being normalized at 1040°C and tempered at 760°C

| Temperature (°C) | Strength (MPa) | | Total elongation (%) | Reduction of area (%) |
|---|---|---|---|---|
| | 0.2% yield | Ultimate tensile | | |
| | | **Measured at ORNL** | | |
| Room | 518 | 645 | 20.86 | 58.71 |
| 204 | 466 | 572 | 18.45 | 59.16 |
| 427 | 417 | 502 | 19.66 | 58.38 |
| 538 | 345 | 373 | 35.91 | 81.76 |
| 649 | 158 | 191 | 44.01 | 93.53 |
| | | **Certified by Atlas** | | |
| Room | 477 | 629 | 24.0 | |

Table 4. Tensile properties of sand-cast elbow of modified 9 Cr-1 Mo steel (heat 456582). The casting was received from Atlas Foundry after being normalized at 1040°C and tempered at 760°C

| Temperature (°C) | Strength (MPa) | | Total elongation (%) | Reduction of area (%) |
|---|---|---|---|---|
| | 0.2% yield | Ultimate tensile | | |
| | | Longitudinal specimens | | |
| Room | 485 | 646 | 24.51 | 57.59 |
| 204 | 427 | 567 | 20.71 | 63.03 |
| 427 | 397 | 499 | 23.43 | 60.44 |
| 649 | 158 | 194 | 51.81 | 88.61 |
| | | Transverse specimens | | |
| Room | 483 | 641 | 20.60 | 46.31 |
| 204 | 430 | 570 | 23.39 | 62.40 |
| 427 | 389 | 501 | 27.61 | 61.55 |
| 649 | 154 | 183 | 41.83 | 89.94 |
| | | Certified by Atlas | | |
| Room | 483 | 690 | 24.0 | |

Table 5. Tensile properties of sand-cast blocks of modified 9 Cr-1 Mo steel (heat 1279). Blocks were received from Ishikawajima-Harima Heavy Industries Company, Limited (IHI), Japan

| Temperature (°C) | Strength (MPa) | | Total elongation (%) | Reduction of area (%) |
|---|---|---|---|---|
| | 0.2% yield | Ultimate tensile | | |
| | | Measured at ORNL | | |
| Room | 480 | 648 | 26.63 | 61.98 |
| 538 | 335 | 370 | 25.09 | 83.53 |
| 649 | 165 | 196 | 45.38 | 92.00 |
| | | Certified by IHI | | |
| Room | 474 | 661 | 27.3 | 65.0 |
| Room | 475 | 662 | 27.5 | 64.8 |

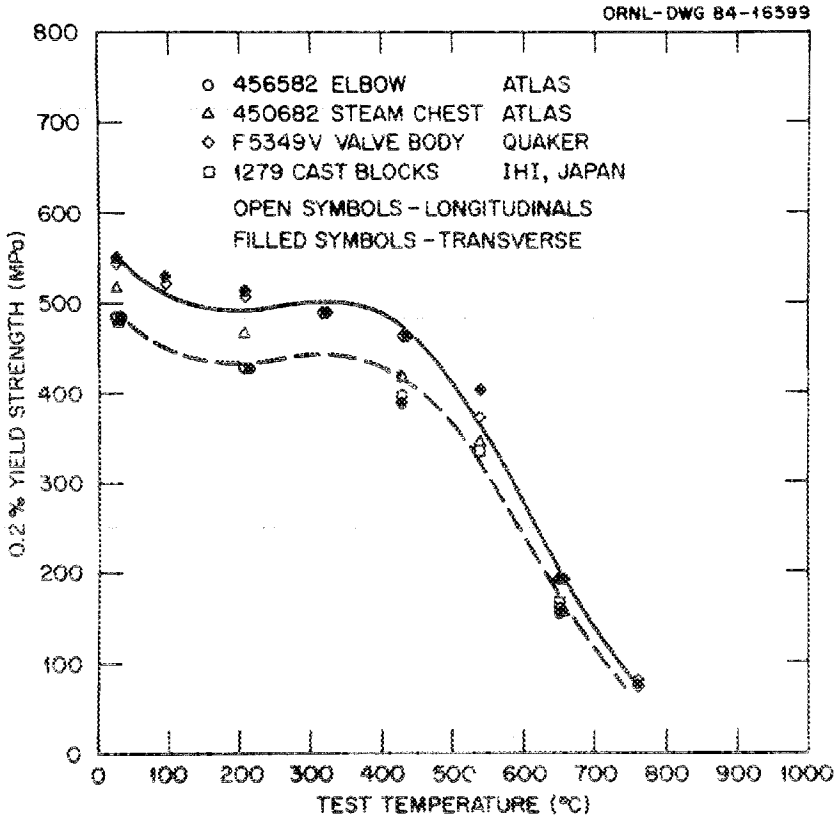


Fig. 8. Yield strength (0.2% offset) versus test temperature for various sand castings of modified 9 Cr-1 Mo steel. The average (solid) and average − 1.65 SEE (dotted) curves for the wrought material are included for comparison. Both castings and wrought material were normalized at 1040°C and tempered at 760°C.

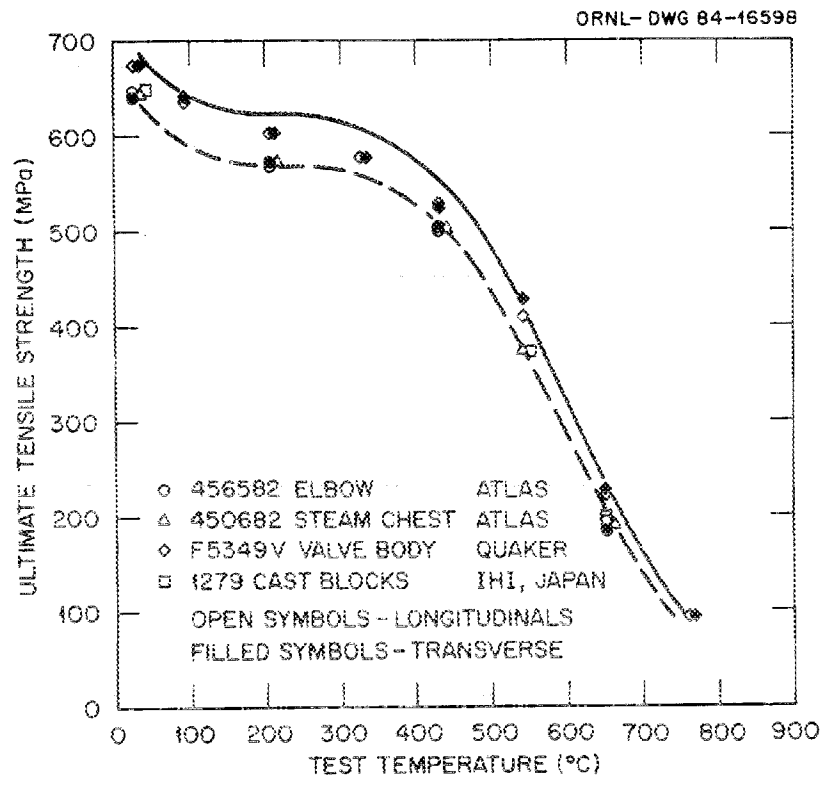


Fig. 9. Ultimate tensile strength versus test temperature for various sand castings of modified 9 Cr-1 Mo steel. The average (solid) and average − 1.65 SEE (dotted) curves for the wrought material are included for comparison. Both castings and wrought material were normalized at 1040°C and tempered at 760°C.

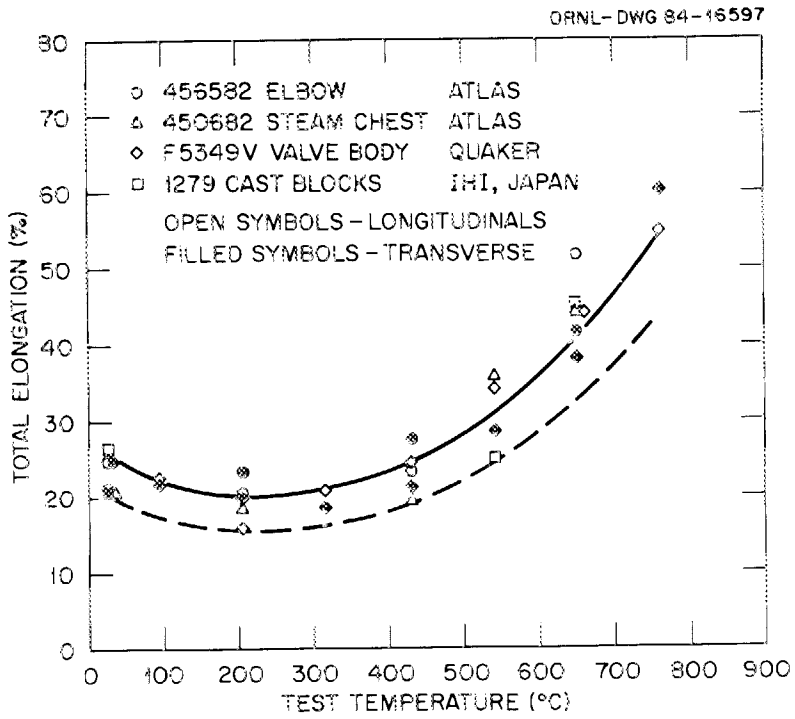


Fig. 10. Total elongation versus test temperature for various sand castings of modified 9 Cr-1 Mo steel. The average (solid) and average − 1.65 SEE (dotted) curves for the wrought material are included for comparison. Both castings and wrought material were normalized at 1040°C and tempered at 760°C.

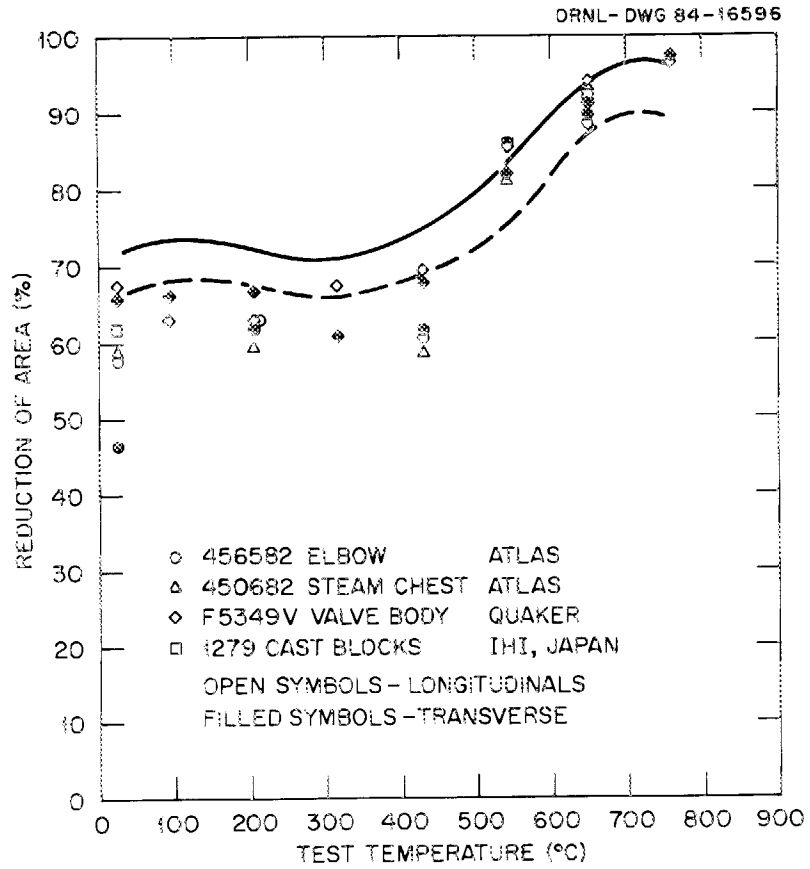


Fig. 11. Reduction of area versus test temperature for various sand castings of modified 9 Cr-1 Mo steel. The average (solid) and average − 1.65 SEE (dotted) curves for the wrought material are included for comparison. Both castings and wrought material were normalized at 1040°C and tempered at 760°C.

the average − 1.65 SEE curve for the wrought material. This observation is true because the room-temperature specified minimum values are below the average − 1.65 SEE values for the wrought material.

## CHARPY IMPACT PROPERTIES

Charpy impact data on various sand castings are presented in Tables 6 through 8. The Charpy impact energy is plotted as a function of test temperature in Fig. 12. The extreme data points on this plot are connected to estimate the range of ductile-to-brittle transition temperature at 68 J energy. This temperature varied from −5 to 82°C. The fracture appearance data in Fig. 13 shows that the 50% shear transition temperature for castings varies from 10 to 63°C. The best impact properties were obtained for the IHI, Japan castings and the worst for the Quaker valve body. The Quaker heat showed poor impact properties even in the wrought condition. We believe that the poor impacts were caused by

Table 6. Charpy impact properties of tangential specimens with radial notch of sand cast valve body of modified 9 Cr-1 Mo steel (heat F5349V). The casting was made at Quaker Foundry and was normalized at 1040°C and tempered at 760°C at ORNL

(All tests were conducted at Metallurgical and Materials Laboratory, Combustion Engineering, Chattanooga, Tenn.)

| Temperature (°C) | Impact energy (J) | | | Fracture (% shear) | | | Lateral expansion (mm) | | |
|---|---|---|---|---|---|---|---|---|---|
| | 1/4 | 1/2 | 3/4 | 1/4 | 1/2 | 3/4 | 1/4 | 1/2 | 3/4 |
| 260 | 146 | 159 | 144 | 100 | 100 | 100 | 1.80 | 2.01 | 1.78 |
| 204 | 136 | 139 | 140 | 100 | 100 | 100 | 1.63 | 1.83 | 1.65 |
| 149 | 112 | 97 | 114 | 100 | 100 | 100 | 1.27 | 1.24 | 1.50 |
| 100 | 84 | 73 | 88 | 90 | 90 | 90 | 1.07 | 1.02 | 1.27 |
| 82 | 65 | 78 | 80 | 60 | 80 | 80 | 0.97 | 1.04 | 1.09 |
| 60 | 59 | 63 | 58 | 50 | 70 | 70 | 0.91 | 0.89 | 0.79 |
| 38 | 33 | 44 | 44 | 15 | 15 | 15 | 0.43 | 0.53 | 0.66 |
| 24 | 38 | 29 | 34 | 10 | 5 | 10 | 0.46 | 0.36 | 0.33 |
| 10 | 19 | 20 | 25 | 0 | 0 | 5 | 0.20 | 0.25 | 0.28 |
| −7 | 11 | 10 | 11 | 0 | 0 | 0 | 0.13 | 0.10 | 0.13 |

Table 7. Charpy impact properties of transverse specimens with longitudinal notch of sand-cast steam chest of modified 9 Cr-1 Mo steel (heat 450682). The casting was received from Atlas Foundry after being normalized at 1040°C and tempered at 760°C

(Tests were conducted at Metallurgical and Materials Laboratory, Combustion Engineering, Chattanooga, Tenn.)

| Temperature (°C) | Impact energy (J) | Fracture (% shear) | Lateral expansion (mm) | Temperature (°C) | Impact energy (J) | Fracture (% shear) | Lateral expansion (mm) |
|---|---|---|---|---|---|---|---|
| 260 | 188 | 100 | 1.78 | 49 | 105 | 40 | 1.30 |
| 204 | 200 | 100 | 1.96 | 38 | 60 | 20 | 0.81 |
| 149 | 199 | 100 | 1.96 | 24 | 56 | 15 | 0.74 |
| 100 | 148 | 90 | 1.65 | 10 | 26 | 5 | 0.28 |
| 82 | 137 | 80 | 1.60 | −7 | 15 | 0 | 0.23 |
| 60 | 133 | 80 | 1.50 | | | | |

Table 8. Charpy impact properties of longitudinal specimens with transverse notch of sand-cast blocks of modified 9 Cr-1 Mo steel (heat 1279). The casting was received from Ishikawajima-Harima Heavy Industries Company, Limited (IHI), Japan. All blocks were normalized at 1040°C and tempered at 760°C

| Temperature (°C) | Impact energy (J) | Fracture (% shear) | Lateral expansion (mm) |
|---|---|---|---|
| | **Block 1** | | |
| 93 | 138 | 100 | 1.82 |
| 24 | 114 | 80 | 1.33 |
| 2 | 70 | 42 | 0.72 |
| −18 | 62 | 35 | 0.77 |
| −73 | 21 | 2 | 0.19 |
| | **Block 2** | | |
| 176 | 150 | 100 | 1.93 |
| 52 | 137 | 100 | 1.82 |
| 24 | 122 | 65 | 1.50 |
| −46 | 31 | 20 | 0.38 |
| −101 | 2 | 2 | 0.06 |
| | **Certified by IHI** | | |
| 0 | 43 | | 1.02 |

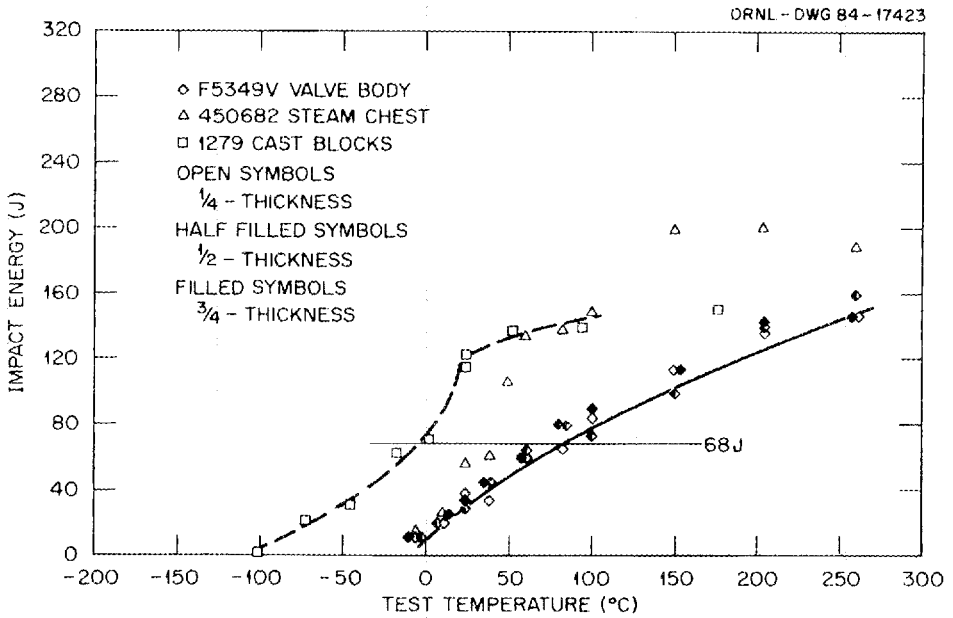


Fig. 12. Charpy impact energy as a function of test temperature for various sand castings of modified 9 Cr-1 Mo steel. All castings were normalized at 1040°C and tempered at 760°C.

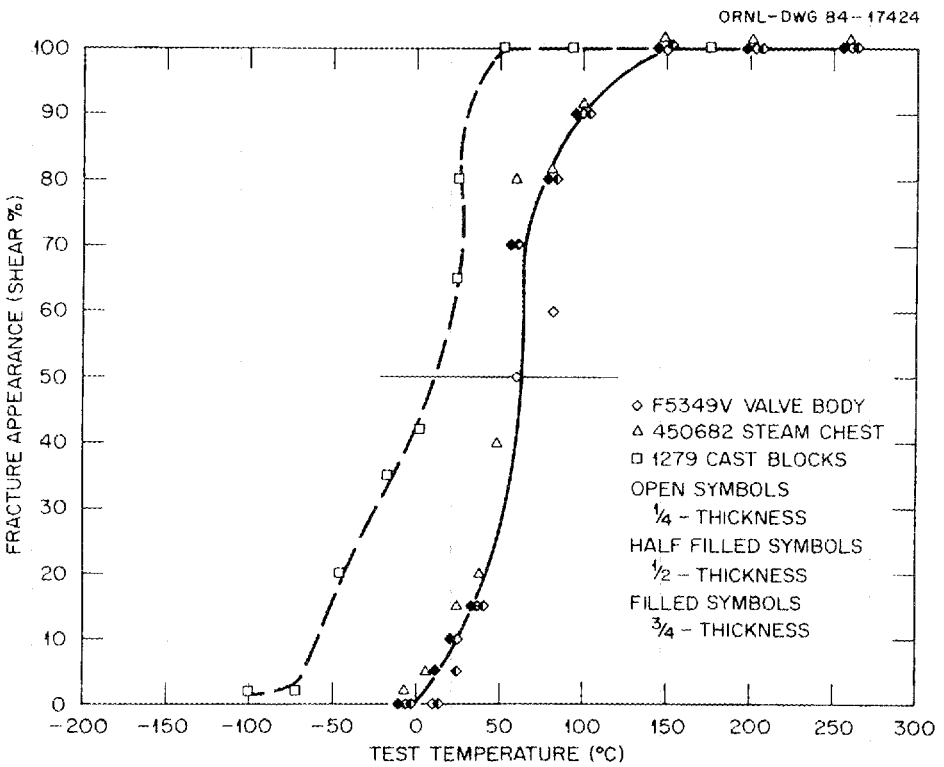


Fig. 13. Fracture appearance (% shear) from Charpy impact tests as a function of test temperature for various sand castings of modified 9 Cr-1 Mo steel. All castings were normalized at 1040°C and tempered at 760°C.

the very high sulfur content (0.015%) of this heat and to some extent by its lower nitrogen content. The steam chest, which had the same nitrogen content as Quaker heat but much lower sulfur content (0.004%), showed better impact properties than the Quaker casting. The IHI casting, which had the correct amount of nitrogen and a low sulfur content, showed the best impact properties.

The 68-J transition temperature for the forging[1] and extruded pipe[2] of a given heat were −36 and −115°C. These values are much lower than −5 to 82°C observed for the sand castings. The reasons for such differences will be explored in the microstructural section.

## EFFECT OF THERMAL AGING ON IMPACT AND HARDNESS

Material from the IHI sand-cast blocks was aged and tested by IHI, Japan. Tests included Charpy impact and microhardness at room temperature. Aging conditions and the property data on the aged IHI blocks are presented in Table 9. The room-temperature Charpy impact energy and hardness are plotted as a function of aging time in Figs. 14 and 15. For the impact data, cross-hatched bands have been drawn for each aging temperature. For hardness data, differences between various aging temperatures are not significant, so we have drawn a single line to represent the data. The impact energy plot in Fig. 14 shows the following points.

1. The first 100 h of aging at all aging temperatures produced either no change or a slight increase in room-temperature impact energy.

2. After 1000 h of aging, the drop in impact energy was most for aging at 550°C and least at 660°C.

3. The results of Fig. 14 indicate that the impact energy might drop for a certain combination of aging temperature and time and that continuing aging either at that or higher temperature might recover the drop in impact energy. Additional work is needed in this area to define the worst aging conditions for this material in the cast condition. Such work is already in progress on two heats of wrought material.

Table 9. Effect of aging on room-temperature Charpy impact and hardness values of sand-cast blocks of modified 9 Cr-1 Mo steel from Ishikawajima-Harima Heavy Industries Company, Limited (IHI), Japan

(All tests were conducted at IHI. All specimens were normalized at 1040°C and tempered at 760°C prior to aging.)

| Aging conditions | | Impact energy (J) | Vickers hardness (VHN) |
|---|---|---|---|
| Temperature (°C) | Time (h) | | |
| | 0 | 90 | 202 |
| | 0 | 103 | 205 |
| | 0 | 97 | 205 |
| 550 | 100 | 103 | 202 |
| 550 | 100 | 112 | 202 |
| 550 | 100 | 97 | 201 |
| 550 | 1000 | 74 | 204 |
| 550 | 1000 | 59 | 210 |
| 550 | 1000 | 67 | 206 |
| 600 | 100 | 103 | 202 |
| 600 | 100 | 111 | 205 |
| 600 | 100 | 99 | 204 |
| 600 | 1000 | 79 | 202 |
| 600 | 1000 | 72 | 195 |
| 600 | 1000 | 83 | 199 |
| 660 | 100 | 118 | 196 |
| 660 | 100 | 113 | 199 |
| 660 | 100 | 113 | 201 |
| 660 | 1000 | 105 | 201 |
| 660 | 1000 | 98 | 201 |
| 660 | 1000 | 99 | 200 |

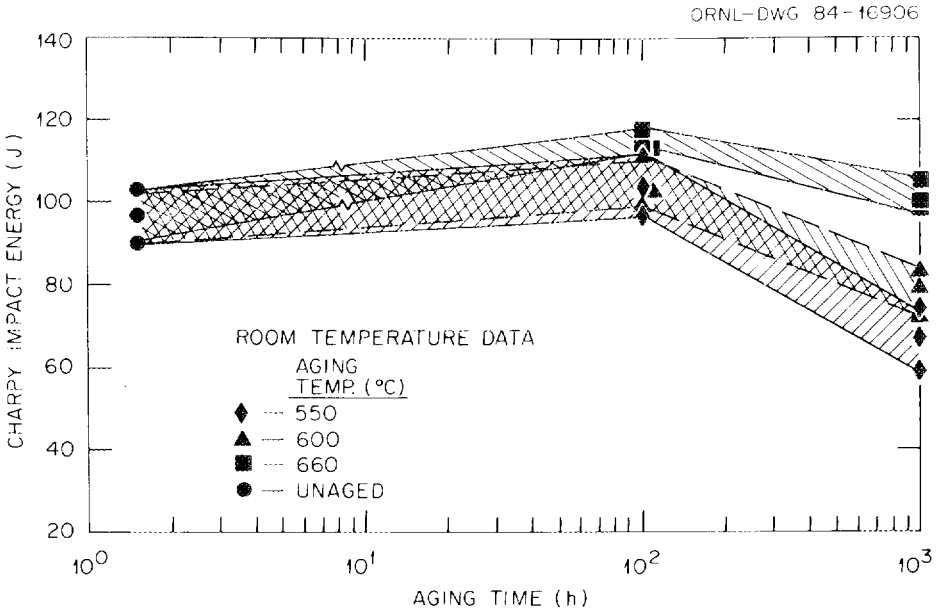


Fig. 14. Room-temperature Charpy impact energy as a function of aging time for sand-cast blocks of modified 9 Cr-1 Mo steel cast, aged, and tested by Ishikawajima-Harima Heavy Industries Company, Limited, Japan. All specimens were normalized at 1040°C and tempered at 760°C prior to aging.

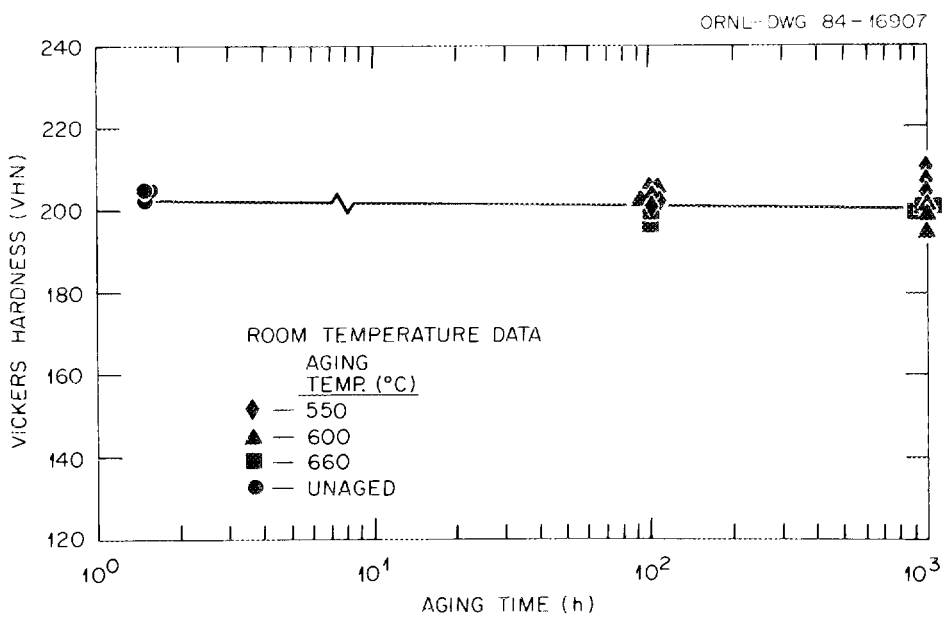


Fig. 15. Microhardness as a function of aging time for sand-cast blocks of modified 9 Cr-1 Mo steel cast, aged, and tested by Ishikawajima-Harima Heavy Industries Company, Limited, Japan. All specimens were normalized at 1040°C and tempered at 760°C prior to aging.

## CREEP PROPERTIES

Four creep specimens have ruptured and two are under test on various sand castings of modified 9 Cr-1 Mo steel. Data available thus far are compared with the average curve for the wrought material in Fig. 16. This figure shows that the creep-rupture strength of sand castings is only slightly below the average for wrought material. The data are not yet sufficient to sort out the effect of nitrogen content (0.01 versus 0.03%) on the creep-rupture strength of sand castings.

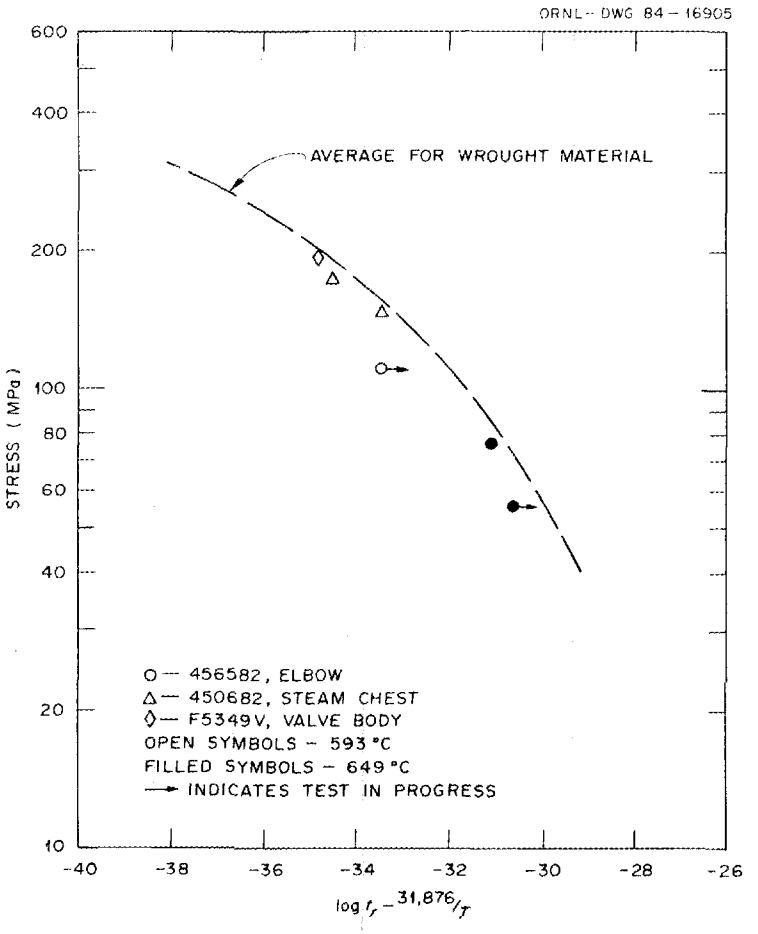


Fig. 16. Comparison of creep-rupture strength of modified 9 Cr-1 Mo sand castings with the average curve for the wrought material. Both castings and wrought material were normalized and tempered at 1040°C and 760°C, respectively, prior to testing.

## FATIGUE PROPERTIES

A limited number of continuous cycle fatigue tests have been conducted by IHI on its sand-cast blocks of modified 9 Cr-1 Mo steel. Also, IHI conducted similar fatigue tests on a forging for comparison. The continuously cycling fatigue data from IHI on the casting and forging are compared with the best fit curve for the U.S. data on the wrought material in Fig. 17. At room temperature, the forging data collected at IHI matches exactly the best fit curve for the U.S. data on the wrought material. However, the castings showed one-fifth to one-half the cyclic lives of the wrought and forged material.

At 593°C, the casting data are also somewhat lower than the forged material (Fig. 18). Data available at present on uniform-gage specimens of wrought material at 593°C are insufficient for comparison.

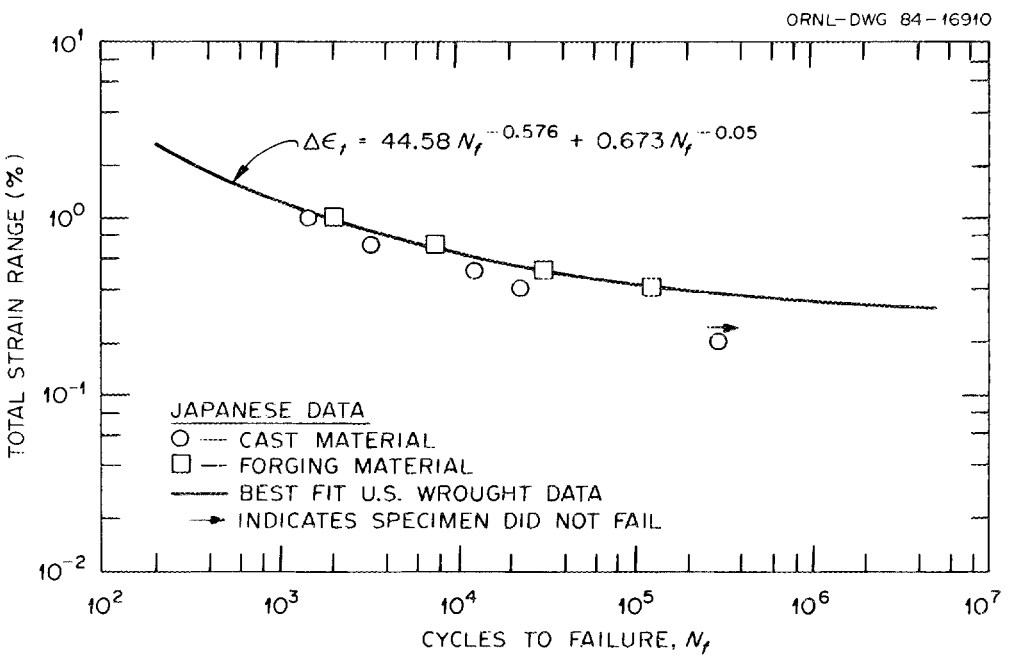


Fig. 17. Comparison of the room-temperature continuous-cycle fatigue behavior for modified 9 Cr-1 Mo steel from two sources (ORNL and Japan) and several product forms. Note that the cast form shows somewhat lower fatigue resistance. All materials were tested after normalizing at 1040°C and tempering at 760°C.

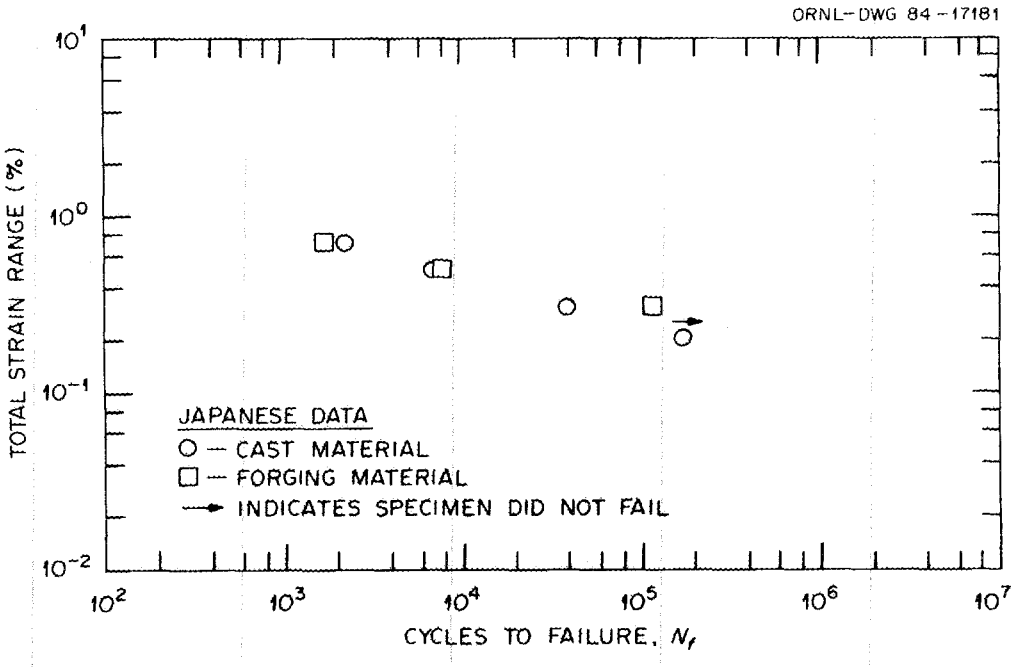


Fig. 18. Comparison of Japanese continuous-cycle fatigue data obtained on several product forms of modified 9 Cr-1 Mo steel at 593°C.

## MICROSTRUCTURE

To explain the slightly lower mechanical properties of sand castings relative to wrought material, we microstructurally examined sand-cast blocks from IHI. Cross sections of three sand-cast blocks were macro-etched (Fig. 19). Unlike stainless steel castings, these castings did not show any large grains. The unetched microstructure (Fig. 20) showed the presence of a large number of fine pores and some larger pores. High-magnification photographs showed that in addition to porosity, some inclusions were also present in the casting. The nature of the inclusions was not investigated. The etched microstructure at various magnifications (Fig. 21) showed fine grain size and precipitate size and distribution very similar to those observed for the wrought material.

The most significant difference in microstructure between sand castings and wrought material is the porosity. We believe that this porosity is responsible for the lower reduction of area in a tensile test, poorer impact properties, and slightly lower creep and fatigue properties than those of the wrought material.

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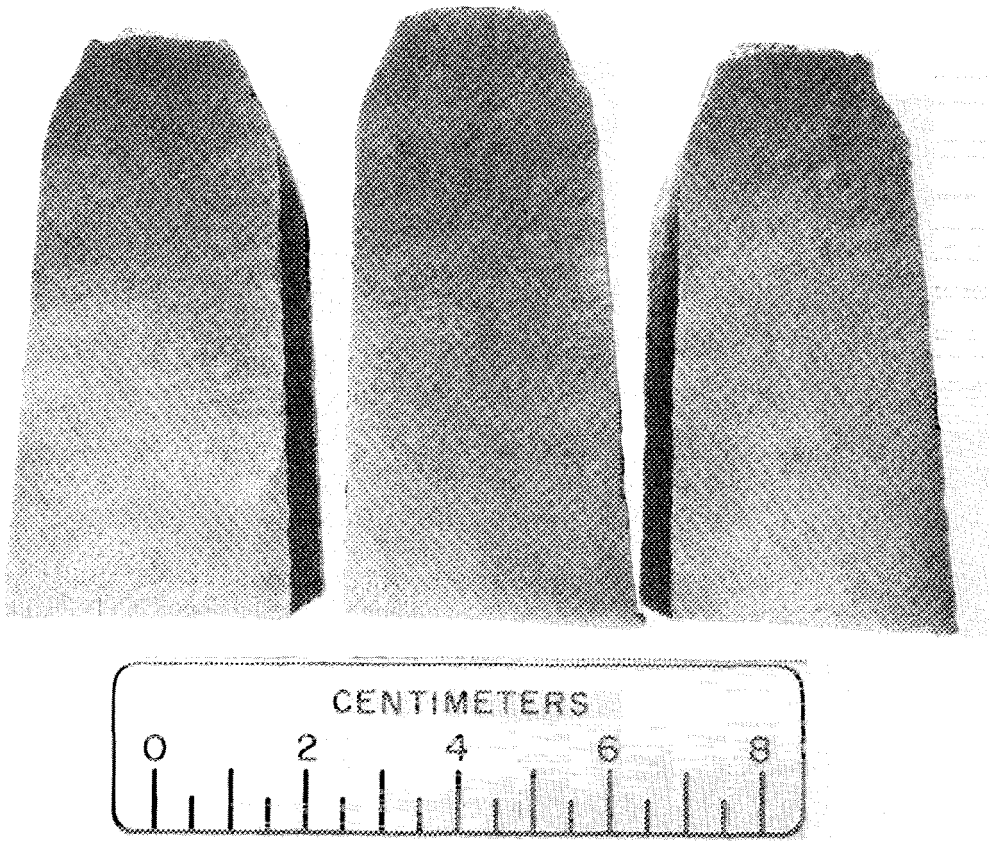


Fig. 19. Macroetched sections of sand-cast blocks of modified 9 Cr-1 Mo steel from Ishikawajima-Harima Heavy Industries Company, Limited, Japan.

## SUMMARY AND CONCLUSIONS

Sand castings of simple blocks, elbows, valve bodies, and a steam chest were characterized by tensile, Charpy impact, hardness, creep, and fatigue tests, and microstructure effects of thermal aging on Charpy impact properties were determined. Properties of the castings were then compared with those observed for the wrought material. The following conclusions were derived from this work:

1. Modified 9 Cr-1 Mo steel sand casting poses no unusual problems. Atlas found that high nitrogen contents resulted in casting porosity near the surface. However, no macroscopic porosity was observed by IHI, Japan,

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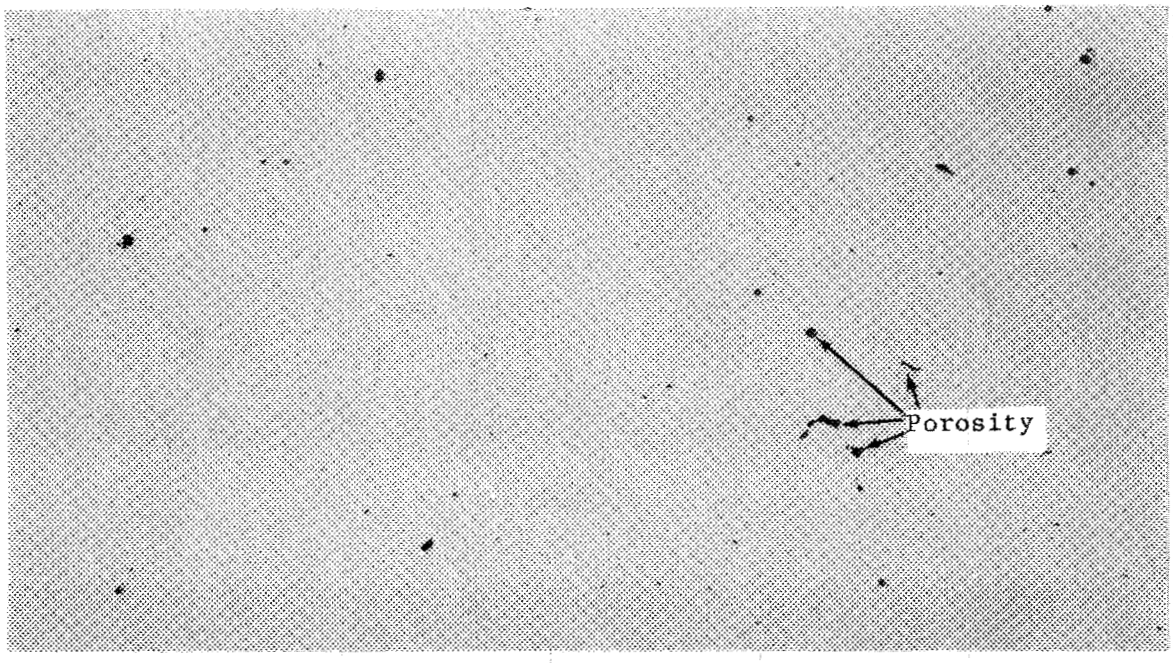


400 μm

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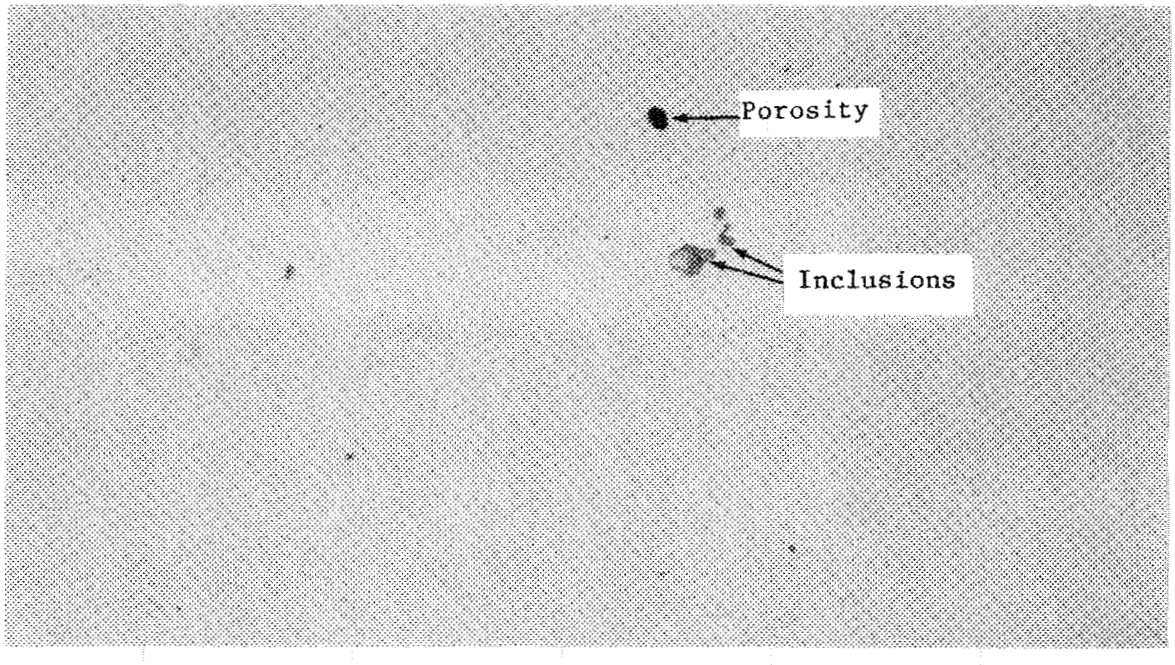


40 μm

Fig. 20. Unetched sections of sand-cast blocks of modified 9 Cr-1 Mo steel from Ishikawajima-Harima Heavy Industries Company, Limited, Japan.

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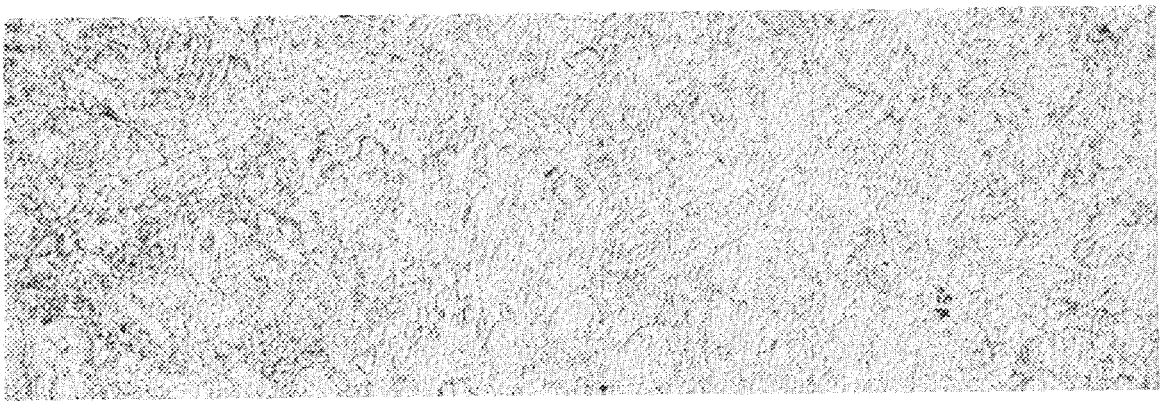

100 μm

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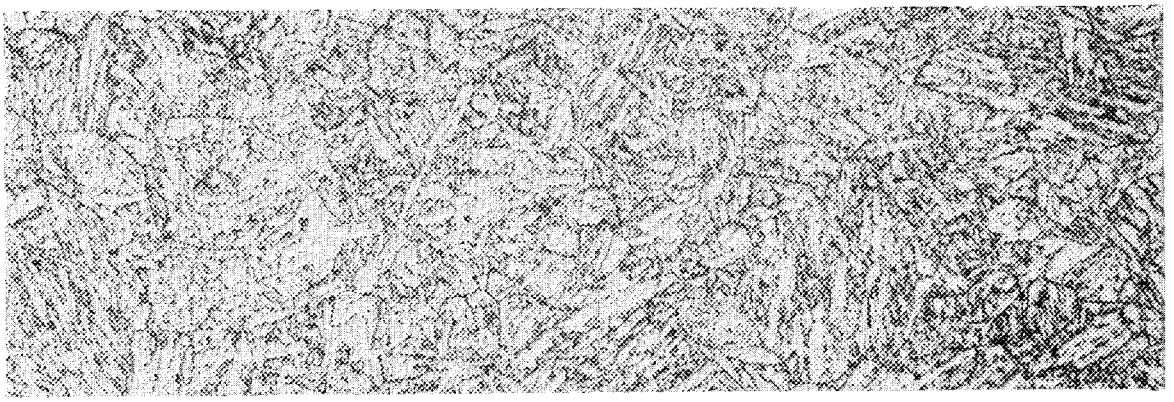

40 μm

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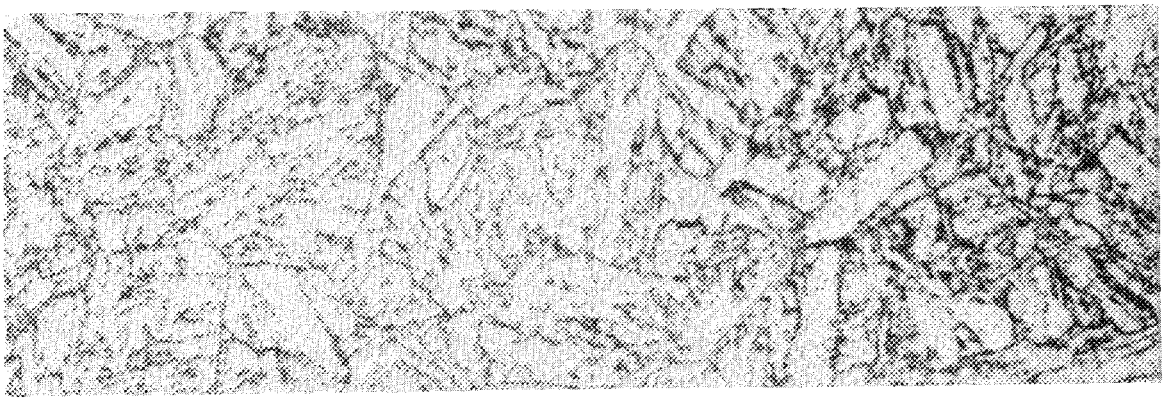

13.4 μm

Fig. 21. Etched sections of sand-cast blocks of modified 9 Cr-1 Mo steel from Ishikawajima-Harima Heavy Industries Company, Limited, Japan.

in its castings even when the nitrogen content was high. Also the valve body cast at Quaker showed no indication of surface porosity compared with some porosity observed in Atlas[1] castings even with 0.01% N. Additional work is needed to sort out the reasons for the surface porosity observed by Atlas.

2. The tensile properties of the castings showed considerable scatter. The scatter was considered to result from compositional differences, slight heat treatment differences, and possibly differences in the foundry practices.

3. The 0.2% yield and ultimate tensile strengths of some castings were slightly below the average − 1.65 SEE curves for wrought material. The total elongation values for all castings were within the average and average − 1.65 SEE curves for the wrought material. The reduction of area for all castings was below the average − 1.65 SEE curve for the wrought material. Lower values in reduction of area are believed to have been caused by the porosity in the castings.

4. The Charpy impact properties of the various castings also showed a significant scatter. The best impact properties were observed for the IHI cast blocks, which had compositions within the specifications for the modified alloy. The castings with poor Charpy properties were the ones with lower nitrogen content (0.01%) or high sulfur content (Quaker casting with 0.015%). Thermal aging degraded the room-temperature Charpy impact energy somewhat with the greatest effect after aging at 550°C. It appeared that the impact energy might recover if aging continued at the same temperature for a longer time or at a higher temperature for a short period.

5. The creep-rupture strength at 593 and 649°C of various castings were only slightly below the average curve for the wrought material.

6. Continuous cycling fatigue properties of the IHI castings were somewhat lower than the average curve for the wrought material.

7. Sand casting (IHI blocks) showed the presence of fine porosity and some inclusions. The grain size and carbide distribution of the casting (IHI) was not much different from those of wrought material. The presence of porosity is considered the main cause of poor properties of sand castings.

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