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# Heat-to-Heat Variation of Tensile Properties of Annealed 2¼ Cr-1 Mo Steel

R. L. Klueh

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**OAK RIDGE NATIONAL LABORATORY**

OPERATED BY UNION CARBIDE CORPORATION FOR THE ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION

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# HEAT-TO-HEAT VARIATION OF TENSILE PROPERTIES OF ANNEALED 2 1/4 Cr-1 Mo STEEL

R. L. Klueh

Date Published: July 1977

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# HEAT-TO-HEAT VARIATION OF TENSILE PROPERTIES OF ANNEALED 2 1/4 Cr-1 Mo STEEL*

R. L. Klueh

## ABSTRACT

The tensile properties of twelve heats of 2 1/4 Cr-1 Mo steel were examined over the range 25 to 566°C. The twelve heats included: five air-melted tubing heats, two pieces from vacuum-arc remelted (VAR) forgings, two pieces from electroslag remelted (ESR) plates, two air-melted plates, and one air-melted forging. Tests were made on the steel in the as-received condition (vendor anneal) and, in order that all heats could be compared from a common basis, material from each of the heats was tested after it was annealed in our laboratory.

For the twelve heats of steel tested, large property variations were observed. Decided differences were noted between the air-melted tubing, the air-melted plates and forging, and the ESR and VAR steels. Explanations for these differences are offered in terms of the types of precipitation reactions that occur in these steels at elevated temperatures.

## INTRODUCTION

For the steam generators of the demonstration liquid metal fast breeder reactor (LMFBR) — the Clinch River Breeder Reactor — annealed 2 1/4 Cr-1 Mo steel will be the structural material. As a result of that application, tensile, creep, and cyclic studies[1] [3] have been made over the range 454 to 566°C (850–1050°F) to determine accurate properties for use in the constitutive equations[4] for this steel. Those studies

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*Work performed under ERDA/RDD 189a No. OH028, Steam Generator Materials Development.

[1] R. L. Klueh and R. E. Oakes, Jr., "High-Strain-Rate Tensile Properties of Annealed 2 1/4 Cr-1 Mo Steel," *J. Eng. Mater. Technol.* 98: 361–68 (1976).

[2] R. L. Klueh, *Creep and Rupture Behavior of Annealed 2 1/4 Cr-1 Mo Steel*, ORNL-5219 (December 1976).

[3] C. E. Jaske et al., "Monotonic and Cyclic Stress-Strain Response of Annealed 2 1/4 Cr-1 Mo Steel," pp. 191–212 in *Structural Materials for Service at Elevated Temperatures in Nuclear Power Generation*, American Society of Mechanical Engineers, New York, 1975.

were done on a single heat of the steel, an air-melted 25.4-mm-thick (1-in.) plate (heat 20017). In that work the mechanical property characteristics were of most importance, and property variations due to differences arising in different heats, product forms, or melting practices were ignored.

The ASME Boiler and Pressure Vessel Code allowable stresses for high-temperature design of nuclear components are given by Code Case 1592. To set the allowable design stresses, average tensile and creep values are determined from all available data taken from steel that meets the appropriate ASME specifications. Minimum values are determined from such a data compilation, and the allowable stresses are conservatively estimated from these minimum values.

The ASME specifications for 2 1/4 Cr-1 Mo steel specify the concentration of several of the important elements and also set required room temperature tensile properties that must be met (Table 1). The U.S. Energy Research and Development Administration Division of Reactor Development and Demonstration has supplemented the ASME requirements, and for any material used for LMFBR applications, these additional requirements (RDT Standards) must be met (Table 1). Although there are slightly different specifications for different product forms, the requirements (Table 1) for the ASME specifications and the RDT Standards are essentially the same for the product forms of interest for the LMFBR steam generators — annealed tubing, plates, and forgings.

Smith[5] has gathered all the available elevated-temperature tensile and creep-rupture data for 2 1/4 Cr-1 Mo steel, and mainly these data were used to determine the allowable stresses for Code Case 1592. These same and later data were used by analysts at Oak Ridge National Laboratory

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[4] C. E. Pugh et al., *Background Information for Interim Methods of Inelastic Analysis for High-Temperature Reactor Components of 2 1/4 Cr-1 Mo Steel*, ORNL/TM-5226 (May 1976).

[5] G. V. Smith, *Supplemental Report on the Elevated-Temperature Properties of Chromium-Molybdenum Steels (An Evaluation of 2 1/4 Cr-1 Mo Steel), ASTM Data Ser. DS 6 S2*, American Society for Testing and Materials, Philadelphia, March 1971.

Table 1. Chemical Composition Specifications for Annealed 2 1/4 Cr-1 Mo Steel (wt %)

| Specification | Chemical Requirements, wt. % | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | C | Mn | P | S | Si | Cr | Mo | Ni | Ti | V | Cu |
| ASME (ASTM)[a] | 0.15 max | 0.30-0.60 | 0.030 max | 0.030 max | 0.50 max | 2.00-2.50 | 0.90-1.10 | | | | |
| | Tensile strength, min: | 413 MPa (60 ksi) | | | | | | | | | |
| | Yield point, min: | 207 MPa (30 ksi) | | | | | | | | | |
| | Elongation in 51 mm (2 in): | 30% | | | | | | | | | |
| RDT[b] | 0.07-0.110 | 0.30-0.60 | 0.015 max | 0.015 max | 0.20-0.40 | 2.00-2.50 | 0.90-1.10 | 0.25 max | 0.03 max | 0.03 max | 0.35 max |

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[a] These requirements apply for tubing, T22 (SA-213), forgings, F 22 (SA-336), and plates, Grade 22 (SA-387).

[b] These requirements apply for tubing (RDT M3-33T) and tubesheet forgings (RDT M 2-19T); plate requirements are similar to SA-387. Strength properties are similar to those for ASME (ASTM).

to correlate data for use in LMFBR design.[6] When the compiled data for the tensile and creep properties are examined, large variations in properties are observed. For example, ultimate tensile strength values for annealed 2 1/4 Cr-1 Mo steel varied by about 125 MPa (18 ksi) at 25°C (77°F) and by almost 250 MPa (36 ksi) at 371 and 538°C (700 and 1000°F).[6]

When correlations or allowable stresses are determined from such data, all annealed data that meet the appropriate specifications are used, regardless of melting practice or product form. In most cases the material from which the allowable stresses for ASME Code Case 1592 were determined or from which the LMFBR design correlations were derived came from air-melted 2 1/4 Cr-1 Mo steel.[6] Likewise, the data used for constitutive equation development were from an air-melted heat.[1–3] To ensure that the tube-to-tubesheet welds for the steam generators will be made on steel free from inclusions and porosity, vacuum-arc remelted (VAR) steel will be used for the tubesheet forgings and electroslag remelted (ESR) steel for the tubing. Few data appear to be available for 2 1/4 Cr-1 Mo steel remelted by these practices, and none appear to have been used in the correlations or for Code Case 1592.[5,6]

The effect of heat-to-heat variations on the elevated-temperature mechanical properties of types 304 and 316 stainless steel has been studied.[7,8] For these austenitic steels, much of the variation could be traced to differences in chemical composition and grain size. The amounts of carbon, nitrogen, and niobium significantly affected the properties. For a ferritic steel such as 2 1/4 Cr-1 Mo steel, the heat treatment will have a pronounced influence on the properties. Obviously, a pronounced difference will be observed between steels that are annealed,

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[6] M. K. Booker et al., *Mechanical Property Correlations for 2 1/4 Cr-1 Mo Steel in Support of Nuclear Reactor Systems Design,* ORNL/TM-5239 (June 1976).

[7] H. E. McCoy, Jr. and R. D. Waddell, Jr., "Mechanical Properties of Several Product Forms of a Single Heat of Type 304 Stainless Steel," *J. Eng. Mater. Technol.* 97: 343–49 (1975).

[8] V. K. Sikka, H. E. McCoy, M. K. Booker, and C. R. Brinkman, "Heat-to-Heat Variations in Creep Properties of Types 304 and 316 Stainless Steels," *J. Pressure Vessel Technol.* 97: 243–51 (1975).

or normalized and tempered, or quenched and tempered. However, differences can also occur among heats of annealed steels that are cooled at slightly different rates.[2,9]

An "annealed" or fully annealed steel is one that has been slowly cooled from the austenitizing temperature to cause the transformation of the austenite to a relatively soft ferrite-pearlite aggregate. A steel is annealed by furnace cooling from the austenitizing temperature. However, for tubing an "isothermal anneal" treatment is generally used to obtain the same ferrite-pearlite aggregate. After austenitizing, a steel is isothermally annealed by cooling to some intermediate temperature where it is held for a time, then cooled to room temperature. For tubing this can be accomplished in a continuous annealing furnace that contains different temperature zones. The tubes are continuously moved through the furnace, from a zone that is maintained at the austenitizing temperature into a zone at which the temperature is held constant, usually between 677 and 732°C. The rate at which the tube cools to the isothermal transformation temperature and the rate at which it cools to room temperature after transformation are thought to be relatively unimportant.

Another common heat treatment employed on 2 1/4 Cr-1 Mo steel, especially for plates and forgings, is to normalize and temper. The steel is normalized by air cooling from the austenitizing temperature, and then tempered, usually between about 593 and 760°C (1100 to 1400°F). The microstructure of a normalized-and-tempered 2 1/4 Cr-1 Mo steel will depend strongly on the section size heat treated; the smaller the size, the greater the amount of bainite that will be present. The ASME specifications for tubing (SA-213), forgings (SA-336), and plates (SA-387) allow the material to be normalized-and-tempered as well as annealed. However, only annealed 2 1/4 Cr-1 Mo steel was approved in Code Case 1592, and the RDT Standards for tubing and tubesheet forgings only allow for an anneal heat treatment.

The present work has four objectives:

1. the determination of heat-to-heat variations in annealed 2 1/4 Cr-1 Mo

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[9] R. L. Klueh, *Heat Treatment Effects on the Tensile Properties of Annealed 2 1/4 Cr-1 Mo Steel*, ORNL-5144 (May 1976).

steel for selected heats;

2. the examination of differences in various product forms — tubing, forgings, and plates;
3. the examination of differences in steel produced by various processes — air-melted, vacuum-arc remelted (VAR), and electroslag remelted (ESR); and
4. the identification of the causes of heat-to-heat variation in mechanical properties.

## EXPERIMENTAL

Tests were made on specimens taken from 12 different heats: five air-melted tubing heats, two pieces from VAR forgings, two pieces from ESR plates, one air-melted forging, and two air-melted plates. The chemical composition for all but one of the heats satisfied the ASME specifications (Table 2). The exception was one VAR forging (heat C60570), which contained 0.034 wt % S (the specifications allow 0.030 max). Since many of the heats were obtained before the RDT Standards had been issued, several do not meet the RDT Standards for carbon (0.11 max) and/or sulfur (0.015 max). These include the tubing heats 36202 and 72781, the VAR heats 13812 and C60570, the ESR plate XXR, and the air-melted plate 3P5601. However, the ASME code allowable stresses[5] and the design correlations[6] were determined on a similar cross section of steels (annealed 2 1/4 Cr-1 Mo steel that met ASME specifications), and the Clinch River Breeder Reactor steam generators will be designed according to those allowable stresses and correlations.

The five tubing heats and the two air-melted plates were obtained from Babcock and Wilcox Corporation. The 38-mm-diam (1.5-in.) tubing had wall thicknesses of 4.8 (heats 36018 and 72871), 7.3 (heats 36202 and X6216), and 9.0 mm (heat 72768) (0.19, 0.29, and 0.35 in.). The VAR forgings were small pieces of material obtained through courtesy of the Foster Wheeler Corporation: one (13812) had been obtained from Jorgensen Company and the other (C60570) from Coulter Company. Both the ESR materials were pieces of 152-mm-thick (6-in.) plate produced by Lukens Steel Company and sold under the trade name Lectrefine: heat

Table 2. Chemical Composition and Grain Size of 2 1/4 Cr-1 Mo Steel as Reported by Vendors

| Heat | Chemical Composition, wt % | | | | | | | Grain Size (ASTM) |
|---|---|---|---|---|---|---|---|---|
| | C | Mn | S | P | Si | Cr | Mo | |
| | | | | Tubing Heats | | | | |
| 36018 | 0.11 | 0.47 | 0.015 | 0.019 | 0.23 | 2.29 | 0.96 | |
| 36202 | 0.12 | 0.47 | 0.021 | 0.014 | 0.36 | 2.32 | 0.98 | 6–7 |
| 72768 | 0.09 | 0.44 | 0.011 | 0.011 | 0.38 | 2.22 | 0.95 | 6–7 |
| 72871 | 0.13 | 0.50 | 0.022 | 0.016 | 0.33 | 2.27 | 0.99 | 6 |
| X6216 | 0.11 | 0.46 | 0.015 | 0.011 | 0.27 | 2.20 | 1.03 | 7 |
| | | | | VAR Forging Heats | | | | |
| 13812 | 0.10 | 0.50 | 0.024 | 0.006 | 0.31 | 2.33 | 0.9 | |
| C60570 | 0.10 | 0.37 | 0.034 | 0.009 | 0.37 | 2.24 | 1.02 | |
| | | | | ESR (Lectrefine)[a] Plates [0.15 m (6 in.) thick] | | | | |
| R0110 | 0.10 | 0.44 | 0.004 | 0.014 | 0.17 | 2.44 | 0.97 | 8 |
| XXR | 0.13 | 0.45 | 0.006 | 0.010 | 0.18 | 2.32 | 0.97 | |
| | | | | Air-Melted Forging | | | | |
| NF60-8746 | 0.09 | 0.39 | 0.009 | 0.009 | 0.35 | 2.40 | 1.01 | 4–6 |
| | | | | Air-Melted Plate [25 mm (1 in.) thick] | | | | |
| 20017 | 0.11 | 0.55 | 0.011 | 0.014 | 0.29 | 2.13 | 0.90 | |
| 3P5601 | 0.12 | 0.35 | 0.022 | 0.009 | 0.27 | 2.30 | 0.96 | |

[a] Lukens Steel Company registered trademark for ESR steels.

R0110 was obtained from Lukens via General Electric Company; heat XXR was obtained via Foster Wheeler Corporation (the designation XXR was arbitrarily assigned by our laboratory, since no vendor heat number was available). The air-melted forging (NF 60-8746) was one of three tubesheet forgings that were purchased from National Forge Company. These forgings, which were manufactured by the electric furnace, air-melted, vacuum-degassed process were obtained before the decision was made to use VAR material. The tubesheet forging from which these specimens were taken was a cylinder 0.84-m-diam by 0.483-m-thick (33 × 19 in.)

The tubing, forgings, and ESR plates were tested in the as-received condition. The tubing and air-melted forging had been "annealed" or "isothermally annealed" and the two VAR forgings and the two ESR plates were normalized and tempered. The two air-melted 25.4-mm-thick (1-in.) plates were received in a normalized-and-tempered condition. Because the microstructures contained large amounts of bainite and the room-temperature strengths were considerably above those allowed by the appropriate ASME specifications and RDT Standards, the as-received material was not studied for these two heats.

In order that all the heats could be compared from a common basis, material from each of the heats was similarly isothermally annealed in our laboratory. They were austenitized by heating 1 hr at 927°C (1700°F), furnace cooled to 704°C (1300°F), held at 704°C for 2 hr, then furnace cooled to room temperature.

Tensile tests were done in air on a 44 kN Instron test machine. The specimens were heated in a three-zone resistance furnace with temperature controlled to ±1°C with less than a 2°C temperature variation along the specimen gage length. The test machine was operated at constant crosshead velocity and the reported strain rates were determined from the crosshead velocity and the initial gage length. The specimens taken from the tubes, the pieces of VAR forging, and ESR plates were of a buttonhead type with a 3.18-mm-diam and a 28.6-mm (0.125 × 1.125 in.) gage section. The specimens taken from the 25.4-mm-thick plates and the air-melted forging had a 6.35-mm-diam × 31.75-mm-long (0.025 × 1.25 in.) reduced section.

# RESULTS

## Metallography

With the exception of the air-melted plates, all of the heats were examined in the as-received condition (vendor heat treatment) and after they were isothermally annealed (Figs. 1–6). Microhardness and grain size determinations were also made in both conditions (Table 3): grain sizes were determined by the line-intercept method.

For the tubing heats in both the as-received and isothermally annealed conditions, the microstructures were primarily proeutectoid ferrite that contained carbide precipitate and bainite (Figs. 1 and 2). A small

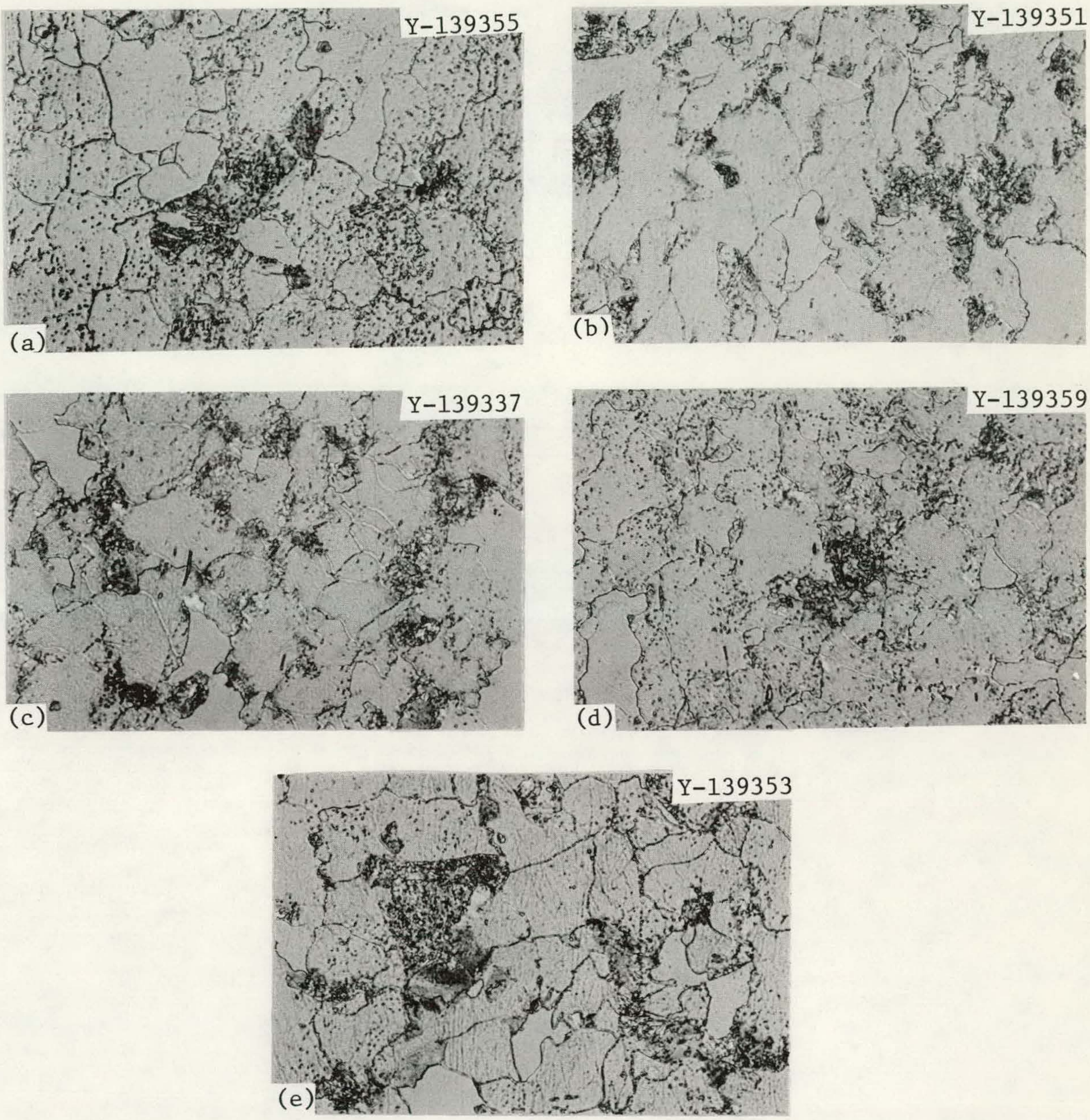

Fig. 1. Microstructures of As-Received Tubing Heats: (a) 36018, (b) 36202, (c) 72768, (d) 72871, and (e) X6216. 500×.

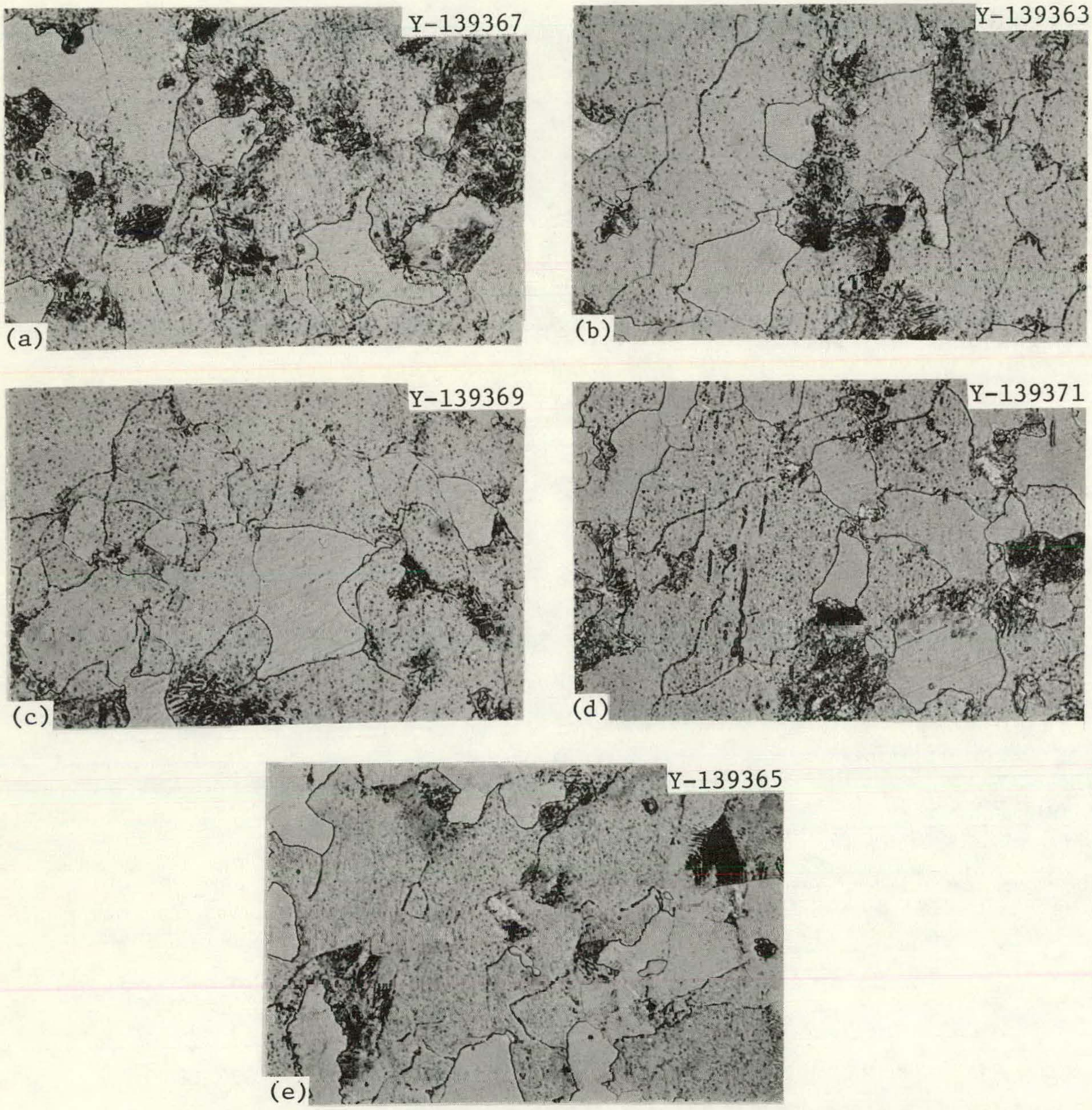

Fig. 2. Microstructures of Laboratory Isothermally Annealed Tubing Heats: (a) 36018, (b) 36302, (c) 72768, (d) 72871, and (e) X6216. 500×.

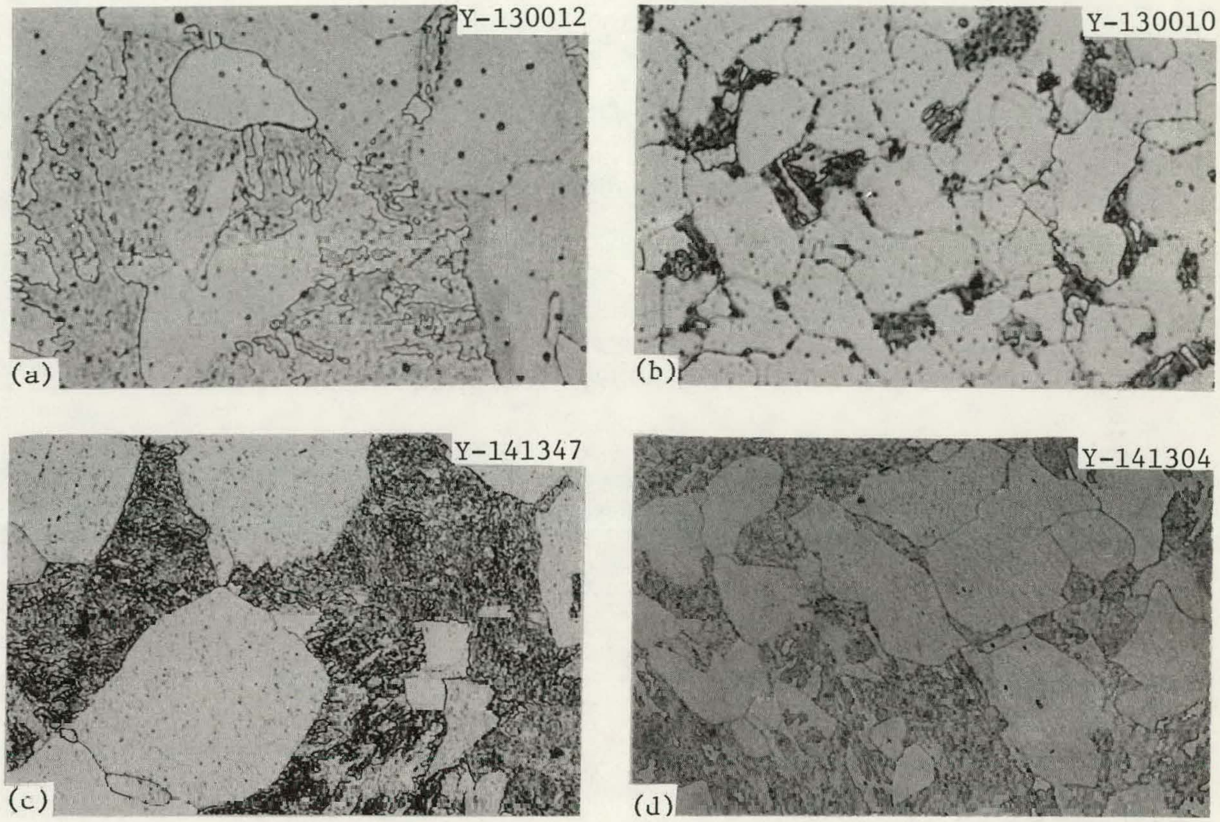

Fig. 3. Microstructures of As-Received VAR Forgings and ESR Plates: (a) VAR heat 13812, (b) VAR heat C60570, (c) ESR heat R0110, and (d) ESR heat XXR. 500×.

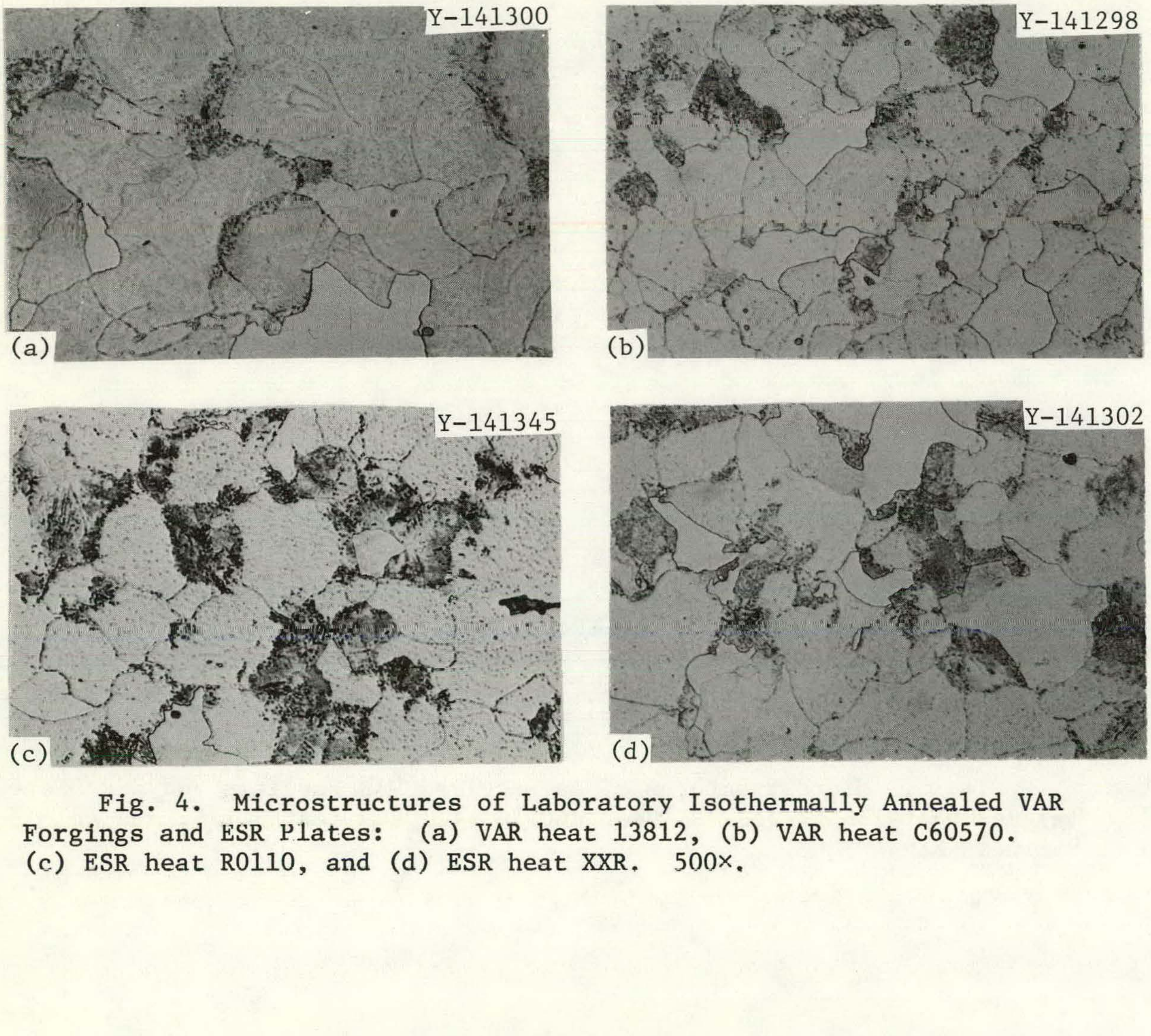

Fig. 4. Microstructures of Laboratory Isothermally Annealed VAR Forgings and ESR Plates: (a) VAR heat 13812, (b) VAR heat C60570. (c) ESR heat R0110, and (d) ESR heat XXR. 500×.

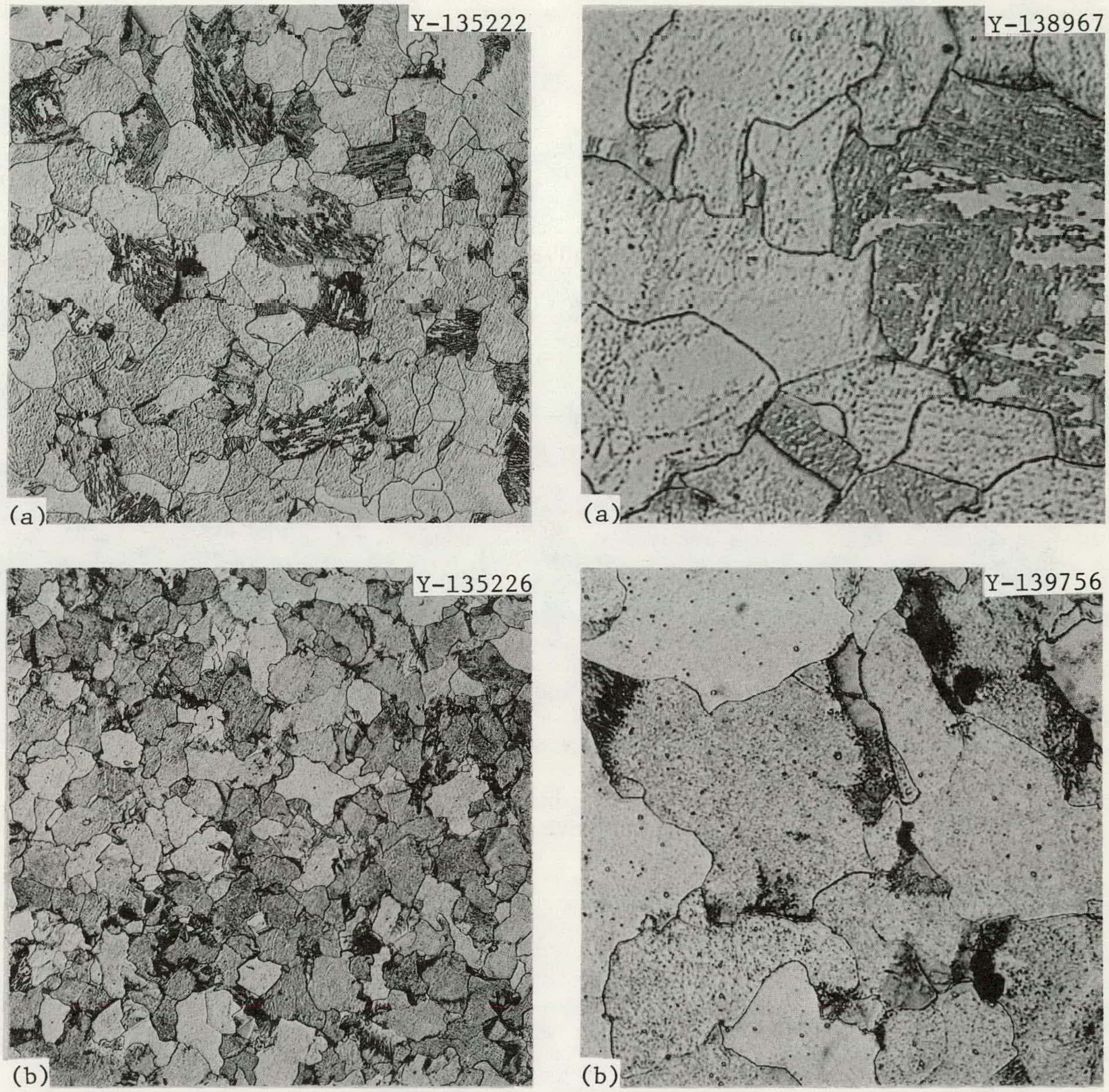

Fig. 5. Microstructures of the Air-Melted Forging: (a) As-received; (b) After Laboratory Isothermal Anneal. Left: 100×; right: 500×.

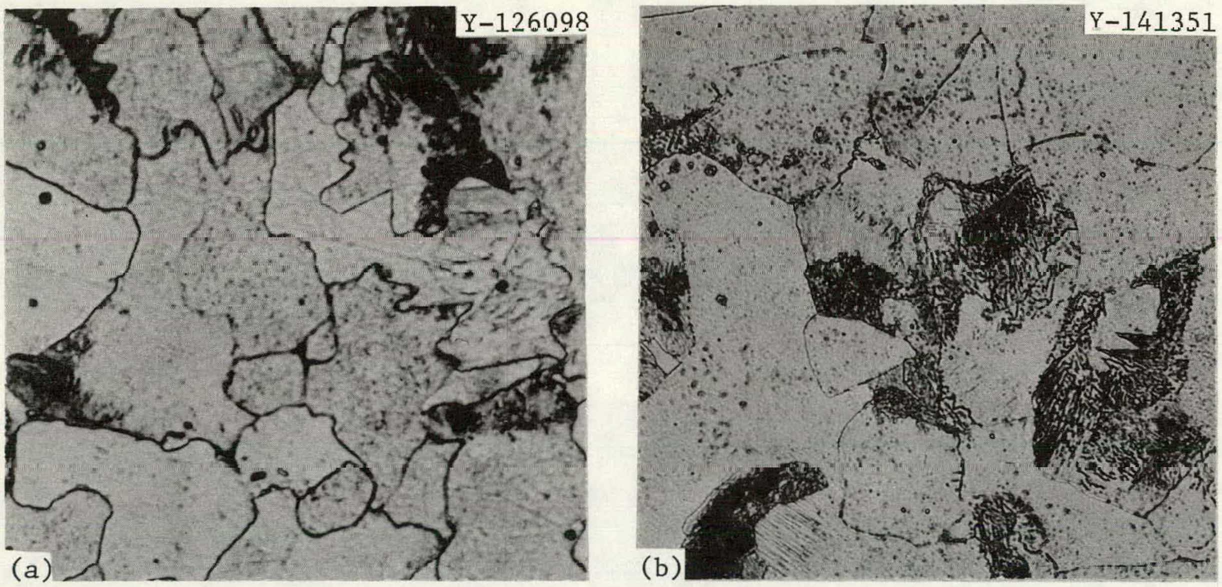

Fig. 6. Microstructures of Laboratory Isothermally Annealed Air-Melted Plates: (a) heat 20017 and (b) heat 3P5601. 500×.

Table 3. Grain Size as Determined by Intercept Method and DPH Microhardness for 2 1/4 Cr-1 Mo Steel Heats

| Heat | Grain Size, ASTM | | Microhardness, DPH | |
|---|---|---|---|---|
| | AR[a] | LIA[b] | AR[a] | LIA[b] |
| **Tubing Heats** | | | | |
| 36018 | 8.2 | 7.3 | 146 | 143 |
| 36202 | 7.7 | 7.8 | 143 | 146 |
| 72768 | 8.8 | 7.3 | 157 | 145 |
| 72871 | 8.8 | 8.2 | 149 | 141 |
| X6216 | 7.9 | 6.5 | 163 | 146 |
| **VAR Forging Heats** | | | | |
| 13812 | 4.8 | 6.5 | 163 | 133 |
| C60570 | 7.6 | 8.4 | 148 | 148 |
| **ESR (Lectrefine) Plates (0.15 m thick)** | | | | |
| R0110 | 6.2 | 7.8 | 154 | 136 |
| XXR | 6.8 | 7.5 | 168 | 136 |
| **Air-Melted Forging** | | | | |
| NF-60-8746 | 4.5 | 5.3 | 153 | 150 |
| **Air-Melted Plates (25 mm thick)** | | | | |
| 20017 | | 5.2 | | 156 |
| 3P5601 | | 4.8 | | 133 |

[a] As received.

[b] Laboratory isothermally annealed.

amount of the precipitate could occasionally be resolved as pearlite; most of the carbide spread through the proeutectoid ferrite matrix appeared as fine particles. There was up to 20% bainite present in the microstructures (most of the large dark patches in the micrographs). The main difference from heat to heat appears to be the amount of fine carbide particles in the proeutectoid ferrite of the microstructures. However, it is difficult to say whether there are large differences in the carbides, because of differences in etching characteristics of the different heats. In most cases the as-received material appears to contain less carbide precipitate than the material that received the laboratory isothermal anneal (Figs. 1–5), although at higher magnification the differences do not appear as great. The precipitates appear to be more dispersed in the as-received steel. In most cases the grain size of the as-received tubing is slightly smaller (larger grain size number) than it is after the laboratory isothermal anneal (Table 3).

The VAR and ESR steels were received in the normalized and tempered conditions (Fig. 3). Thus, the as-received microstructures contained considerable banite (about 35–40%). After the laboratory isothermal anneal, the microstructures were primarily proeutectoid ferrite with perhaps 20% bainite (Fig. 4). In this case, the grain size was smaller after the isothermal anneal (Table 3).

The specimens from the air-melted forging were taken from about 0.25 to 0.28 m (10–11 in.) from the center of the cylindrical forging. At this distance into the forging, considerable bainite was observed [Fig. 5(a)]. After the laboratory isothermal anneal, the microstructure was primarily proeutectoid ferrite with small amounts of carbide precipitates and bainite [Fig. 5(b)]. The microstructure of the laboratory isothermally annealed air-melted plates, heats 20017 and 3P5601, were primarily proeutectoid ferrite containing small precipitates and about 20% bainite (Fig. 6). The grain sizes of the air-melted plates and air-melted forgings are considerably larger than for both the as-received and laboratory isothermally annealed tubing heats (Table 3); they are also considerably larger than for the ESR plates and the one VAR forging after the laboratory isothermal anneal.

Metallography revealed that two types of bainite form, depending on how the steel was cooled through the bainite transformation temperature range. The different types of microstructure are demonstrated by the metallography of the air-melted forging (Fig. 5), where the massive dark constitutents in both microstructures are bainite.

When the steel is air cooled through the bainite transformation temperature region, the bainite has a blocky character and somewhat acicular appearance [Fig. 5(a)]. Although the as-received forging was isothermally annealed, it was air cooled from the isothermal hold temperature (732°C). The normalized (air cooled from the austenitizing temperature) and tempered forgings show a similar microstructure (Fig. 3). This type of bainite has been discussed quite extensively.[10,11] Habraken and Economopoulos[10] called this granular or massive bainite, since it differs morphologically from normal upper or lower bainite. These authors found that granular bainites formed more easily by continuous cooling, whereas the classical bainites form more readily during isothermal transformation.

Upper bainite formed when the specimens were furnace cooled after the isothermal hold; the black constitutent in Fig. 6(b) is the best illustration of this bainite. A furnace cool through this temperature range can be quite slow, allowing most of the transformation to occur at the upper temperature end of the bainite transformation temperature range. There is a tendency to want to identify this constituent as a fine pearlite, since it often has a lamellar (feathery) appearance, especially at high magnification. However, even at 1500× these platelets are usually not completely resolvable, which is typical of upper bainite.[12] There are two other reasons for concluding that this is

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[10] L. J. Habraken and M. Economopoulos, "Bainitic Microstructures of Low-Carbon Alloy Steels and Their Mechanical Properties," pp. 69–107 in *Transformation and Hardenability of Steels* (Climax Molybdenum Company, Ann Arbor, Michigan, 1967).

[11] R. L. Klueh, "Effect of Carbon on 2 1/4 Cr-1 Mo Steel (I) Microstructure and Tensile Properties," *J. Nucl. Mater.* 54: 41–54 (1975).

[12] F. B. Pickering, "The Structure and Properties of Bainite in Steels," pp. 109–129, *Transformation and Hardening of Steels* (Climax Molybdenum Company, Ann Harbor, Michigan, 1976).

bainite: (1) except for cobalt, all alloying elements increase the interlamellar spacing over what it is in carbon steels; hence, we would expect large spacings for 2 1/4 Cr-1 Mo steel. (2) When the same steel was given an identical isothermal anneal, but cooled differently from the isothermal hold temperature — one air cooled, the other furnace cooled — similar amounts of the two bainites were obtained.[9] Scattered pearlite with quite large spacings was occasionally seen in the microstructures of these steels.

## Tensile Properties

The tensile properties for all heats were determined at 25, 204, 371, 454, 510, and 566°C at a nominal strain rate of $7 \times 10^{-4}$/sec (Tables 4—9). A graphical presentation of the entire data compilation is difficult, since many of the data overlap. Therefore, the strengths for the various product forms in the as-received and laboratory isothermally annealed conditions are presented separately, along with a comparison of as-received and laboratory isothermally annealed steels for given product forms or melting practices (Figs. 7—9).

The as-received tubing heats show considerable scatter (Fig. 7(a)], with heat X6216 significantly stronger than the others in both the 0.2% yield strength and the ultimate tensile strength. After the laboratory isothermal anneal, the properties of the five heats differ much less, although X6216 is still the strongest [Fig. 7(b)]. With the exception of the as-received strength of X6216, the difference between the strength properties before and after the laboratory isothermal anneal (Fig. 7(c)] is not large. The ultimate tensile strengths are comparable, but the yield strengths of the laboratory isothermally annealed steels fall slightly below those of the as-received tubing at the higher temperatures.

A comparison of the strength properties of the VAR forgings and the ESR plates (Fig. 8) shows that after the laboratory isothermal anneal, the differences in strengths are considerably reduced. As might be expected, since the as-received material is normalized and tempered, it is stronger than the laboratory annealed material [Fig. 8(c)]. The yield strengths of as-received steel are considerably greater at all

Table 4. Tensile Properties[a] of Annealed 2 1/4 Cr-1 Mo Steel Tubing — As Received

| Temperature | | Stress, MPa (ksi) | | | Strain, % | | Reduction of Area (%) |
|---|---|---|---|---|---|---|---|
| (°C) | (°F) | Yield | Ultimate | Fracture | Uniform | Total | |
| | | | Heat 36018 | | | | |
| 25 | 77 | 324(47.0) | 495(71.9) | 288(41.8) | 15.0 | 25.3 | 73.6 |
| 204 | 400 | 270(39.2) | 452(65.6) | 282(40.9) | 9.4 | 16.3 | 65.8 |
| 371 | 700 | 220(31.9) | 513(74.4) | 327(47.4) | 9.6 | 15.8 | 62.9 |
| 454 | 850 | 217(31.5) | 478(69.4) | 277(40.2) | 8.6 | 16.4 | 68.4 |
| 510 | 950 | 201(29.1) | 435(63.2) | 213(30.9) | 9.5 | 19.5 | 70.5 |
| 566 | 1050 | 196(28.5) | 374(54.3) | 152(22.0) | 11.5 | 26.1 | 80.6 |
| | | | Heat 36202 | | | | |
| 25 | 77 | 299(43.4) | 504(73.1) | 276(40.9) | 14.4 | 23.7 | 76.4 |
| 204 | 400 | 263(38.2) | 450(65.3) | 263(38.1) | 9.5 | 16.6 | 70.8 |
| 371 | 700 | 229(33.3) | 508(73.8) | 300(43.6) | 9.1 | 16.3 | 65.3 |
| 454 | 850 | 207(30.0) | 449(65.2) | 207(30.0) | 9.2 | 18.0 | 72.3 |
| 510 | 950 | 209(30.3) | 422(61.2) | 174(25.2) | 9.1 | 19.7 | 80.0 |
| 566 | 1050 | 199(28.9) | 347(50.3) | 123(17.8) | 11.1 | 26.4 | 84.7 |
| | | | Heat 72768 | | | | |
| 25 | 77 | 339(49.2) | 548(79.6) | 314(45.5) | 13.0 | 22.7 | 69.3 |
| 204 | 400 | 281(40.8) | 477(69.3) | 287(41.7) | 11.1 | 18.4 | 68.8 |
| 371 | 400 | 240(34.8) | 533(77.3) | 327(47.4) | 9.3 | 15.8 | 65.2 |
| 454 | 850 | 229(33.2) | 480(69.6) | 254(36.8) | 10.0 | 18.2 | 68.8 |
| 510 | 950 | 221(32.1) | 431(62.6) | 192(27.8) | 8.4 | 20.1 | 73.7 |
| 566 | 1050 | 203(20.4) | 348(50.5) | 123(17.8) | 10.1 | 29.2 | 82.8 |
| | | | Heat 72871 | | | | |
| 25 | 77 | 319(46.3) | 500(72.5) | 280(40.6) | 14.6 | 25.3 | 73.0 |
| 204 | 400 | 260(37.8) | 446(64.8) | 263(38.2) | 9.8 | 17.6 | 72.2 |
| 371 | 700 | 225(32.7) | 511(74.1) | 305(44.2) | 9.5 | 16.0 | 66.7 |
| 454 | 850 | 208(30.2) | 464(67.4) | 241(35.0) | 9.7 | 18.0 | 69.5 |
| 510 | 950 | 204(29.6) | 409(59.3) | 174(25.3) | 9.0 | 21.0 | 79.2 |
| 566 | 1050 | 181(26.2) | 325(47.2) | 106(15.4) | 9.4 | 28.3 | 82.8 |
| | | | Heat X6216 | | | | |
| 25 | 77 | 353(51.3) | 562(81.5) | 324(47.0) | 12.4 | 20.0 | 71.1 |
| 204 | 400 | 314(45.5) | 510(74.0) | 312(45.3) | 8.8 | 15.3 | 66.8 |
| 371 | 700 | 288(41.8) | 565(82.0) | 349(50.6) | 9.0 | 15.9 | 61.0 |
| 454 | 850 | 291(42.2) | 516(74.9) | 265(38.4) | 8.7 | 16.6 | 71.2 |
| 510 | 950 | 260(37.8) | 467(67.8) | 202(29.3) | 8.6 | 17.8 | 75.4 |
| 566 | 1050 | 254(36.9) | 391(56.7) | 147(21.3) | 8.7 | 23.5 | 79.9 |

[a] Crosshead speed: 0.02 mm/sec (0.05 in./min; nominal strain rate: $7.3 \times 10^{-4}$/sec.

Table 5. Tensile Properties[a] of Annealed 2 1/4 Cr-1 Mo Steel Tubing — Laboratory Isothermally Annealed

| Temperature | | Stress, MPa (ksi) | | | Strain, % | | Reduction of Area |
|---|---|---|---|---|---|---|---|
| (°C) | (°F) | Yield | Ultimate | Fracture | Uniform | Total | (%) |
| | | | Heat 36018 | | | | |
| 25 | 77 | 313(45.4) | 505(73.3) | 306(44.4) | 13.1 | 23.8 | 71.9 |
| 204 | 400 | 279(40.5) | 479(69.5) | 323(46.9) | 7.5 | 14.0 | 67.4 |
| 371 | 700 | 233(33.8) | 525(76.2) | 344(49.9) | 8.9 | 14.7 | 60.9 |
| 454 | 850 | 206(29.9) | 483(70.1) | 255(37.0) | 9.3 | 17.1 | 71.0 |
| 510 | 950 | 193(28.0) | 440(63.8) | 198(28.8) | 9.0 | 17.7 | 70.1 |
| 566 | 1050 | 185(26.9) | 340(49.4) | 107(15.5) | 9.4 | 27.5 | 85.3 |
| | | | Heat 36202 | | | | |
| 25 | 77 | 305(44.2) | 514(74.6) | 309(44.8) | 13.5 | 24.5 | 72.4 |
| 204 | 400 | 263(38.2) | 473(68.6) | 311(45.2) | 8.7 | 18.3 | 67.8 |
| 371 | 700 | 238(34.6) | 521(75.6) | 344(49.9) | 9.3 | 15.8 | 58.9 |
| 454 | 850 | 187(27.2) | 480(69.6) | 263(38.2) | 10.5 | 17.7 | 68.7 |
| 510 | 950 | 185(26.9) | 427(62.0) | 201(29.2) | 9.5 | 20.3 | 74.7 |
| 566 | 1050 | 172(24.9) | 340(49.4) | 123(17.9) | 9.0 | 31.1 | 84.6 |
| | | | Heat 72768 | | | | |
| 25 | 77 | 303(44.0) | 485(70.4) | 268(38.9) | 14.2 | 24.7 | 80.1 |
| 204 | 400 | 251(36.4) | 456(66.2) | 274(39.7) | 8.7 | 16.7 | 73.9 |
| 371 | 700 | 232(33.6) | 505(73.3) | 304(44.1) | 9.1 | 16.7 | 67.9 |
| 454 | 850 | 187(27.1) | 460(66.8) | 235(34.1) | 8.5 | 16.8 | 78.6 |
| 510 | 950 | 172(24.9) | 416(60.4) | 178(25.9) | 9.2 | 19.0 | 72.4 |
| 566 | 1050 | 165(23.9) | 328(47.6) | 101(14.6) | 11.3 | 28.4 | 84.7 |
| | | | Heat 72871 | | | | |
| 25 | 77 | 315(45.7) | 511(74.2) | 297(43.1) | 13.7 | 23.2 | 77.0 |
| 204 | 400 | 260(37.8) | 456(66.2) | 280(40.7) | 8.7 | 16.5 | 72.2 |
| 371 | 700 | 238(34.5) | 516(74.9) | 319(46.3) | 9.5 | 16.2 | 63.4 |
| 454 | 850 | 194(28.2) | 475(68.9) | 251(36.5) | 9.1 | 18.1 | 65.1 |
| 510 | 950 | 179(25.9) | 424(61.5) | 184(26.7) | 9.0 | 19.4 | 73.6 |
| 566 | 1050 | 163(23.7) | 306(44.4) | 100(14.5) | 8.2 | 33.1 | 86.0 |
| | | | Heat X6216 | | | | |
| 25 | 77 | 323(46.9) | 523(75.9) | 299(43.4) | 12.7 | 21.0 | 73.4 |
| 204 | 400 | 271(39.4) | 484(70.3) | 299(43.4) | 7.4 | 14.1 | 70.8 |
| 371 | 700 | 251(36.4) | 546(79.2) | 345(50.0) | 8.9 | 15.6 | 64.8 |
| 454 | 850 | 224(32.5) | 496(72.0) | 253(36.7) | 8.2 | 16.3 | 72.1 |
| 510 | 950 | 216(31.3) | 441(64.0) | 181(26.3) | 8.9 | 20.3 | 79.0 |
| 566 | 1050 | 205(29.7) | 332(48.0) | 89(12.9) | 6.8 | 27.0 | 85.4 |

[a] Crosshead speed: 0.02 mm/sec (0.05 in./min); nominal strain rate: 7.3 × $10^{-4}$/sec.

Table 6. Tensile Properties[a] of VAR and ESR Forgings — As Received

| Temperature | | Strength, MPa(ksi) | | | Elongation, % | | Reduction of Area |
|---|---|---|---|---|---|---|---|
| (°C) | (°F) | Yield | Ultimate | Fracture | Uniform | Total | (%) |
| | | | Heat 13812 (VAR) | | | | |
| 25 | 75 | 325(47.1) | 533(77.3) | 308(44.7) | 9.4 | 17.9 | 66.9 |
| 204 | 400 | 301(43.7) | 464(67.3) | 302(43.9) | 7.5 | 14.8 | 66.0 |
| 371 | 700 | 295(42.8) | 482(69.9) | 306(44.4) | 6.9 | 12.2 | 49.8 |
| 454 | 850 | 292(42.3) | 439(63.7) | 272(39.5) | 6.3 | 13.4 | 45.3 |
| 510 | 950 | 265(38.5) | 383(55.6) | 179(26.0) | 6.3 | 18.3 | 64.2 |
| 566 | 1050 | 251(36.4) | 316(45.9) | 90(13.0) | 5.0 | 21.7 | 73.9 |
| | | | Heat C60570 (VAR) | | | | |
| 25 | 75 | 361(52.3) | 527(76.5) | 369(53.6) | 13.4 | 22.3 | 60.6 |
| 204 | 400 | 299(43.3) | 464(67.3) | 280(40.7) | 10.2 | 18.3 | 72.2 |
| 371 | 700 | 265(38.4) | 492(71.4) | 331(48.1) | 8.8 | 14.9 | 60.1 |
| 454 | 850 | 263(38.2) | 455(66.0) | 266(38.6) | 8.8 | 16.1 | 65.6 |
| 510 | 950 | 232(33.6) | 416(60.4) | 249(36.1) | 9.8 | 18.7 | 65.6 |
| 566 | 1050 | 239(34.7) | 352(51.4) | 136(19.7) | 10.1 | 23.9 | 80.5 |
| | | | Heat XXR (ESR) | | | | |
| 25 | 75 | 365(52.9) | 570(82.6) | 296(42.9) | 9.6 | 18.4 | 73.9 |
| 204 | 400 | 327(47.4) | 501(72.6) | 285(41.3) | 8.1 | 16.3 | 73.1 |
| 371 | 700 | 322(46.7) | 513(74.4) | 325(47.2) | 6.9 | 13.5 | 61.0 |
| 454 | 850 | 310(44.9) | 473(68.6) | 241(35.0) | 6.5 | 15.8 | 66.9 |
| 510 | 950 | 301(43.7) | 426(61.8) | 190(27.5) | 6.1 | 18.2 | 77.1 |
| 566 | 1050 | 272(39.4) | 356(51.6) | 96(13.9) | 6.4 | 22.3 | 82.6 |
| | | | Heat R0110 (ESR) | | | | |
| 25 | 77 | 313(45.5) | 521(75.6) | 271(39.4) | 11.5 | 22.9 | 76.5 |
| 204 | 400 | 269(39.1) | 446(64.8) | 229(33.2) | 9.9 | 18.7 | 72.5 |
| 371 | 700 | 282(40.9) | 455(66.1) | 276(40.1) | 7.9 | 15.6 | 68.2 |
| 454 | 850 | 269(39.1) | 427(62.0) | 229(33.2) | 8.5 | 17.8 | 72.3 |
| 510 | 950 | 257(37.3) | 376(54.5) | 172(24.9) | 6.8 | 18.3 | 74.9 |
| 566 | 1050 | 240(34.9) | 318(46.2) | 114(16.5) | 6.8 | 30.8 | 81.8 |

[a] Crosshead speed: 0.02 mm/sec (0.05 in./min; nominal strain rate: $7.3 \times 10^{-4}$/sec.

Table 7. Tensile Properties[a] of VAR and ESR Forgings — Laboratory Isothermal Anneal

| Temperature | | Strength MPa (ksi) | | | Elongation, % | | Reduction of Area |
|---|---|---|---|---|---|---|---|
| (°C) | (°F) | Yield | Ultimate | Fracture | Uniform | Total | (%) |
| | | | Heat 13812 (VAR) | | | | |
| 25 | 75 | 273(39.6) | 503(73.0) | 302(43.9) | 12.2 | 20.2 | 70.8 |
| 204 | 400 | 223(32.3) | 417(60.5) | 265(38.4) | 10.0 | 17.2 | 65.2 |
| 371 | 700 | 209(30.3) | 465(67.4) | 314(45.6) | 9.0 | 14.8 | 58.0 |
| 454 | 850 | 210(30.4) | 432(62.6) | 262(38.1) | 9.2 | 17.6 | 56.1 |
| 510 | 950 | 202(29.3) | 386(56.0) | 196(28.5) | 8.8 | 17.4 | 63.0 |
| 566 | 1050 | 191(27.7) | 312(45.2) | 123(17.8) | 7.5 | 26.0 | 72.2 |
| 25 | 75 | 254(36.9) | 508(73.7) | 328(47.6) | 11.3 | 20.9 | 66.6 |
| 204 | 400 | 225(32.7) | 429(62.2) | 277(40.2) | 8.9 | 17.2 | 63.5 |
| 316 | 600 | 244(35.4) | 464(67.4) | 329(47.7) | 7.2 | 14.8 | 55.5 |
| 371 | 700 | 251(36.4) | 468(67.9) | 260(37.8) | 8.0 | 14.6 | 55.6 |
| 454 | 850 | 225(32.7) | 433(62.8) | 273(39.6) | 8.2 | 16.5 | 61.6 |
| 510 | 950 | 220(31.9) | 390(56.6) | 240(34.8) | 8.8 | 17.4 | 60.4 |
| 566 | 1050 | 203(29.5) | 318(46.1) | 90(13.1) | 8.4 | 29.4 | 78.3 |
| | | | Heat C60570 (VAR) | | | | |
| 25 | 75 | 289(41.9) | 467(67.7) | 287(41.7) | 14.6 | 25.6 | 66.7 |
| 204 | 400 | 229(33.2) | 396(57.5) | 270(39.2) | 13.5 | 20.7 | 62.6 |
| 371 | 700 | 199(28.9) | 436(63.2) | 329(47.8) | 9.5 | 15.2 | 56.4 |
| 454 | 850 | 174(25.2) | 409(59.3) | 252(36.5) | 9.8 | 18.7 | 65.6 |
| 510 | 950 | 166(24.0) | 366(53.1) | 164(23.8) | 9.6 | 20.6 | 76.1 |
| 566 | 1050 | 161(23.3) | 310(45.0) | 113(16.4) | 9.7 | 27.3 | 74.5 |
| 25 | 75 | 272(39.5) | 469(68.0) | 315(45.7) | 16.9 | 26.5 | 62.6 |
| 204 | 400 | 222(32.2) | 398(57.7) | 287(41.7) | 13.7 | 22.2 | 63.9 |
| 316 | 600 | 201(29.2) | 413(60.0) | 287(41.6) | 10.1 | 17.5 | 55.9 |
| 371 | 700 | 194(28.1) | 422(61.3) | 294(42.7) | 9.7 | 16.4 | 51.7 |
| 454 | 850 | 178(25.9) | 402(58.4) | 246(35.7) | 9.8 | 19.1 | 61.4 |
| 510 | 950 | 189(27.4) | 362(52.6) | 191(27.7) | 9.7 | 22.2 | 68.6 |
| 566 | 1050 | 165(24.0) | 305(44.3) | 130(18.9) | 8.4 | 28.8 | 78.3 |
| | | | Heat XXR (ESR) | | | | |
| 25 | 75 | 276(40.0) | 461(66.9) | 259(37.6) | 15.2 | 25.6 | 75.5 |
| 204 | 400 | 217(31.4) | 390(56.5) | 202(29.3) | 10.9 | 19.6 | 74.6 |
| 371 | 700 | 200(28.1) | 419(60.7) | 266(38.6) | 8.1 | 15.1 | 67.8 |
| 454 | 850 | 170(24.6) | 406(58.9) | 230(33.4) | 9.2 | 16.8 | 65.0 |
| 510 | 950 | 168(24.3) | 370(53.7) | 184(26.7) | 10.1 | 18.6 | 70.6 |
| 566 | 1050 | 159(23.1) | 312(45.2) | 90(13.0) | 10.2 | 29.6 | 78.5 |
| | | | Heat R0110 (ESR) | | | | |
| 25 | 75 | 267(38.7) | 476(69.1) | 282(40.9) | 14.2 | 23.3 | 73.7 |
| 204 | 400 | 237(34.4) | 433(62.9) | 263(38.2) | 10.9 | 19.2 | 73.0 |
| 371 | 700 | 206(29.9) | 464(67.4) | 311(45.1) | 8.2 | 14.9 | 63.5 |
| 454 | 850 | 190(27.6) | 442(64.1) | 255(37.0) | 8.7 | 17.2 | 66.4 |
| 510 | 950 | 194(28.2) | 416(60.4) | 217(31.5) | 9.6 | 20.0 | 67.1 |
| 566 | 1050 | 186(27.0) | 342(49.7) | 136(19.7) | 10.0 | 27.2 | 82.3 |

[a] Crosshead speed: 0.02 mm/sec (0.05 in./min; nominal strain rate: $7.3 \times 10^{-4}$/sec.

Table 8. Tensile Properties of Air-Melted 2 1/4 Cr-1 Mo Steel Tubesheet Forging[a]

| Temperature |  | Strength, MPa (ksi) |  |  | Elongation, % |  | Reduction of Area |
|---|---|---|---|---|---|---|---|
| (°C) | (°F) | Yield | Ultimate | Fracture | Uniform | Total | (%) |
|  |  |  | As Received |  |  |  |  |
| 25 | 77 | 254(36.9) | 522(75.7) | 393(57.0) | 14.7 | 27.8 | 52.7 |
| 204 | 400 | 239(34.7) | 473(68.6) | 366(53.1) | 12.2 | 22.3 | 47.5 |
| 316 | 600 | 246(35.7) | 504(73.1) | 416(60.6) | 10.2 | 17.7 | 43.4 |
| 371 | 700 | 230(33.4) | 508(73.7) | 422(61.3) | 9.5 | 17.8 | 42.7 |
| 454 | 850 | 225(32.6) | 521(75.6) | 429(62.2) | 9.9 | 18.2 | 39.7 |
| 510 | 950 | 231(33.5) | 513(74.4) | 387(56.1) | 10.5 | 19.8 | 42.2 |
| 566 | 1050 | 232(33.6) | 478(69.4) | 336(48.8) | 11.9 | 23.4 | 51.6 |
|  |  |  | Laboratory Isothermal Annealed |  |  |  |  |
| 25 | 77 | 262(38.0) | 515(74.7) | 289(42.0) | 12.1 | 30.1 | 74.9 |
| 204 | 400 | 221(32.1) | 446(64.7) | 247(35.9) | 10.5 | 24.2 | 73.1 |
| 316 | 600 | 240(34.8) | 491(71.3) | 331(48.1) | 8.4 | 20.0 | 68.5 |
| 371 | 700 | 232(33.7) | 502(72.9) | 336(48.7) | 9.6 | 20.0 | 60.7 |
| 454 | 850 | 234(34.0) | 466(67.7) | 276(40.1) | 9.1 | 22.8 | 67.9 |
| 510 | 950 | 231(33.5) | 423(61.4) | 197(28.6) | 7.9 | 24.2 | 72.4 |
| 566 | 1050 | 207(30.1) | 339(49.2) | 50( 7.2) | 6.4 | 33.4 | 82.5 |

[a] Crosshead speed: 0.02 mm/sec (0.5 in/min); nominal strain rate: $7.3 \times 10^{-4}$/sec.

Table 9. Tensile Properties of Air-Melted 25.4-mm-Thick Plates of 2 1/4 Cr-1 Mo Steel After a Laboratory Isothermal Anneal[a]

| Temperature | | Strength, MPa (ksi) | | | Elongation, % | | Reduction of Area (%) |
|---|---|---|---|---|---|---|---|
| (°C) | (°F) | Yield | Tensile | Fracture | Uniform | Total | |
| | | | | Heat 20017 | | | |
| 25 | 75 | 254(36.8) | 521(75.6) | 309(44.9) | 12.4 | 27.8 | 70.8 |
| 204 | 400 | 220(31.9) | 452(65.6) | 288(41.8) | 10.2 | 23.0 | 67.3 |
| 316 | 600 | 225(32.7) | 495(71.8) | 355(51.5) | 10.1 | 21.0 | 62.1 |
| 371 | 700 | 228(33.1) | 505(73.3) | 349(50.7) | 9.7 | 20.5 | 57.7 |
| 454 | 850 | 217(31.5) | 475(68.9) | 271(39.4) | 8.9 | 23.6 | 65.2 |
| 510 | 950 | 214(31.0) | 423(61.4) | 189(27.5) | 8.2 | 23.6 | 71.7 |
| 566 | 1050 | 207(30.1) | 354(51.4) | 78(11.3) | 7.1 | 32.8 | 80.2 |
| | | | | Heat 3P5601 | | | |
| 25 | 75 | 220(32.0) | 484(70.3) | 321(46.6) | 14.9 | 28.4 | 67.1 |
| 204 | 400 | 214(31.1) | 429(62.2) | 274(39.7) | 8.4 | 19.1 | 68.2 |
| 316 | 600 | 187(27.2) | 449(65.1) | 330(47.9) | 9.9 | 19.4 | 60.1 |
| 371 | 700 | 192(27.8) | 458(66.5) | 328(47.6) | 9.6 | 19.1 | 60.8 |
| 454 | 850 | 177(25.7) | 423(61.4) | 258(37.5) | 11.1 | 23.5 | 69.1 |
| 510 | 950 | 178(25.8) | 376(54.6) | 185(26.9) | 11.0 | 26.5 | 74.0 |
| 566 | 1050 | 169(24.5) | 311(45.1) | 132(19.1) | 9.8 | 34.8 | 82.4 |

[a] Crosshead speed: 0.02 mm/sec (0.05 in./min; nominal strain rate: $7.3 \times 10^{-4}$/sec.

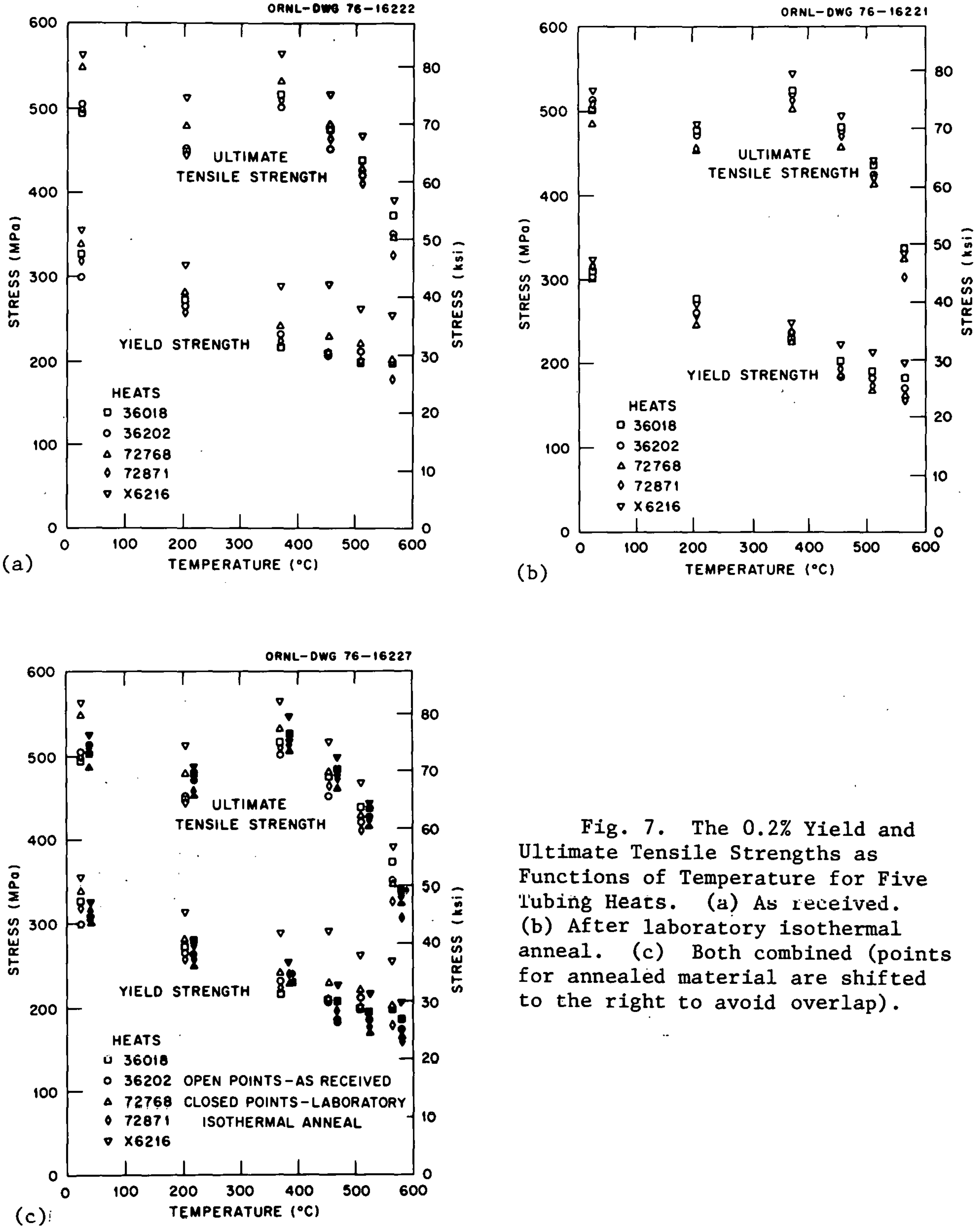

Fig. 7. The 0.2% Yield and Ultimate Tensile Strengths as Functions of Temperature for Five Tubing Heats. (a) As received. (b) After laboratory isothermal anneal. (c) Both combined (points for annealed material are shifted to the right to avoid overlap).

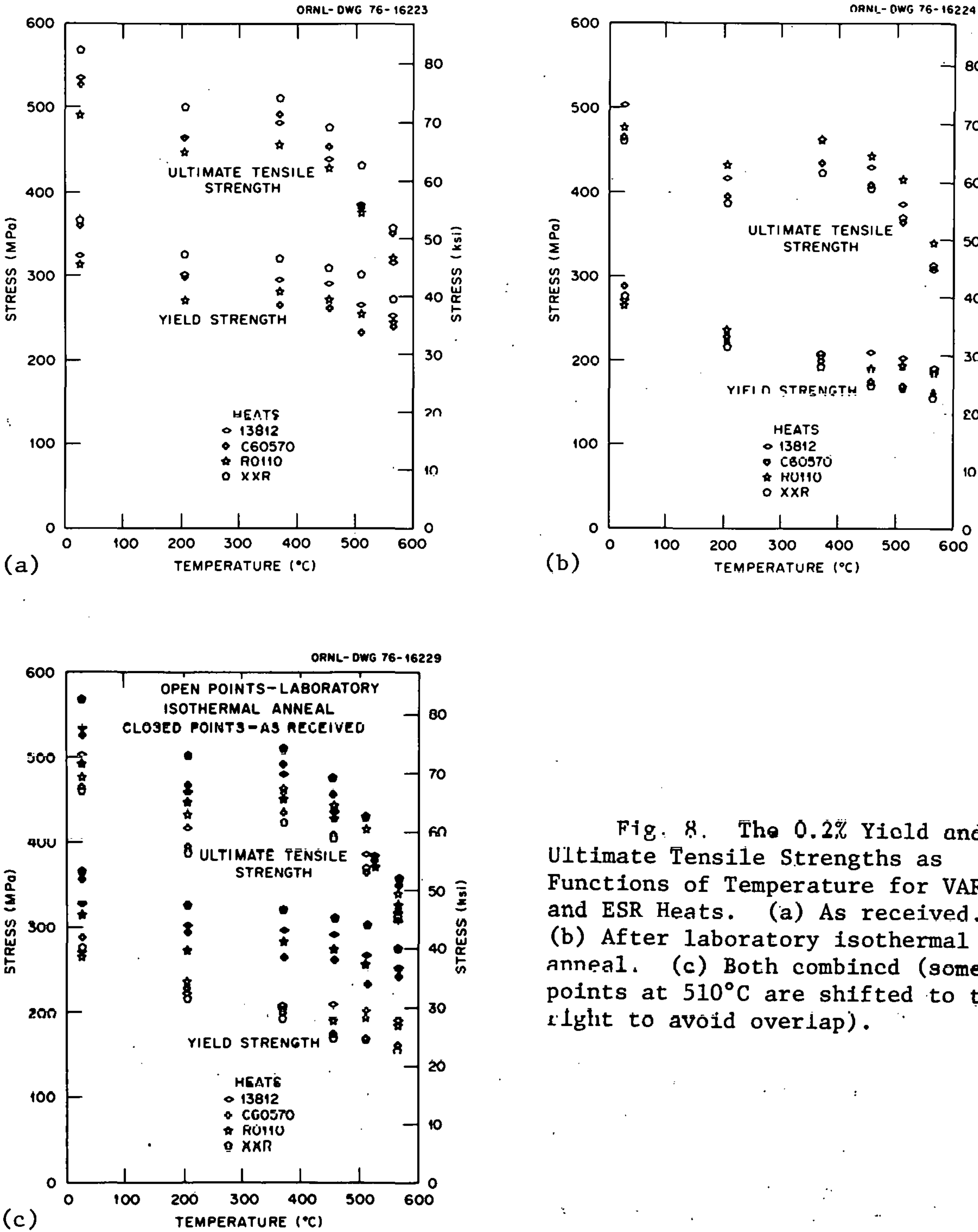

Fig. 8. The 0.2% Yield and Ultimate Tensile Strengths as Functions of Temperature for VAR and ESR Heats. (a) As received. (b) After laboratory isothermal anneal. (c) Both combined (some points at 510°C are shifted to the right to avoid overlap).

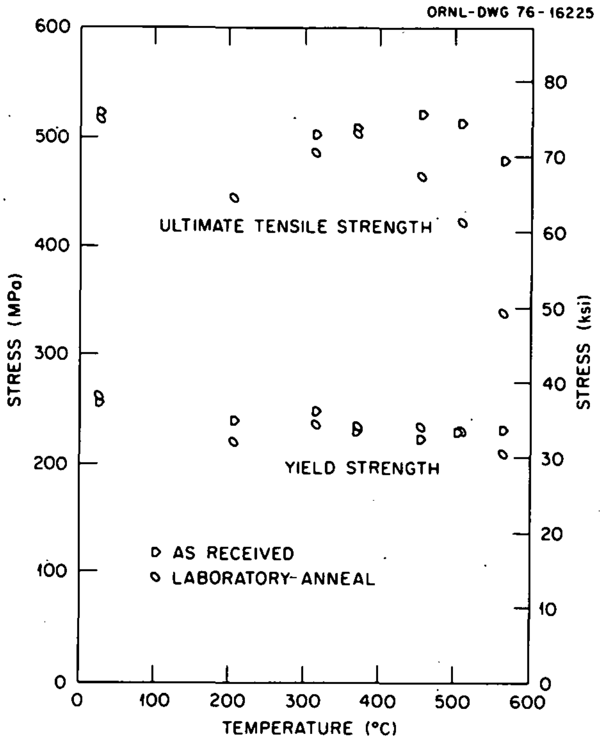

Fig. 9. The 0.2% Yield Strength and Ultimate Tensile Strength for Air-Melted Forging As-Received and Laboratory Isothermally Annealed.

temperatures; however, the ultimate tensile strengths of the as-received and laboratory isothermally annealed steels approach each other above 454°C [Fig. 8(c)]. The narrow range of the properties of the four steels shows that the VAR and ESR strengths differ little after they have been similarly heat-treated [Fig. 8(b)].

Although the yield strengths for the air-melted forging in the as-received condition (isothermally annealed) and the laboratory isothermally annealed condition are similar, the ultimate tensile strengths for the two heat treatments differ considerably above 371°C. This difference is primarily due to the difference in the temperature of the dynamic strain aging peak for the two different heat treatments. The peak occurs near 454°C for the as-received forging but near 371°C for the laboratory isothermally annealed material. Above the peak temperatures, the strength drops off considerably faster for the laboratory isothermally annealed steel [Fig. 9(a)].

In the isothermally annealed condition, heat 20017 was the stronger of the two air-melted plates (Fig. 10). It also exhibited a higher dynamic strain aging peak relative to the room-temperature ultimate tensile strength.

The ductilities[13] for these different product forms were all quite similar (Tables 4—8). With a few exceptions, at 25°C the total elongation was between 20 and 30%, the reduction of area between 70 and 80%; the uniform elongation for all heats was between 10 and 15%. The exceptions for the total elongation or the reduction of area include the as-received VAR and ESR steels, the as-received air-melted forging, and the air-melted plate heat 3P5601. The as-received VAR and ESR steels are normalized and tempered and are expected to have a reduced ductility. Actually, their 25°C ductilities fall only slightly below the range of values cited above. Similarly most of the other exceptions fall only slightly below the range of values noted. Although the air-melted

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[13] Note that a direct comparison of the ductilities for all the steels is difficult since two types of specimen geometry were tested.

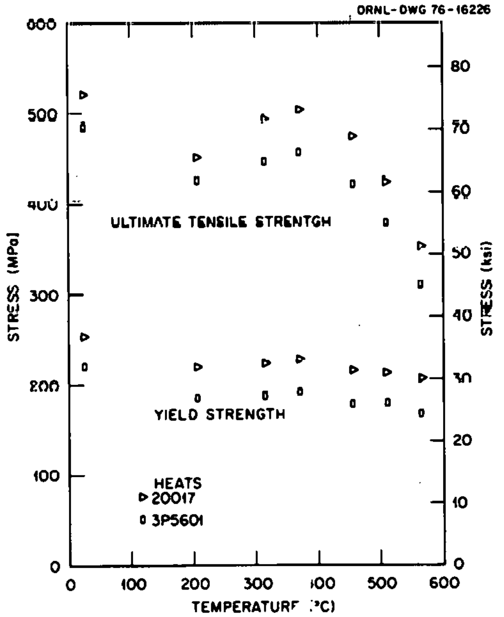

Fig. 10. The 0.2% Yield Strength and Ultimate Tensile Strength for Air-Melted Plates in the Laboratory Isothermally Annealed Condition.

forging in the as-received conditions had only a 52% reduction of area, it had a total elongation of almost 28%. It also exhibited a greater than average uniform elongation.

The ductility behavior with temperature is also similar for all heats: the total elongation and reduction of area go through minima with increasing temperature; the highest values for these indices occur at 566°C, the highest test temperature, where the reduction of area generally exceeds 70% and the total elongation exceeds about 24%. Two of the normalized-and-tempered heats (13812 and XXR) had slightly smaller total elongations. Both the total elongation and reduction of area of the as-received air-melted forging at 566°C fall below these values. The reduction of area is only 52%, considerably below the 70% or more observed for all other heats. Note that this forging had been isothermally annealed by the National Forging Company.

The uniform elongation shows a general decrease with increasing temperature. The uniform elongation values for the as-received air-melted forging were quite a bit larger than for the laboratory isothermally annealed condition; this was the opposite of the observations on total elongation and reduction of area discussed above. Similarly, a comparison of data (Tables 4 and 5) for the tubing heats indicates that the uniform elongations of the as-received steels are generally greater than those that received the laboratory isothermal anneal. The laboratory isothermal anneal generally led to slightly greater total elongations and reductions of area and lower strengths than those of the as-received tubing.

## DISCUSSION

To compare the strength properties among the various heats, they must receive a common heat treatment. This was the purpose of the laboratory isothermal anneal. Quite a range of strength properties are presented by the 12 heats tested. In order that the different melting practices and product forms can be more easily compared, the data were replotted as scatter bands and curves (Fig. 11). The as-received steel shows considerably more scatter.

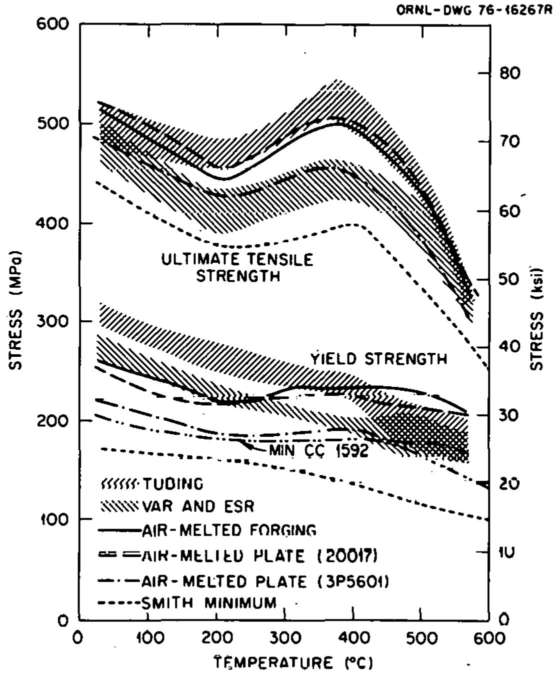

Fig. 11. The 0.2% Yield Strength and Ultimate Tensile Strength for the 12 Heats of 2 1/4 Cr-1 Mo Steel in the Laboratory Isothermally Annealed Condtion. Scatterbands are shown for the tubing and VAR and ESR data and curves for the air-melted plates and forgings. Also shown are the minimum values from Code Case 1592 and Smith's data compilation.

All the data fall above the Smith[5] minimum, and with the exception of VAR and ESR tests between 400 and 500°C, the data fell above the Code Case 1592 minimum. All data fell below the upper limits in Smith's compilation for yield and tensile strength, although the upper limit of the tubing heats approached that limit between 25 and 371°C.

Since the strengths of the as-received material of each product form fell above those for the laboratory isothermal anneal, these data obviously fell above the Smith and Code Case 1592 minimums. The ultimate tensile strength of the tubing heat X6216 fell above the Smith upper limit between 25 and 371°C, while the yield strength approached the upper limit over the entire temperature range. The ultimate tensile strength of the VAR and the ESR steels, which were normalized and tempered, fell within Smith's scatter bands. On the average, the ultimate tensile strengths for the as-received VAR and ESR heats were less than those for the tubing heats while the yield strengths were greater.

The strength of a steel over and above that of pure iron can be considered to be the result of a combination of several effects: (1) grain size, (2) solid solution strengthening, (3) strength due to dislocations acting as barriers to the motion of other dislocations, and (4) dispersion strengthening due to precipitates. The yield strength $\sigma_y$ can therefore be written as:

$$\sigma_y = \sigma_{Fe} + \Delta\sigma_{gs} + \Delta\sigma_{ss} + \Delta\sigma_d + \Delta\sigma_p \ , \tag{1}$$

where $\sigma_{Fe}$ is the basic strength of unalloyed iron, $\Delta\sigma_{gs}$, $\Delta\sigma_{ss}$, $\Delta\sigma_d$, and $\Delta\sigma_p$ are contributions to the strength due to grain size, solid solution hardening, dislocations, and precipitate particles, respectively.

The grain size effect is explained by the well-known Hall-Petch relation:[14,15]

$$\Delta\sigma_{gb} = k_y d^{-1/2} \ , \tag{2}$$

where $k_y$ is a constant and $d$ the average grain diameter. The Hall-Petch relation is generally written as:

$$\sigma_y = \sigma_0 + k_y d^{-1/2} \ , \tag{3}$$

where $\sigma_0$ is a lattice friction stress that includes effects of precipitates, solid solution, and dislocations, which are being treated separately in this discussion.

For the solid solution strengthening effect, all solutes must be considered; thus,[16]

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[14] E. O. Hall, "Deformation and Aging of Mild Steel III. Discussion of Results," *Proc. Phys. Soc. (London)* 64B: 747–53 (1951).

[15] N. J. Petch, "Cleavage Strength of Polycrystals," *J. Iron Steel Inst.* 174: 25–8 (1953).

[16] F. B. Pickering and T. Gladman, "An Investigation Into Some Factors Which Control the Strength of Carbon Steels," *Metallurgical Development in Carbon Steels, Iron Steel Inst. London Spec. Rep.* 81: 10–20 (1963).

$$\Delta\sigma_{ss} = \sum k_i \ (X_i) \ , \qquad (4)$$

where $X_i$ is the concentration of the $i$th solute and $k_i$ is the proportionality constant for the $i$th solute. If we consider chemical composition differences between heats (Table 2), there is little variation in the concentration of any given element. With respect to carbon, which is often considered most important, only about 0.01% is soluble; thus, all heats are on an equal basis relative to solid solution hardening by carbon. All heats were analyzed for nitrogen and again no significant differences were detected: all heats contained between 0.011 and 0.012 wt %.

Chalco[17] analyzed the overall contribution due to solid solution strengthening for 2 1/4 Cr-1 Mo steel and found it made an insignificant contribution. This result follows from the fact that chromium has a negative $k_i$.[15] Hence, even though the absolute value of $k_i$ for elements such as C, N, Mo, and Mn are larger than those for Cr, the $X_i$ values are small. Thus, the negative chromium effect cancels the effect due to the other elements.

Strengthening can arise from dislocations: in the matrix which act as barriers to the motion of other dislocations and from dislocations in subgrain boundaries. If only the strength after the initial heat treatment is considered, the latter effect will be insignificant. For the first effect,

$$\Delta\sigma_d = \beta G b \rho^{1/2} \ , \qquad (5)$$

where $\beta$ is a constant, $G$ the shear modulus, $b$ the Burger's vector, and $\rho$ the dislocation density. Part of the strength difference between the as-received and the laboratory isothermally annealed properties of the tubing heats could be the result of such a strengthening process. Tubes are often straightened in the mill after annealing. Such straightening introduces cold work and thus increases the dislocation density.

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[17] P. A. Chalco, *Microstructure and Mechanical Properties of Cr-Mo Steels,* Ph.D. Thesis, University of California at Los Angeles, 1974.

Finally, hardening due to dispersion strengthening is usually discussed in terms of the Orowan-Ashby equation,[18]

$$\Delta\sigma_p = \frac{0.13\ Gb}{\lambda} \ln \frac{r}{b} , \qquad (6)$$

where $\lambda$ and $r$ are the particle spacing and radius respectively. Dispersion strengthening should make a significant contribution to the strength.

This discussion indicates that the strength differences among the heats after a common anneal will be due to differences in grain size and precipitate. Differences due to dislocation structures and solid solution hardening should be minimal after a common anneal.

Generally, the grain size effect is greatest at low temperatures. When the room temperature data are examined, the expected inverse relationship between yield strength and grain size is qualitatively obeyed for the air-melted plates and tubes (Fig. 11). That is, heat 3P5601 has the lowest yield strength, followed by 20017, the air-melted forging, and then the scatter band for the tubing heats. This is the same order as that in which the grain size number increases and is inverse to the change in grain diameter. However, when the tubing heats themselves are examined we find that X6216 has the largest grain size and the highest strength — just the opposite of what is expected from the Hall-Petch relationship [Eq. (2)].

Since the grain size effect becomes less important with increasing temperature, the chief strength difference among the laboratory isothermally annealed heats at elevated temperatures would appear to be caused by differences in precipitate dispersion. Assuming only minor differences in particle size [$r$ of Eq. (6)], the heats with the highest density of precipitate particles will be the strongest. To establish this would require a detailed electron microscopy study, which was beyond the scope of this work. The precipitate expected to provide the most strengthening is $Mo_2C$ (ref. 19), which forms many small needle or platelike particles.

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[18] M. F. Ashby, "Results and Consequences of a Recalculation of Frank-Reed and the Orowan Stress," *Acta. Metall.* 14: 679–81 (1966).

[19] R. G. Baker and J. Nutting, "The Tempering of 2 1/4 Cr-1 Mo Steel After Quenching and Normalizing," *J. Iron Steel Inst.* 192: 257–68 (1959).

If the air-melted forging and heat 20017 contain more precipitate particles than the tubing heats and the VAR and ESR heats, this would account for the relative differences in the yield strengths of these heats. The air-melted forging and heat 20017 are considerably weaker than the tubing and VAR and ESR heats at the low temperatures, but then become relatively stronger as the temperature is increased. The air-melted forging and heat 20017 have much larger grain sizes, which causes the low room-temperature strength.

According to Pickering and Gladman,[16] for a ferrite-pearlite microstructure with up to 20% pearlite, Eq. (1) also applies to the ultimate tensile strength when an additional term is added to account for the percentage of pearlite in the microstructure (here we ignore the dynamic strain aging effect, which will be discussed below). Although the steels tested in this study contained little pearlite, they did contain bainite, which would presumably have a similar effect. However, after the laboratory isothermal anneal, all the heats contained 15–20% bainite. Thus, only slight differences from one heat to another should result from this effect, and the conclusions reached above for the yield strength should apply qualitatively to the ultimate tensile strength.

One dominant characteristic of annealed 2 1/4 Cr-1 Mo steel tensile data is the dynamic strain aging peak in the plots of ultimate tensile strength as a function of temperature. The relative heights of these peaks for the various heats appear to be characteristic of given heats. Previous work[20] has shown that the heat treatment process can significantly affect the properties of annealed 2 1/4 Cr-1 Mo steel. In that work two sections of a 25.4-mm-thick plate (heat 20017) were fully annealed, but furnace cooled at different rates. Another section was isothermally annealed. The tensile properties of all three plates were controlled by the proeutectoid ferrite, which made up the bulk of the microstructure (there was less than 20% bainite in any of the steels). The annealed steel that was cooled faster was significantly stronger than the other two heat treatments, and the dynamic strain aging peak for this heat treatment occurred at a higher temperature than for the other two plates.

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[20] R. L. Klueh, *Heat Treatment Effects on the Tensile Properties of Annealed 2 1/4 Cr-1 Mo Steel*, ORNL-5144 (May 1976).

The dynamic strain aging was concluded to be the result of interaction solid solution hardening in proeutectoid ferrite as originally proposed by Baird and Jamieson.[21] Interaction solid solution hardening occurs in a system that contains in solid solution substitutional and interstitial atoms that have an affinity for one another. The interaction of the substitutional-interstitial atom pairs or clusters with dislocations then gives rise to the strain-aging peaks. In annealed 2 1/4 Cr-1 Mo steel we concluded that interaction solid solution hardening was due to the interaction of molybdenum and carbon atoms or atom clusters with dislocations.[20] The larger dynamic strain aging effect in the steel cooled most rapidly resulted because the faster cooling rate for this plate had not allowed the precipitation of molybdenum and carbon in the proeutectoid ferrite to proceed as far as it had in the more slowly cooled plates. Precipitation removes these species from solid solution, thus making them unavailable for interaction solid solution hardening.

Undoubtedly, many of the differences in dynamic strain aging noted between heats of a given product form in the as-received and laboratory isothermally annealed conditions are due to heat treatment effects. If we consider the tubing heats, the higher peak for the as-received materials probably reflects somewhat faster cooling during the commercial heat treatment. The faster the cool, the more molybdenum and carbon that remain in solution to combine and lead to interaction solid solution hardening. Obviously, the differences between the as-received and laboratory isothermally annealed VAR and ESR steels is the result of different heat treatment processes, since the as-received steel was normalized and tempered. Similarly, the amount of bainite in the as-received microstructure of the air-melted forging indicates that the difference in properties in this steel can be attributed to different cooling rates.

Although the cooling rates can partially account for differences in dynamic strain aging effects for a given heat between the as-received

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[21] J. D. Baird and A. Jamieson, "High-Temperature Tensile Properties of Synthesized Iron Alloys Containing Molybdenum and Chromium," *J. Iron Steel Inst.* 210: 841–46 (1972).

and laboratory annealed steels, it does not account for differences between heats after a common anneal. Although the differences among a given product form or melting practice are decreased by a common anneal, there are still large differences among the different product forms or melting practices (e.g., the VAR and ESR steels have substantially lower peaks in the ultimate tensile strength-temperature plots than the air-melted heats).

There is no straightforward way to compare the relative dynamic strain aging effects among the different heats. The strengths at 371°C, where dynamic strain aging has its maximum strengthening effect, cannot be directly compared for the different heats, since much of the difference is accounted for in the effects discussed above (i.e., differences in precipitate content and grain size). However, if it is assumed that the strength due to dynamic strain aging is a maximum at 371°C, the relative strength change over that at 25°C can be calculated. When such a calculation is done, the results fall into three categories: (1) the tubing heats show relative strength increases of 1–4%; (2) the air-melted plates and the air-melted forging show strength decreases of 2–5%; and (3) the VAR and ESR heats, with one exception (heat R0110 decreased 2%), show strength decreases of 7 to 9%.

There do not appear to be any differences in chemical composition (Table 2) that could account for these differences in the dynamic strain aging effect. However, one possibility is that the difference could involve a difference in the number of heterogeneous precipitation sites that are available in the different heats.

The proeutectoid ferrite that forms during heat treatment is supersaturated with respect to $Mo_2C$ formation. Although some $Mo_2C$ forms during the heat treatment, the remainder of the supersaturation is relieved when the steel is exposed to an elevated temperature (during test or in service). Precipitation of $Mo_2C$ must be preceded by the agglomeration of molybdenum and carbon atoms in solution before incorporation of $Mo_2C$ precipitate, thus giving rise to the interaction solid solution hardening as discussed above. The more molybdenum and carbon that remain in solution during the heat treatment and test, the greater the dynamic strain aging effect. It would then be expected that the steel with available nucleation sites to hasten precipitation would display the least dynamic strain aging when all the heats are given a common anneal. Such an effect could arise from different deoxidation procedures in the steelmaking process. Unfortunately, no details on such procedures for the air-melted heats are available.

## SUMMARY AND CONCLUSIONS

The tensile properties of twelve heats of 2 1/4 Cr-1 Mo steel were determined over the range 25–566°C at a strain rate of $7 \times 10^{-4}$/sec. Included in these heats were five commercial tubing heats, a forging and two commercial plate heats — all prepared by air melting; two pieces of vacuum-arc remelted (VAR) forgings; and two pieces of electroslag remelted (ESR) plates. Except for the two air-melted plates, all the steels were tested in the as-received condition. For the commercial tubing, this was an annealed condition; the air-melted forging was isothermally annealed, and the VAR and ESR steels were normalized and tempered. For more direct comparison, all twelve heats were also tested after they had received a common laboratory isothermal anneal.

The following observations and conclusions were made:

1. A large heat-to-heat variation in strength properties was observed.

2. For a given heat, the strengths of the as-received steels were always greater than the properties after the steel had received a common laboratory isothermal anneal.

3. When compared after a common laboratory isothermal anneal, the ultimate tensile strengths of the VAR and ESR steels fell below the air melted properties up to about 500°C. Above 500°C, the properties for all steels approached each other. Dynamic strain aging effects resulted in a peak in the ultimate tensile strength-temperature relationship.

4. The 0.2% yield strength for the steels given a common laboratory isothermal anneal also showed a reduced scatter in the properties as the temperature was increased. With the exception of two datum points (for

a VAR and ESR heat at 454°C), the yield strengths for all heats were greater than the expected minimum values in Code Case 1592.

5. The differences in yield strength are the result of differences in grain size and precipitate distribution. Differences in dynamic strain aging effects are the result of differences in precipitation kinetics.

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