OTS PB 151074

AD-A278 522

DMIC Report 118
October 12, 1959

1

N-77569

COPY 2

WELDING OF HIGH-STRENGTH STEELS FOR AIRCRAFT AND MISSILE APPLICATIONS

DISTRIBUTION STATEMENT A
Approved for public release;
Distribution Unlimited

94-10481

DTIC
S ELECTE D
APR 1994
B

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
Columbus 1, Ohio

DTIC QUALITY INSPECTED 3

94 4 6 008

The Defense Metals Information Center was established at Battelle Memorial Institute at the request of the Assistant Secretary of Defense (R&E) to provide Government contractors and their suppliers technical assistance and information on titanium, beryllium, refractory metals, high-strength alloys for high-temperature service, corrosion and oxidation resistant coatings, and thermal protection systems. Its functions, under the direction of the Office of the Secretary of Defense, are as follows:

1. To collect, store, and disseminate technical information on the current status of research and development of the above materials.

2. To supplement established Service activities in providing technical advisory services to producers, melters, and fabricators of the above materials, and to designers and fabricators of military equipment containing these materials.

3. To assist the Government agencies and their contractors in developing technical data required for preparation of specifications for the above materials.

4. On assignment, to conduct surveys, or laboratory research investigations, mainly of a short-range nature, as required, to ascertain causes of troubles encountered by fabricators, or to fill minor gaps in established research programs.

Contract No. AF 18(600)-1375

OTS PB 151074

DMIC Report 118
October 12, 1959

WELDING OF HIGH-STRENGTH STEELS FOR AIRCRAFT AND MISSILE APPLICATIONS

by

H. W. Mishler, R. E. Monroe, and P. J. Rieppel

to

OFFICE OF THE DIRECTOR OF DEFENSE
RESEARCH AND ENGINEERING

DEFENSE METALS INFORMATION CENTER
Battelle Memorial Institute
Columbus 1, Ohio

ACKNOWLEDGMENTS

Appreciation is expressed to the organizations listed below who made this report possible by their assistance. Personnel who were interviewed in the course of the preparation of this report are listed in Appendix A.

Aerojet-General Corporation, Azusa, California
Aerojet-General Corporation, Sacramento, California
Allegheny Ludlum Steel Corporation, Pittsburgh, Pennsylvania
Armco Steel Corporation, Baltimore, Maryland, and Middletown, Ohio
Boeing Airplane Company, Seattle, Washington
Consolidated Western Steel Company, Los Angeles, California
Convair, Division of General Dynamics Corporation, Pomona, California
Convair, Division of General Dynamics Corporation, San Diego, California
Convair-Astronautics, Division of General Dynamics Corporation, San Diego, California
Crucible Steel Company, Pittsburgh, Pennsylvania
Douglas Aircraft Company, Inc., Santa Monica, California
Grumman Aircraft Engineering Corporation, Bethpage, Long Island, New York
Harnischfeger Corporation, Milwaukee, Wisconsin
Lockheed Aircraft Corporation, Burbank, California
Lockheed Aircraft Corporation, Sunnyvale, California
The Martin Company, Baltimore, Maryland
Menasco Manufacturing Company, Burbank, California
Norris-Thermador Corporation, Los Angeles, California
North American Aviation, Inc., Columbus, Ohio
North American Aviation, Inc., Los Angeles, California
Northrop Aircraft, Inc., Hawthorne, California
Pacific Alloy Engineering Company, El Cajon, California
Research Welding and Engineering Company, Los Angeles, California
Rheem Manufacturing, Downey, California
Rohr Aircraft Corporation, Chula Vista, California
Ryan Aeronautical Company, San Diego, California
Solar Aircraft Company, San Diego, California
U. S. Naval Research Laboratory, Washington, D. C.
United States Steel Corporation, Research Laboratory, Monroeville, Pennsylvania
Vanadium-Alloys Steel Company, Latrobe, Pennsylvania

The authors also wish to thank Mr. R. P. Sopher, Electric Boat Division, General Dynamics Corporation, formerly with Battelle Memorial Institute, for his help in conducting the interviews with the above organizations and for his editorial comments on the report.

TABLE OF CONTENTS

APPENDICES

WELDING OF HIGH-STRENGTH STEELS FOR AIRCRAFT AND MISSILE APPLICATIONS

SUMMARY

The numerous high-strength steels being used in the fabrication of aircraft and missiles may be welded by most of the usual processes. A variety of techniques must be applied so that the weld joints will be sound and of a strength approaching that of the parent metal. A survey of the procedures currently being used is presented.

Low-Alloy Martensitic Steels

AISI 4340, AMS 6434, X200, 300M, and 17-22AS all are used at high strength levels. They may be welded by inert-gas arc-welding processes using filler wire of the base metal composition. Type 502 stainless steel or 17-22AS filler wires give joints of lower strength than the parent metal except in thin sheets where the weld metal is dilute and stronger. Covered-electrode welding, flash, and pressure welding may be used for joining AISI 4340. Weld-metal cracking can be reduced by preheat and postheat and by the use of clean filler metals containing extra low sulfur and phosphorus. Maximum tensile strengths of arc-welded joints vary from 200,000 psi for 17-22AS to nearly 300,000 psi for X200 and 300M steels, with those for AISI 4340 and AMS 6434 falling between these values. Maximum yield strengths of about 235,000 psi are obtained from X200 and 300M welds.

Hot-Work Die Steels

Hot-work die steels can be heat treated to the highest strength levels of any steels being used in aircraft and missiles. They fall into two AISI classes: H-11 and H-13. Vascojet 1000 is an example of hot-work die steel used as airframe material. Similar welding procedures used for each steel include inert-gas tungsten-arc welding for joining thin sections and covered-electrode welding for thicker sections. A preheat to at least 500 F is used and postheat at preheat temperature should be maintained until the weldment is stress relieved. Hot-work die steels are heat treated to 300,000 psi. Pressure vessels fabricated from Vascojet 1000 and heat treated to high strength levels, however, have burst at hoop stresses much lower than those calculated from the strength of test specimens similarly heat treated. Optimum burst strengths have been obtained when a lower strength level (255,000 psi ultimate) was used. The crack-propagation resistance as measured by notch-unnotched tensile ratio is also better at less than the maximum heat-treated strength.

Martensitic Stainless Steels

The inert-gas tungsten-arc process and filler wires of the parent metal composition are used in welding martensitic stainless steels. Covered electrodes are available but seldom used for welding the thin sections customarily used in aircraft and missiles. Postheating of the weld joint is necessary to prevent cracking, the postheat temperatures and times depending on the particular steel. Welds in Types 422 and 12 MoV steels may be heat treated to 270,000 psi ultimate, Type 431 to 220,000 psi, and Type 410 to 200,000 psi. Pressure vessels fabricated from Type 422 show optimum burst strength when heat treated to a lower level (210,000 psi ultimate) than the maximum obtainable.

Precipitation-Hardening Stainless Steels

Good corrosion resistance makes precipitation-hardening steels attractive even though their strength is lower than that of some other steels. They may be welded readily using inert-gas-shielded processes and filler wires similar to the base metal, though the composition must be adjusted to control the delta ferrite in 17-4PH, 17-7PH, and PH 15-7Mo weld metals. Some delta ferrite suppresses hot cracking but too much reduces weld metal ductility. Covered electrodes can be used for all precipitation-hardening steels except 17-7PH and PH 15-7Mo steels. Hardening of 17-7PH and PH 15-7Mo depends on precipitation of an aluminum-nickel compound, and it is difficult to transfer aluminum across the arc when coated electrodes are used. Neither preheating nor postheating is necessary. Weld-metal cracking of A-286 is minimized by using Hastelloy W or X filler wire. Restraint of the weld joint should be eliminated. The precipitation-hardening steels can be resistance welded easily. Weld joints in 17-4PH, 17-7PH, and AM-350 may be heat treated to strengths of 190,000 to 200,000 psi ultimate tensile; AM-355 to 215,000 psi; and PH 15-7Mo to 235,000 psi.

Design and Testing and Inspection

Fabrication of high-strength materials into reliable structures based on a low design factor (slightly greater than unity) requires elimination of stress concentrations by good design, optimum welding techniques, and careful subsequent handling to prevent nicks, scratches, or dents. The welding technique should assure a smooth weld contour and complete penetration. The steel and filler wire used should be so selected that the weld will be resistant to crack propagation when heat treated to the design strength level. Current development of crack-propagation tests should assist in better selection of steels in the future.

In steels heat treated to strengths above 200,000 psi after welding, the minimum flaw size required to start a running crack when the structure is stressed often is too small to be detected by conventional nondestructive tests. New inspection tests are being developed for determining such things as flaw orientation, size, and depth below the surface.

INTRODUCTION

The performance and success of current aircraft and missiles depend to a great extent on the material from which they are constructed. The weight savings resulting from the use of higher strength materials are responsible for the ever-increasing speed and load-carrying capacity of these vehicles. Since the requirements of future designs are constantly being raised, there is a continual quest for materials of higher and higher strength-to-weight ratios. As a result of such a trend, it has been natural to turn from the light metals to the very-high-strength steels. In addition to the improved strength properties of steel, many of the alloys also are highly resistant to high-temperature scaling and retain their strength at the high operating temperatures that result from high flight speeds.

No material, however, can be considered to be satisfactory for use in flight vehicles unless it can be fabricated into components. One of the prime considerations as to the fabricability of a steel is its weldability. Not only must the steel be capable of being welded but the resulting weld joints must have strength properties similar to those of the steel. Otherwise, the high-strength advantages of such a steel are lost. In addition to strength considerations, the weld joint must be sound and free from porosity and cracks and other types of flaws such as undercut, incomplete penetration, and rollover, which might result in stress concentrations. Recent work related to the fabrication of rocket motors has disclosed that the weld metal's resistance to crack propagation also is of great importance.

Extensive work has been done in the past and is continuing to perfect the techniques of welding high-strength steels and to improve their weldability. This report has been compiled to bring together in one publication as much information as possible concerning the techniques currently being used in the welding of the various aircraft and missile steels. The information was obtained from interviews with representatives of the aircraft and missile industry and steel producers, from reports of industrial organizations and Government agencies, and from technical papers appearing in the published literature.

Each classification of steel is considered in separate sections of the report, which are arranged in roughly decreasing order of industry-wide interest: low-alloy martensitic steels, hot-work die steels, martensitic stainless steels, and precipitation-hardening stainless steels. This order may not necessarily apply for all users. A rearrangement in the order of decreasing tensile strengths could be accomplished by placing the hot-work die steels at the top. In addition to data on the particular classes of steel, a discussion has been included on design considerations and testing and inspection techniques.

LOW-ALLOY MARTENSITIC STEELS

The steels of this class have been the mainstays of the aircraft industry for years. The alloys that have been most widely used have been AISI 4130, 4140, and 4340. However, only the AISI 4340 steel has the ultra-high-strength requirements of current missile and aircraft designs. Some of the required strength properties are too high even for this steel. For this reason, several new alloys have been developed. These new alloys are of interest because (1) they can be heat treated to higher strength levels using existing heat-treating procedures and (2) they can be tempered at higher temperatures than those used for AISI 4340 to produce comparable strength levels. The high tempering temperatures are advantageous because some stress relief can be obtained at the tempering temperatures. Since most of these new alloys are still in the development stage, information on their welding is limited. However, most of the newer steels bear some resemblance to better-known members of the class compositionwise, as shown in Table 1, so it is probable that the welding techniques will be similar.

TABLE 1. NOMINAL COMPOSITIONS OF LOW-ALLOY MARTENSITIC STEELS

	Chemical Composition, per cent						
Steel	C	Mn	Si	Ni	Cr	Mo	V
AISI 4340	0.40	0.70	0.30	1.75	0.80	0.25	--
AMS 6434	0.33	0.70	0.30	1.75	0.80	0.35	0.20
17-22AS	0.30	0.50	0.65	--	1.25	0.50	0.25
X200	0.45	0.85	1.60	--	2.10	0.55	0.06
300M	0.40	0.75	1.60	1.85	0.85	0.40	0.08

Since the AISI 4300 series of steels has been so widely used over the years, it was logical to specify these steels in the first missile designs. The low design factor applied to missiles has required the use of highly refined welding techniques. It has been necessary, therefore, to expend much effort in additional study of the weldability of the AISI 4300 steels. Although the trend now is toward the newer alloys, these studies of the AISI 4300 steels have been valuable in helping to solve some of the new problems in the field of missile production. This work has shown that the ability to obtain the desired high-strength properties in weld joints depends as much on the welding techniques used as on the use of proper heat treatment and steel composition.

The favored method for welding the low-alloy martensitic steels is the inert-gas-shielded welding process. Both consumable-electrode and tungsten-electrode processes are used, depending on the material thickness. Covered electrodes are available for welding thick material. In addition to arc welding, flash welding and gas-pressure welding are used. Resistance, spot, and seam welding are seldom used in production for joining these steels. Although all low-alloy martensitic steels have similar welding characteristics, some differences both in technique and in weld-joint properties occur for each alloy.

AISI 4340 and AMS 6434

The compositions of AISI 4340 and AMS 6434 differ only in the carbon and molybdenum contents and in the presence of vanadium in the AMS 6434. The AISI 4340 steel has been used ordinarily in the form of bar, strip, sheet, and plate. The AMS 6434 has been used primarily in sheet form for the fabrication of large rocket cases. The same welding techniques may be used with either steel. Thicker sections of 4340 are welded by pressure or flash welding, by the use of covered electrodes, by the submerged-arc process, or by the inert-gas consumable-electrode process. The inert-gas tungsten-arc process is used for welding thin sheet of either steel. The submerged-arc process has been used primarily where a high rate of production is desired and where the weld joints will not be heat treated to extremely high strength levels. Rohr Aircraft welds 5/8-inch-thick AISI 4335 by this process with AISI Type 502 filler wire (C-0.10 per cent max, Mn-1.00 per cent max, Si-1.00 per cent max, Cr-4 to 6 per cent). These weldments are heat treated to ultimate strengths in the 180,000 to 200,000-psi range.

Welding Procedures. Several different covered electrodes are available for welding AISI 4340; 90LH (E10016) and P&H 21 (E15016), which are manufactured by the Harnischfeger Corporation, may be used for strength levels up to 200,000 and 225,000 psi, respectively. Harnischfeger also has developed a series of covered electrodes which deposit welds that may be heat treated to 275,000 psi ultimate.(1)* Filler wires for use with the inert-gas welding processes are of several compositions. The most commonly used are Type 502 and 17-22AS (also known as CMV or Linde 71). AISI 6130 has been used in a few applications. Ryan uses a filler wire with the same composition as the 90LH-2 covered electrode in addition to the two more common wires. These filler wires may be used for welding either the AISI 4340 or AMS 6434 steels. For fabricating large, thin-walled pressure vessels of AMS 6434, Aerojet-General (Sacramento) has specified either Type 502 or 17-22AS, although preference is given to the 17-22AS wire due to the higher yield strength of the weld metal. Lockheed (Burbank) uses the Type 502 filler wire for welding pressure vessels of AISI 4340 steel. For normal applications of 4340 in which heat treating will be done after welding, filler wire of P&H 21 or CMS-32 composition is used. In those applications where no heat treating of the weldment will be performed, Lockheed uses Oxweld No. 7 (Linde Company, Division of Union Carbide Corporation) filler wire. A filler wire with the same composition as the base metal also may be

---

*References are given in Appendix B.

used for inert-gas welding. Consolidated Western Steel Company uses AMS 6434 filler wire for welding AMS 6434. They have found that generally high strengths result from the use of a similar composition wire. In contrast, Lockheed avoids the use of filler wires of the same composition as the base material since they have had trouble with weld-metal cracking when such filler wires are used.

For many years, landing-gear components have been fabricated from AISI 4340 by Menasco Manufacturing Company using gas-pressure welding. This is an ideal process for joining large, thick-walled tubing. Presently, Menasco also is fabricating spherical gas-storage bottles from this steel. This method of welding consists of butting the mating surfaces of the pieces to be welded together, heating the joint area by means of gas torches to the welding temperature, and applying upsetting pressure axially to the pieces. Although the welding temperature is high, melting does not occur. The success of the process depends on precise control of the time-temperature-pressure cycle and on the careful machining and matching of the mating surfaces. Cleanliness of the joint area also is important. All grease and dirt must be removed from the mating surfaces prior to welding. By the very nature of the process, defects that may occur in an arc weld do not appear in pressure welds. Porosity does not occur since the metal is not melted. By maintaining welding pressure on the joint during cooling from the welding temperature, weld-metal cracking may be prevented. The weld joints produced by this method have excellent quality and attain strengths equal to those of the base material upon heat treating. The process is limited somewhat as to thinness of material that can be welded and to the configuration of the parts.

The thermal treatment applied to inert-gas arc-welded joints before, during, and after welding varies somewhat for different fabricators. The susceptibility of the weld metal to cracking depends greatly on the magnitude of the pre- and postweld temperatures. Cracking tests conducted by Aerojet General (Azusa) were used to evaluate the effect of various degrees of preheat on the cracking resistance of the different weld metals. This test makes use of a circular-groove type of specimen, 5 x 5 x 1/2 inch. The groove is 0.250 inch wide by 0.220 inch deep by 1-3/4 inches in diameter. Although Aerojet had used preheats only up to 300 F, it was found that preheat definitely reduced weld-metal cracking. When tungsten-arc welding AMS 6434 using the Type 502 filler wire, 300 F is the maximum preheat temperature used by Ryan. At preheat temperatures much above this limit, they have had difficulty with porosity. The complete thermal treatment used by Ryan includes the 300 F preheat and the maintaining of a 600 F postheat until the weldment can be placed in a stress-relieving furnace at 1200 F. The part is not allowed to cool at any time before being placed in the stress-relieving furnace. Similar thermal treatments are specified by Norris-Thermador and Aerojet-General for the welding of large thin-walled vessels of AMS 6434. Norris-Thermador preheats to 500 F and maintains this temperature during welding. After welding and until the part is stress relieved, it is covered with an asbestos blanket to prevent an excessive temperature drop. Stress relieving is done at 1150 F. Aerojet-General's procedure requires a preheat, interpass, and postheat temperature of 550 F. They also specify that the temperature of the part shall not drop below 550 F prior to stress relieving. When welding small pressure vessels of these same steels, a slightly different schedule is used by Norris-Thermador. The parts are preheated to 700 to 800 F. Immediately after welding, the part is heated to about 1100 F (dull red) with a gas torch. This heating is of the weld zone only and takes place before there is any appreciable temperature drop in this zone. With thermal treatments of these types, weld deposits of the maximum quality may be made in the AISI 4340 and AMS 6434 steels. However, in contrast to these somewhat complex procedures, Rheem Manufacturing has indicated that AMS 6434 sheet may be inert-gas tungsten-arc welded with 17-22AS filler wire, using neither preheat nor postheat. They indicated that weld joints of satisfactory quality were produced.

Cracking is the most serious weld-metal defect that occurs when the low-alloy martensitic steels are welded. As mentioned above, the proper use of preheating and postheating will reduce greatly the susceptibility of a weld metal to cracking. However, it has been found that when welds are deposited under a high degree of restraint, the composition of the filler material plays an important role in the prevention of cracking.(2, 3, 4, 5) The constituents most responsible for weld metal hot cracking are sulfur and phosphorus. When the contents of these two residual elements in the filler wire are kept extra low, the tendency for the weld metal to crack under high restraint is greatly reduced. Aerojet-General (Sacramento) concurs with the findings given in the above references that the maximum allowable sulfur or phosphorus content permissible in filler wire should be 0.010 per cent. They currently are preparing specifications for the procurement of filler wires in which these limits are incorporated. At the Azusa plant of Aerojet-General, a series of circular-groove-type weld-metal cracking tests were made to study the cracking susceptibility of 17-22AS and Type 502 filler wires. The test welds were deposited in 1/2-inch-thick AMS 6434 test specimens. Results indicated that the 17-22AS weld deposit has the better cracking resistance of the two weld metals.

To obtain welds of the highest quality, it is essential that the filler wire be free of all surface oxides, grease, and other contaminants. The wire also must be properly packaged to maintain cleanliness and it should be marked as to composition to prevent the use of a wrong type of wire. To purchase wire of such quality commercially has been extremely difficult. Aerojet-General has all of its commercially purchased wire specially cleaned and packaged by a private concern. As a step toward solving this problem, an Aeronautical Material Specification(6) recently has been accepted which specifies methods of identification, cleaning, and packaging of welding filler wires. Filler wires purchased to this specification should meet all company standards as to cleanliness.*

---

*Although this specification is discussed in this section on low-alloy martensitic steels, it applies to filler wires for welding all steels mentioned in this report.

A variety of welding techniques is used for the inert-gas welding of AISI 4340 and AMS 6434 steels. However, these depend a great deal on the thickness of material, application, in-house practices of the particular fabricator, etc. A few of these are mentioned as examples of some of the practices currently in use.

For the automatic inert-gas tungsten-arc welding of the circumferential weld in thin-walled pressure vessels, Ryan uses the continuous-pass technique. The vessel is rotated beneath a stationary welding torch. At the end of one revolution (one pass), rotation continues without stopping or pausing, thus placing the second pass in the joint. The vessel is rotated until the required number of passes is made. With such a technique, only one start and one stop are made. The tendency for the formation of crater cracks is kept to a minimum and welds of maximum quality are produced.

Consolidated Western Steel Company deposits three passes when welding thin (0.090 inch) sheet for missile cases. The first two passes are made with filler wire. The third pass is a "dry" pass or one made without the addition of any filler material. This third pass helps to eliminate any weld-metal porosity that may be present. Another dry-pass technique is to make the first pass without the addition of filler wire to ensure complete penetration. Filler wire then is added in succeeding passes.

Aerojet-General (Azusa) has investigated the welding of AISI 4340 and AMS 6434 in thicknesses from 0.090 to 0.160 inch using two passes. The weld joint has an included angle of 90 degrees with a land of 0.020 to 0.030 inch. A copper backup bar is used in which is machined a groove 5/16 inch wide by 1/4 inch deep. Argon flows through this groove to back up the weld metal. Sufficient gas pressure is maintained so that the molten weld metal is supported by the backing gas. Besides protecting the rear of the weld joint from the atmosphere, the argon gas also prevents the molten metal from contacting the copper. Weld-metal cracking will result if contact occurs.

There is some difference of opinion as to the merits of automatic versus manual tungsten-arc welding of the thin-walled missile cases. The proponents of the manual technique feel that, by using this process, a nonsymmetrical freezing pattern results from the diverse motions of the hand-held welding torch. By breaking up the freezing pattern of the weld metal, a plane of weakness caused by the meeting of the dendritic grains along the weld centerline is avoided. However, those that favor the automatic welding technique feel that the weld produced automatically is of higher quality and has a smoother surface and a more uniform contour. They feel also that rollover of the edge of the weld bead, which could result in an area of stress concentration, is avoided. These are differences of opinion only; to date, there have appeared no quantitative data to support either argument. It should be noted, also, that operator comfort has some bearing on which method is used. When the parts are heated to high preheat temperatures, it can be quite difficult to use the manual technique.

Weld-Joint Properties. The tensile strengths to which weld joints in AISI 4340 are heat treated cover the range from 180,000 to 280,000 psi. The actual strength level attained depends on the heat treatment, the welding process used and, in the case of arc welding, the filler material used. Weld joints in AISI 4340 and AMS 6434 are heat treated after welding by normalizing at 1600 F to 1700 F, austenitizing at about 1550 F (1650 F for AMS 6434), oil quenching, and tempering at a temperature (400 F to 900 F) to produce the desired strength. The normalizing treatment may be omitted in those applications where the heat treatment is not critical, i.e., where very high strength levels are not desired.

Weld joints made with the Type 502 filler wire are heat treated to strength levels of 180,000 to 200,000 psi ultimate tensile by Rohr and Ryan. For certain applications, the yield strength is used as the criterion for joint strength rather than the ultimate tensile strength. Type 502 weld joints in AISI 4340 and AMS 6434 sheet are heat treated to yield strengths of 190,000 to 210,000 psi by Norris-Thermador, Rheem, and Aerojet-General. Some difficulty has been encountered in obtaining yield strengths greater than 190,000 psi with the Type 502 filler wire. In such cases, the use of 17-22AS filler wire will permit yield strengths of 210,000 psi to be reached. The Type 502 and the 17-22AS weld deposits cannot reach strength levels much above 225,000 psi ultimate.

Higher strength levels might be attained if welds are made in thin sheet, e.g., 0.090 inch, in which the weld deposit is diluted by the fused base material. More satisfactory results may be obtained, however, by the use of a different filler wire. If thicker material is welded, a different filler material is essential, since the dilution of the weld deposit is much less in thicker joints. The A. O. Smith Corporation has conducted an evaluation study(7) of various filler metals for welding AMS 6434 steel. These weld joints were given heat treatments that resulted in base-material strengths of 235,000 and 260,000 psi ultimate. In Table 2 are listed the tensile properties of welds made with several of these filler materials.

Fatigue tests also were made of these weld joints. The corrected fatigue strengths, as determined by the Prot method, are shown in Figure 1 for weld joints made with the various filler materials. At Consolidated Western Steel Company, arc-welded joints have been made in AMS 6434 using AMS 6434 filler wire. They have obtained 100 per cent joint efficiency at a strength level of 280,000 psi ultimate (230,000 psi yield strength). Parts fabricated from AISI 4340 by gas-pressure welding and flash welding at Menasco are heat treated to strength levels up to 280,000 psi ultimate with 100 per cent joint efficiency.(8) Tensile properties for gas-pressure welds in AISI 4340 are listed in Table 3. Lockheed obtains similar results with flash and pressure-welded AISI 4340 components heat treated to 260,000 psi ultimate. Flash welds in AMS 6434 produced by Northrop have the same strengths as the base material.

TABLE 2. TENSILE PROPERTIES OF WELD JOINTS MADE IN 1/4-INCH-THICK AMS 6434 STEEL(7)

Filler Material	Welding Process	Tempering Temperature(a), F	Ultimate Tensile Strength, psi	Yield Strength, psi	Elongation In 2 Inches, per cent	Elongation In 1/2 Inch, per cent
Base-metal test	--	400	259,000	222,000	10.0	--
		660	235,000	209,000	9.0	--
SAE 6130	TIG	400	250,000	224,000	5.5	17.0
		660	220,000	206,000	7.0	24.0
SAE 4340	TIG	400	255,000	222,000	9.0	11.0
		660	219,000	203,000	9.5	4.5
P&H 4340	Covered electrode	400	253,000	222,000	10.0	5.0
		660	225,000	208,000	8.0	2.0
P&H 9240	Covered electrode	400	244,000	207,000	10.0	3.0
		660	221,000	206,000	8.0	0.0

(a) All specimens were heat treated prior to final machining as follows:
(1) Place in furnace at 1000 F
(2) Heat to 1650 F and hold 1 hour
(3) Quench in oil at 70 F
(4) Temper for 2 hours at indicated temperature.
In addition, the welded specimens were stress relieved at 1150 F for 1 hour following welding.

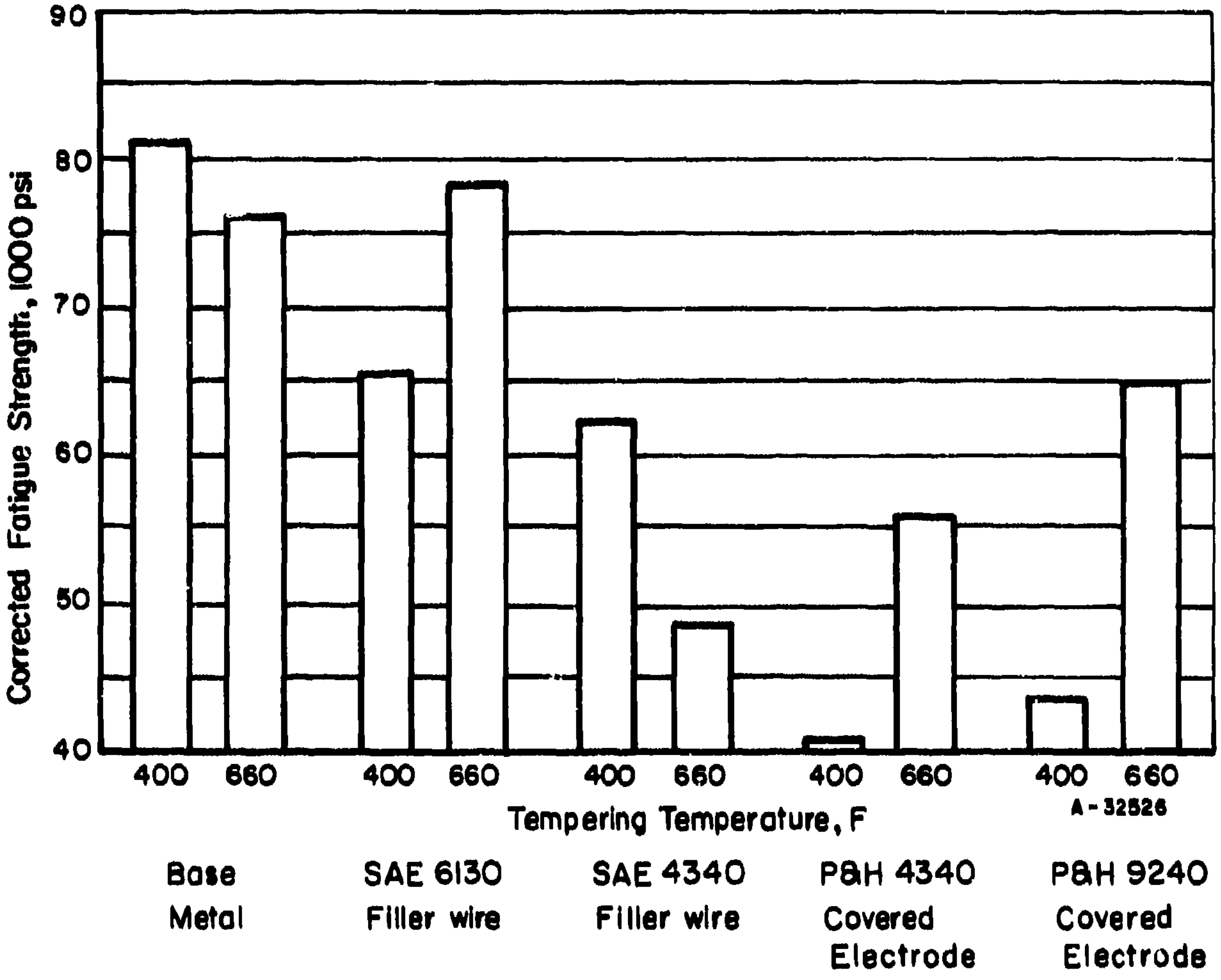

FIGURE 1. FATIGUE STRENGTHS OF WELD JOINTS IN 1/4-INCH-THICK AMS 6434 STEEL(7)

The corrected fatigue strengths were determined by the Prot method.

TABLE 3. MECHANICAL PROPERTIES OF GAS-PRESSURE-WELDED AND FLASH-WELDED JOINTS IN AISI 4340 STEEL(8)

Welding Process	Tempering Temperature(a), F	Specimen Type	Ultimate Tensile Strength, psi	Elongation in 1 Inch, per cent	Reduction of Area, per cent
Gas pressure	700	Base metal	232,500	11.0	46.5
		Weld joint	235,000	12.5	51.0
	435	Base metal	282,000	13.5	48.5
		Weld joint	286,000	13.0	49.0
Flash	700	Base metal	236,000	24.5	46.5
		Weld joint	232,500	12.5	10.0
	435	Base metal	282,000	25.5	40.0
		Weld joint	279,500	12.0	10.5

(a) Specimens were heat treated as follows:
- (1) Stress relieve at 1100 F for 1 hour (flash welds only)
- (2) Normalize at 1600 F for 1 hour
- (3) Rough machine
- (4) Austenitize at 1500 F for 1 hour
- (5) Oil quench
- (6) Temper 4 hours at indicated temperature
- (7) Finish machine.

AMS 6434 is one of the materials being tried for construction of the motor cases for the Polaris missile. In the course of inspection of failure of these cases during proof testing, the Naval Proving Ground(9) and the Naval Research Laboratory(10) determined the critical crack-extension force (G_c) of the AMS 6434 parent metal, of the heat-affected zone, and of the Type 502 weld metal used in these vessels (the method of determining G_c is described in the section of this report entitled "Design, Testing, and Inspection"). The yield strength of the base material of these cases was 195,000 psi. Failure had occurred at a hoop stress of about 170,000 psi. Some of the failures had initiated from small cracks in the longitudinal weld seam, while another failure initiated at a crack at the toe of a weld bead. The values of G_c that were determined were 1050 in-lb/in.^{2} for the base material, 850 in-lb/in.^{2} for the heat-affected zone, and 500 in-lb/in.^{2} for the weld metal (in a longitudinal direction). From examination of the fracture, it was estimated that the G_c for the weld metal in the thickness direction was less than 200 in-lb/in.^{2}. A G_c value of 1000 in-lb/in.^{2} tentatively has been established as the minimum requirement for rocket cases. These values are not necessarily typical of AMS 6434 weldments heat treated to this strength level. However, this illustrates the need for a material that will successfully resist crack propagation, since the flaws from which failure initiated are not unusual in a large welded structure.

17-22AS

Although this steel is used rather widely in the form of filler wire for welding, Ryan is the only company that has indicated that it is fabricating components from this steel. This alloy has two important advantages over some of the other low-alloy martensitic steels. First, it has improved strength properties at elevated temperatures and, second, components fabricated from previously heat-treated material need only be tempered after welding to attain the desired weld-joint strength.

The components that Ryan fabricates are from heat-treated material. After welding, using 17-22AS filler wire, the parts are stress relieved (tempered) at 900 F to 1000 F. Ryan has found no appreciable hardness drop in the heat-affected zone even when making multipass welds. The ultimate tensile strength that results from this treatment is about 200,000 psi. The thickness of the material joined has ranged up to 5/8 inch. By the elimination of the hardening treatment following welding, several advantages may be realized. Distortion that may occur during heat treating is greatly reduced and, as a result, the elaborate fixturing sometimes necessary to prevent this distortion may be eliminated. The furnace capacity that would be required for the austenitizing treatment would be reduced, since the hardening treatment would be applied to the component parts rather than to the completed assembly.

X200 and 300M

Both of these alloys are relatively new and thus have not as yet been used to any great extent in the air weapon industry. The 300M steel has been used for the production of landing gear, and both steels are being used in the fabrication of large, thin-walled pressure vessels. Most of the welding that has been done has been of a developmental nature. Although the results of the preliminary studies appear promising, it is possible that the production usage of these steels will entail the solving of additional welding problems.

Consolidated Western Steel Company has inert-gas tungsten-arc-welded thin X200 sheet using two different filler wires, Unimach 1 (composition listed in Table 6) and X200. Consolidated has obtained higher yield strengths and more uniform ductility using the Unimach 1 filler wire. The weld joints are heat treated by austenitizing at 1725 F, air cooling, and tempering at 700 F. The 700 F tempering temperature appears to be optimum. Using this heat treatment, the tensile properties obtained are given in Table 4. Welding tests were contemplated using 17-22AS filler wire but it was expected that a lower yield strength would be obtained although the ductility would be improved.

TABLE 4. MECHANICAL PROPERTIES OF WELD JOINTS IN 0.100-INCH X200 STEEL SHEET

Weld joints deposited with Unimach 1 filler wire.

	Ultimate Tensile Strength, psi	0.2 Per Cent Yield Strength, psi	Elongation in 2 Inches, per cent
Base metal	290,000	245,000	8
Weld joint (transverse)	--	230,000	6

Courtesy Consolidated Western Steel Company.

The Aerojet-General Corporation (Azusa) included X200 in its series of weld-metal cracking tests. X200 filler wire was deposited in both air- and vacuum-melted X200 base plate. The incidence of weld-metal cracking in the air-melted stock was about 60 per cent when no preheat was used. The application of a 300 F preheat lowered the amount of cracking to about 5 per cent. No higher preheat temperatures were studied. Weld-metal cracking was absent when the welds were deposited in the vacuum-melted plate.

Aerojet-General is planning on using X200 as the material of construction for a thin-walled pressure vessel. However, they are anticipating using it in the strength range of 200,000 to 210,000 psi yield. They indicated that a tempering temperature of less than 1000 F is never used, since the resistance to crack propagation of X200 is low when it is tempered at less than 1000 F.

The welding characteristics of 300M are very similar to those of X200. It may be welded by the inert-gas processes using 300M filler wire. In addition, Harnischfeger Corporation has developed a covered electrode that produces satisfactory weld joints in this steel. This electrode is known as P&H Heat Treatable Electrode No. 9240. Harnischfeger recommends that a preheat and interpass temperature of 450 F be used.(11) The weld metal will develop an ultimate tensile strength of 275,000 psi, yield strength of 250,000 psi, elongation of 10 per cent, and reduction of area of 32 per cent using the following heat treatment: (1) normalize at 1700 F, (2) austenitize at 1600 F, (3) oil quench, and (4) temper at 600 F.

A study of the flash welding of 5-1/2-inch-diameter by 3/4-inch-wall tubes was performed at the Cleveland Pneumatic Tool Company for the Wright Air Development Center. Satisfactory welds were obtained by this process. The strength properties of such weld joints tempered at 400 F are listed in Table 5.

TABLE 5. MECHANICAL PROPERTIES OF FLASH-BUTT-WELDED JOINTS IN 300M STEEL TUBING(12)

Tubing size: 5-1/2-inch diameter by 3/4-inch wall.
Weld joints were oil quenched and tempered at 400 F.

	Ultimate Tensile Strength, psi	Notched Tensile Strength(a), psi	Elongation(a), per cent	Reduction of Area, per cent
Base metal	302,500	270,000	9	18
Weld joint (transverse)	285,600	246,000	3	7

(a) Notched test specimen geometry and gage length for elongation measurement not reported.

Aerojet-General is considering the use of 300M sheet in the fabrication of thin-walled pressure vessels. The yield-strength range anticipated is 230,000 to 240,000 psi.

HOT-WORK DIE STEELS

Hot-work die steels have several advantages over the conventional high-strength aircraft steels. They are characterized by their high tempering temperatures and, because of their high tempering temperature, they resist softening at high operating temperatures. In addition, they are air hardening and are capable of attaining very high strength levels.

Most of the welding of hot-work die steels has been exploratory in nature. However, many companies are engaged in development work on these steels and an increasing amount of information is being obtained on the mechanical properties of weld joints, welding techniques, etc. The nominal compositions of seven of the more popular of these steels are given in Table 6. Hot-work die steels fall roughly into two AISI classes: H-11 and H-13. The chief difference between the classes is the vanadium content, this being 0.40 per cent for Class H-11 and 1.00 per cent for the Class H-13. The H-11 class is considered the more promising because the higher vanadium content of the H-13 steels is believed to cause lower ductility.

The procedures used to weld all of these steels are similar. The inert-gas tungsten-arc process is the method used chiefly, although covered electrodes have been developed and may be used on thicker sections. It is recommended that these steels be preheated prior to welding, and that the weldments should not be allowed to cool to room temperatures until they have been stress relieved. Hardening of the weldments is accomplished following stress relieving. To prevent decarburization, the stress-relief and hardening treatments should be carried out in a protective atmosphere or salt bath.

Peerless 56

Crucible Steel Company of America reports that sound ductile welds can be obtained in Peerless 56 by either the inert-gas-shielded or covered-electrode welding processes.(13) Filler wire of the same composition as the base material is recommended for use for inert-gas welding. Weld joints with at least 90 per cent joint efficiency may be obtained with the inert-gas welding process. Harnischfeger BA 127 covered electrodes (composition, per cent: C-0.40, Mn-0.70, Si-0.95, Cr-5.5, Mo-1.6, V-0.50) are available also.

It is recommended that parts be preheated to 600 F prior to welding and that a postheat of 1400 F be applied immediately following welding. The hardening treatment follows welding and consists of austenitizing at 1850 F to 1900 F for 1 hour per inch of cross section, air cooling to below 150 F, and immediately tempering at the desired temperature. Double tempering tends to eliminate any retained austenite present.

The best properties are obtained when Peerless 56 is welded in the annealed condition. Previously hardened material may be annealed to form a spheroidized structure with maximum ductility in the following manner: heat to 1600 F, hold for 1-1/2 hours per inch of cross section, cool at 50 F per hour to 1400 F, hold 8 to 10 hours, cool slowly to 1200 F, and then air cool. If ductility is not of prime importance, the parts may be heated to 1600 F, held for 1-1/2 hours per inch of cross section, and furnace cooled.

Mechanical properties of welded and unwelded Peerless 56 sheet are given in Table 7.

TABLE 6. NOMINAL COMPOSITIONS OF HOT-WORK DIE STEELS

Name	Producer	Chemical Composition, per cent						
		C	Mn	Si	Cr	Ni	Mo	V
Halcomb 218	Crucible	0.38	0.40	1.00	5.00	--	1.35	0.35
Peerless 56	Crucible	0.40	0.55	1.00	3.25	--	2.50	0.33
Potomac A	Allegheny-Ludlum	0.40	0.30	0.90	5.00	--	1.30	1.00
Potomac M	Allegheny-Ludlum	0.40	0.30	1.00	5.25	--	1.15	1.00
Unimach 1 (Thermold A)	Universal-Cyclops	0.35	0.45	1.00	5.00	--	1.40	0.45
Unimach 2 (Thermold J)	Universal-Cyclops	0.50	0.35	1.00	5.00	1.50	1.75	1.00
Vascojet 1000	Vanadium Alloys	0.40	0.35	0.90	5.00	--	1.30	0.50

TABLE 7. TENSILE PROPERTIES AND HARDNESSES OF WELD JOINTS IN 0.147-INCH-THICK PEERLESS 56 HOT-WORK DIE STEEL(13)

Welds made by manual inert-gas tungsten-arc process

Test Temperature, F	Specimen Type[a]	Ultimate Tensile Strength, psi	0.2 Per Cent Yield Strength, psi	Elongation in 2 Inches, per cent	Weld-Metal Hardness, Rockwell C
Room	Base metal	337,000	266,000	3.0	59
	Weld joint	304,000	260,000	2.0	58
1000	Base metal	235,000	173,000	8.0	58
	Weld joint	227,000	169,000	3.0	58
1100	Base metal	158,000	127,000	7.0	53
	Weld joint	152,000	122,000	4.0	53

(a) Welded specimens were preheated to 600 F, welded, postheated 1400 F for 2 hours immediately following welding. Weld reinforcement was removed prior to heat treating.

Heat treatment consisted of austenitizing in argon at 1900 F for 1 hour, air cooling, double tempering at 1000 F for 2 hours. Specimens tested at 1100 F were double tempered at 1100 F.

Norris-Thermador is welding Peerless 56 with 17-22AS filler wire. However, the material is thin (0.040 inch to 1/8 inch) so dilution of the weld metal by the base metal is high. As a result, weld-joint strength is nearly equal to that of the base material. A preheat of 900 F and a postheat of 1000 F are used.

Peerless 56, 0.090 inch to 0.160 inch thick, is being welded by Aerojet-General Corporation, Azusa, by the inert-gas process using Vascojet 1000 filler wire. A two-pass technique is used with an argon-gas backup. They have made cracking tests with a circular-groove type of specimen of the type described in the section of this report entitled "Low-Alloy Martensitic Steels". Welds are deposited with Vascojet 1000 filler wire in air-melted and vacuum-melted Peerless 56 die steel. Cracking was not observed in welds made without preheat or after a 300 F preheat was used.

Halcomb 218

Halcomb 218 may be welded satisfactorily by either the covered-electrode process (Type 502 electrodes) or the inert-gas tungsten-arc process. Halcomb 218 filler wire is available for the inert-gas process. Norris-Thermador has used 17-22AS filler wire for welding thin Halcomb 218 sheet. The welding procedures are nearly the same as those used for Peerless 56. The hardening treatment differs in that the austenitizing temperature is 1800 F to 1850 F. Tensile properties of weld joints in Halcomb 218, both in the stress-relieved and hardened condition, appear in Table 8. Republic Aviation Corporation has reported(15) mechanical properties at elevated temperatures for Halcomb 218 as given in Table 9. The heat treatment used with these latter tests should be noted, as it differs somewhat from the standard heat treatment.

Vascojet 1000

One of the more widely used and investigated of the die sheets is Vascojet 1000. Nearly every missile or aircraft manufacturer who has conducted any investigative work with die steels has included Vascojet 1000 in their program. North American Aviation (Columbus) has used Vascojet 1000 in their products to a great extent. A large percentage of the structural members of some of their recent aircraft (such as the A3J-1) have been fabricated from this steel.

Vascojet 1000 may be welded either by the covered-electrode process (Eureka No. 72 electrodes manufactured by Welding Equipment and Supply Company) or by the inert-gas tungsten-arc process using Vascojet 1000 filler wire.(16) Vanadium Alloys Steel Company recommends preheating the

TABLE 8. MECHANICAL PROPERTIES OF WELD JOINTS IN HALCOMB 218 HOT-WORK DIE STEEL(14)

Sheet Thickness, inch	Electrode or Filler Wire	Heat-Treated Condition of Weld Joint	Ultimate Tensile Strength, psi	Elongation in 2 inches, per cent	Reduction of Area, per cent	Location of Failure
0.120	Unwelded	Stress relieved 1250 F, 4 hr	86,500	21.0	58.5	--
	Type 502	Ditto	84,500	14.5	57.0	Base metal
	Halcomb 218	"	89,500	16.5	56.0	Base metal
	Unwelded	Austenitized 1850, 1/2 hr, air cooled double tempered at 1050 F, 2 hr	230,000	8.0	33.5	--
	Type 502		145,000	5.0	42.0	Weld
	Halcomb 218		201,000	8.0	26.0	Weld
0.060	Unwelded	Stress relieved 1250 F, 4 hr	89,500	21.0	57.5	--
	Type 502	Ditto	110,500	8.5	21.5	Base metal
	Halcomb 218	"	94,500	11.0	31.0	Base metal
	Unwelded	Austenitized 1850 F, 1/2 hr, air cooled, double tempered at 1050 F, 2 hr	225,000	8.5	20.0	--
	Type 502		155,000	4.0	32.0	Weld
	Halcomb 218		208,000	5.0	19.0	Weld

Note: Yield strengths not available.

TABLE 9. ROOM- AND ELEVATED-TEMPERATURE MECHANICAL PROPERTIES OF WELD JOINTS IN 0.040-INCH-THICK HALCOMB 218 HOT-WORK DIE STEEL(15)

Welds made by the inert-gas tungsten-arc process using Halcomb 218 filler wire.

Test Temperature, F	Specimen	Ultimate Tensile Strength,(a) psi	Elongation in 2 inches, per cent	Location of Failure
Room	Base steel	179,000	7.0	--
	Weld joint	171,000	4.0	Fusion line and base metal
600	Weld joint	156,000	3.5	Fusion line
800	Weld joint	151,000	4.5	Fusion line
1000	Weld joint	108,000	5.0	Weld

Note: Yield strengths not available.

(a) Specimens were heat treated after welding as follows: austenitize at 1825 F-1850 F for 1/2-hour, quench in molten salt at 800 F for 5 minutes, air cool, temper 4 hours at 1100 F, air cool, retemper 4 hours at 1125 F.

parts to be welded to 1000 F and maintaining the temperature above 600 F during welding. Aerojet-General (Azusa) has conducted cracking tests similar to those used with Peerless 56 on welds made by depositing Vascojet 1000 filler wire in air-melted and vacuum-melted Vascojet 1000 plate. Tests were made with either no preheat or 300 F preheat. No weld-metal cracking occurred.

If machining operations are required following welding, the weldment may be fully annealed by heating to 1500 F to 1550 F and slow cooling to 1000 F. The hardening treatment for Vascojet 1000 consists of austenitizing at 1800 F to 1900 F for 20 to 30 minutes followed by air cooling to room temperature. Tempering is done between 950 F and 1200 F. As with the other die steels, double tempering is recommended. The tempering time and temperature depend on the size of the part and the hardness desired. Tensile properties of Vascojet 1000 weldments are given in Table 10. An increase in the yield and tensile strengths is obtained by the removal of the specimen surface that is decarburized by heat treating. A further increase in the tensile properties can be accomplished by modifying the heat treatment slightly. This modified heat treatment is indicated in Table 10.

North American Aviation (Columbus) has had considerable experience in the welding of Vascojet 1000. The procedure found most satisfactory consists of preheating the parts to 500 F and welding until the temperature of the pieces drops to 250 F. The parts are then reheated to 500 F and welding is continued. Immediately after welding, the structures are stress relieved at 1450 F for 2 hours and air cooled. The 1450 F treatment is below the lower critical temperature of this steel, and its purpose is to soften the heat-affected zone and relieve stresses. After this treatment, the final forming or machining operations are performed. If forming operations are not required, the stress-relief temperature may be lowered to 1200 F. If the assembly cannot be stress relieved immediately after welding, as in the case of some repair welds, it is given a postweld heat treatment at 600 F for several hours before the parts are allowed to cool to room temperature. However, in this condition (unannealed), the weld and heat-affected zones are very brittle and may crack if not handled carefully.

The hardening treatment used by North American consists of austenitizing at 1850 F for 2 hours, air cooling, then triple tempering at 975 F for 2 hours. North American believes that the triple temper for 2 hours is better than a double temper at the same temperature for a longer period of time. When this heat treatment is followed, the material has an ultimate strength of about 300,000 psi. Transverse tension tests indicate that welded joints have better then 95 per cent joint efficiency with 6 [illegible] per cent elongation.

All of North American's welding is done by the manual inert-gas tungsten-arc process. Filler wire is swaged from strips sheared from the base plate. A mixture of 80 per cent argon-20 per cent helium shielding gas has been found to be the most satisfactory; it combines the shielding properties of argon with the penetrating characteristics of helium. Evaluation of the inert-gas

TABLE 10. TENSILE PROPERTIES AND HARDNESSES OF WELD JOINTS IN 0.086-INCH-THICK VASCOJET 1000 DIE STEEL(17)

Welds made by inert-gas tungsten-arc process using Vascojet 1000 filler wire.

Tempering Temperature, F	Specimen Condition	Ultimate Tensile Strength, psi	0.2 Per Cent Yield Strength, psi	Elongation in 2 Inches, per cent	Reduction of Area, per cent	Hardness, Rockwell C	Location of Failure
950(a)	Full size(c)	280,000	242,000	6.5	22	54-55	Base metal
	Ground(d)	290,000	258,000	7.0	23	54-55	Base metal
975(b)	Full size	303,000	282,000	3.2	10.3	56	Base metal
1000(a)	Full size	264,000	237,000	6.0	27	52-53	Base metal
	Ground	273,000	246,000	6.3	25	52-53	Base metal

(a) Welds were annealed at 1525 F following welding. Test specimens were austenitized at 1850 F for 30 minutes, air cooled, and double tempered at temperature for 2 hours.

(b) Welds were stress relieved at 1100 F. Test specimens were preheated 1 hour at 1500 F, austenitized 45 minutes at 1825 F, air cooled, and double tempered at temperature for 2 hours.

(c) Flat surface in the as-rolled and as-welded condition.

(d) Flat surfaces ground to 0.070-inch thickness, thus reducing weld to same dimension as sheet and removing as-rolled and heat-treated surface.

consumable-electrode and resistance welding processes for welding this steel is in progress.

In its investigation of the weldability of Vascojet 1000, Boeing Airplane Company has studied the effect of various postweld heat treatments on the hardnesses of the weld metal, heat-affected zone, and base metal. Inert-gas tungsten-arc welds were made in 0.050-inch-thick sheet. The pieces were preheated to 800 F. The results of tests of welds made in spheroidized sheet are given in Table 11. The treatments indicated would be used to soften the weldments for forming operations. Tests also were conducted of welds made in sheet material heat treated to 280,000 ultimate tensile strength (54-55 Rockwell C hardness) prior to welding. Such welds could be likened to repair welds. Results of these latter tests are given in Table 12.

The Martin Company (Baltimore) has investigated Vascojet 1000 for use in thin-walled pressure vessels.(19) These tests consisted of fabricating small pressure vessels which were hardened and then tempered at various temperatures. In addition, control specimens of the base material and transverse welds were heat treated along with each pressure vessel. (These tests are described more thoroughly in the section of this report entitled "Design, Testing, and Inspection".)

All welding was done by the manual inert-gas tungsten-arc process using 1/32-inch Eureka 1000 filler wire having the same chemical composition as Vascojet 1000. The vessels were welded without preheat and stress relieved at 1325 F for 2 hours. The vessels and control specimens were austenitized at 1850 F for 30 minutes, air cooled to room temperature, and triple tempered at the desired temperature for 2 hours.

The results of tension tests on the welded and unwelded control specimens are given in Table 13, and those of the pressure tests of the welded vessels are given in Table 14. The graph in Figure 2 shows the relationship between the tension-test data and pressure-vessel burst data. This graph indicates that there is no correlation between yield strength and elongation measured in the tension test and the behavior of a material in a pressure-vessel application. The Martin Company attributed the difference between the tempering temperature for maximum strength and that required for maximum bursting pressure to the low ductility and notch sensitivity of Vascojet 1000 at the higher strength levels. (Similar tests were made with Type 422 martensitic stainless steel. The results of these tests appear in the section "Martensitic Stainless Steels" and may be compared with the above performance of Vascojet 1000.)

To study the notch sensitivity of a material or its resistance to crack propagation, several tests have been devised. The Armco Steel Corporation has been using a test of this type that was devised by the Naval Research Laboratory(20) to evaluate the crack-propagation resistance of several steels.(21) This test method consists of comparing the ultimate strength

TABLE 11. HARDNESSES OF WELD JOINTS MADE IN SPHEROIDIZED VASCOJET 1000 SHEET SUBJECTED TO VARIOUS POSTWELD HEAT TREATMENTS (18)

Weld-Joint Heat Treatment	Time at 1350-1400 F, minutes	Weld and Heat Affected Zone Hardness, Rockwell C	Base-Metal Hardness, Rockwell C
Cooled to 400 F, reheated to 1350-1400 F	1/2	53-55	28-32
	1	49-50	17-20
	5	42-44	19
	20	34-39	17
	90	24-31	14
Cooled to 150 F, reheated to 1350-1400 F	1/2	51-52	24
	1	46	14
	5	37-39	13-17
	20	33-36	15
	90	27-33	13
Not cooled, heated to 1350-1400 F	1/2	53-55	25
	1	53-56	16
	5	52-54	15
	20	45-49	15
	90	19-22	15

TABLE 12. HARDNESSES OF WELD JOINTS AFTER VARIOUS POSTWELD HEAT TREATMENTS MADE IN VASCOJET 1000 SHEET HEAT TREATED TO 280,000 PSI ULTIMATE (54-55 ROCKWELL C)(18)

Weld-Joint Heat Treatment	Weld Hardness, Rockwell C	Heat-Affected Zone Hardness, Rockwell C
Cooled to room temperature	52	45-48
Cooled to 400 F, reheated to 950 F for 2-1/2 hours	51-53	38-45
Cooled to 150 F, reheated to 950 F for 2-1/2 hours	53-55	46
Cooled to 400 F, reheated to 950 F for 1 hour, cooled to room temperature, reheated to 950 F for 1-1/2 hours	52-55	41-43
Cooled to 150 F, reheated to 950 F for 1 hour, cooled to room temperature, reheated to 950 F for 1-1/2 hours	52-55	41-43

TABLE 13. MECHANICAL PROPERTIES OF VASCOJET 1000 CONTROL SPECIMENS PROCESSED IN THE HEAT TREATMENT OF EXPERIMENTAL PRESSURE VESSELS(19)

Tempering Temperature, F	Specimen Type	Ultimate Tensile Strength[a], psi	Yield Strength, psi	Elongation in 2 Inches, per cent
950	Weld joint	298,300	228,700	3.3
	Base metal	299,700	231,800	3.7
1000	Weld joint	279,800	227,300	5.0
	Base metal	281,400	227,330	5.6
	Weld joint	280,300	227,100	5.1
	Base metal	280,450	227,400	5.5
1050	Weld joint	255,450	214,775	4.4
	Base metal	254,520	216,540	5.0
	Weld joint	253,600	214,400	4.5
	Base metal	254,100	214,650	4.9
1075	Weld joint	240,810	200,180	6.1
	Base metal	242,600	199,800	6.0
1100	Weld joint	218,800	186,370	6.5
	Base metal	210,400	187,550	6.7
	Weld joint	217,630	185,670	6.4
	Base metal	218,100	186,100	6.5
1200	Weld joint	145,300	117,370	7.0
	Base metal	151,800	120,050	11.5

(a) All specimens failed in the base metal.

TABLE 14. BURSTING PRESSURE OF VASCOJET 1000 EXPERIMENTAL PRESSURE VESSELS(19)

Tempering Temperature, F	Bursting Pressure		Ultimate Strength of Control Specimens, psi	Calculated Hoop Stress of Cylinder at Actual Bursting Pressure[a], psi	Ratio of Actual Bursting Pressure to Calculated Bursting Pressure
	Actual, psi	Calculated, psi			
950	980	2056	299,700	142,880	0.48
1000	1150	1930	281,400	167,670	0.59
	1225	1923	280,450	178,640	0.64
1050	1680	1752	255,450	244,940	0.96
	1610	1742	254,100	234,790	0.92
1075	1550	1664	242,600	226,040	0.93
1100	1300	1443	210,400	189,540	0.90
	1200	1496	218,100	174,990	0.80
1200	1020	1041	151,800	148,720	0.98

(a) $S = \frac{Pr}{t}$ where S = hoop stress, psi
P = bursting pressure, psi
r = radius of pressure vessel cylinder, inch
t = wall thickness of pressure vessel, inch

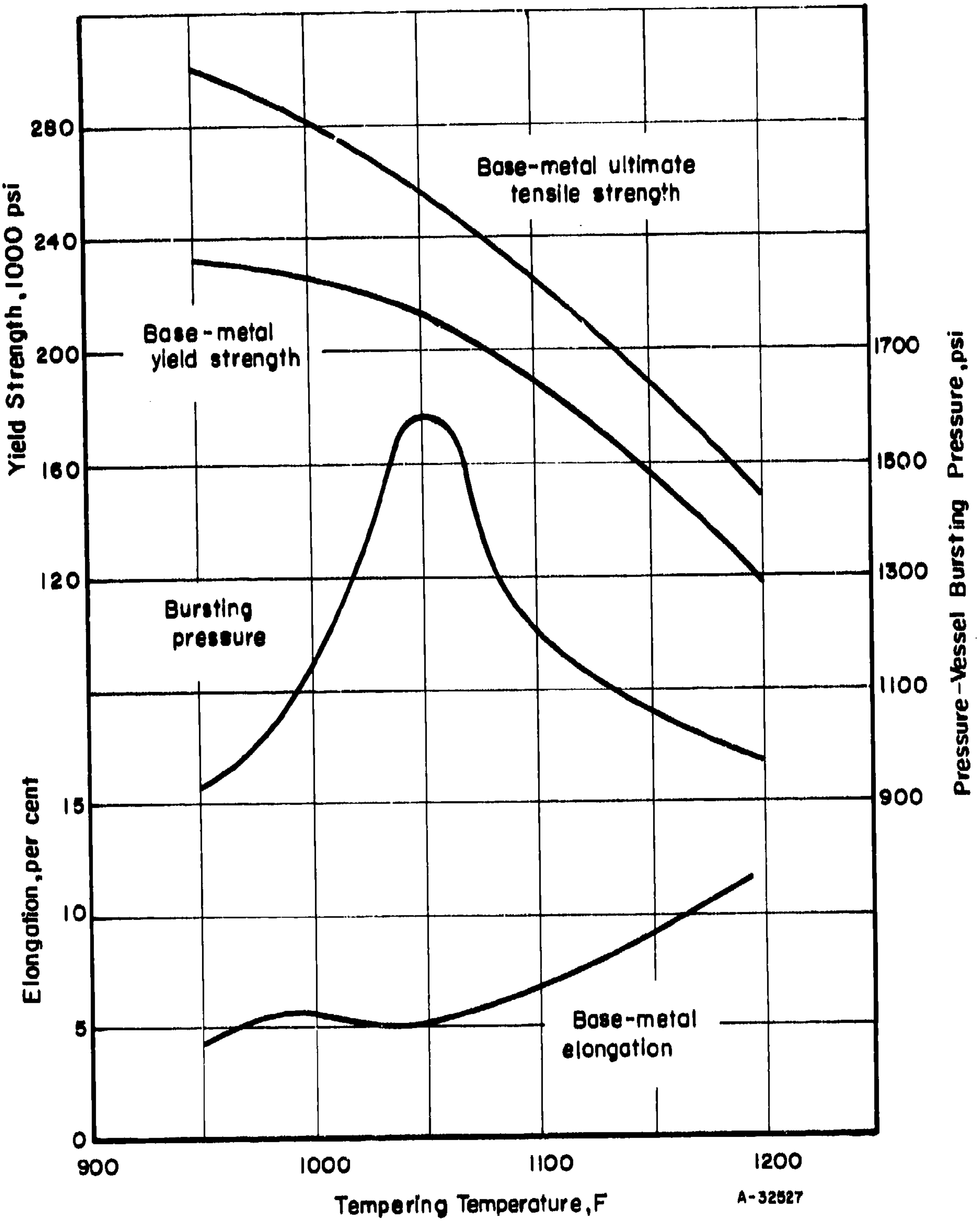

FIGURE 2. EFFECT OF TEMPERING TEMPERATURE ON BASE-METAL TENSILE PROPERTIES AND PRESSURE-VESSEL BURSTING PRESSURE FOR VASCOJET 1000 DIE STEEL(19)

determined by a standard tension test with the strength of a notched specimen. A very sharp notch is placed in the specimen by means of a hydrogen embrittling technique. The details of the test procedure are given in the section "Design, Testing, and Inspection".

The net fracture stress of the cracked specimen is calculated by the formula:

$$F_{net} = \frac{P}{t\,(b-c)} ,$$

where

P = maximum load, lb

t = specimen thickness, inch

b = specimen width, inch

c = length of initial crack, inch.

The ratio of the net fracture stress of the cracked specimen to the ultimate tensile strength of the standard tensile specimen is called the cracked-specimen strength ratio,

$$(C = F_{net}/F_{tu}) .$$

Armco included Vascojet 1000 in their studies. They tested this material at various strength levels. Figure 3 shows how the ratio C varies with tempering temperature. The ratio of pressure-vessel bursting pressure to calculated bursting pressure as determined by Martin for Vascojet 1000 pressure vessels also is shown. On the basis of these curves, there appears to be a definite correlation between the two types of tests. This would indicate that the decrease in bursting pressure for the Vascojet 1000 pressure vessels with increasing material strength is caused by the poorer resistance to crack propagation of this material at the higher strength levels. Solar Aircraft Company (San Diego) has conducted an extensive series of tests of subsized pressure vessels welded from various die steels (including Vascojet 1000) and also has found the optimum tempering temperature for these vessels to be around 1025 F to 1050 F. At tempering temperatures above and below this range, the bursting pressure decreases. The various crack-propagation and pressure-vessel bursting tests indicate that Vascojet 1000 has poor crack-propagation properties when heat treated above 200,000 psi yield. Primarily for this reason, Aerojet-General (Azusa) is not planning on using any of the die steels for pressure vessels.

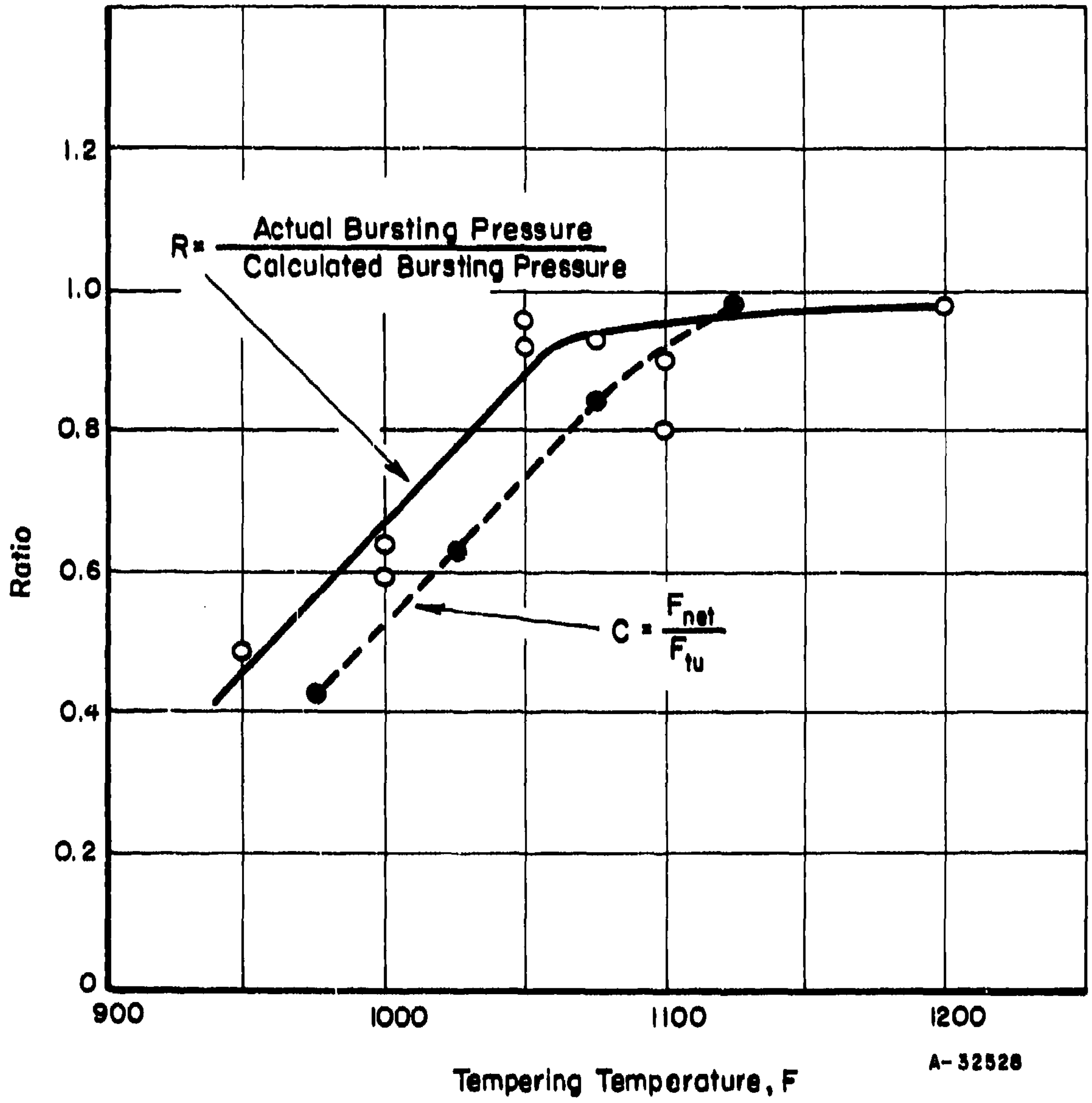

FIGURE 3. RELATIONSHIP BETWEEN BURSTING-PRESSURE DATA(19) FOR PRESSURE VESSELS AND CRACK-PROPAGATION RESISTANCE DATA(21) FOR VASCOJET 1000 DIE STEEL

Other Die Steels

Ryan Aeronautical Company has conducted welding tests of Unimach 1 steel, using Vascojet 1000 filler wire. Various thermal treatments of the weld joints were studied and the best was found to be: preheat to 450 F, allow weld to cool to 150 F, reheat to stress-relief temperature (1250 F). Hardening of the weld joints produced an ultimate tensile strength of about 300,000 psi (95 to 100 per cent joint efficiency) with 3 per cent elongation. The ductility of the weld metal and base plate were about equal.

Allegheny-Ludlum recommends(22) that Potomac A be welded in the annealed condition by either the inert-gas tungsten-arc process or by resistance-welding methods. A preheat of 900 F and a postheat of 1375 F applied for 1 hour should be used. The application of the postheat sufficiently anneals the weldment that optimum results will be obtained from subsequent heat treatment. Potomac A is hardened by austenitizing at 1850 F and air cooling. A multiple tempering treatment is used: 2 hours at 1000 F, air cool, 2 hours at 1050 F. Base-metal properties resulting from this heat treatment are: 280,000 psi ultimate, 220,000 psi yield, and 5 per cent elongation in 2 inches.

Tensile properties of inert-gas tungsten-arc welds in 0.050-inch-thick Potomac M have been reported by Solar Aircraft Company.(23) The ultimate tensile strength of manual welds was about 290,000 psi, the yield strength was 253,000 psi, and elongation was 4 per cent in 2 inches. These weldments were austenitized at 1850 F, air cooled, tempered 2 hours at 950 F, and retempered 2 hours at 650 F. An increase of about 7,000 psi in the yield and ultimate strengths could be obtained by welding automatically. Convair (Pomona) achieved about the same results with similar tests of Potomac M. Circular-groove cracking tests conducted by Convair failed to disclose any tendency for weld-metal cracking when welding Potomac M.

MARTENSITIC STAINLESS STEELS

Particular interest currently is being shown by the aircraft industry in five alloys of the AISI 400 series of martensitic stainless steels: Types 410, 419, 422, 431, and a modified 422 produced by U. S. Steel and designated by them as 12 MoV. The nominal compositions of these five alloys are given in Table 15.

TABLE 15. NOMINAL COMPOSITIONS OF MARTENSITIC STAINLESS STEELS

Designation	Producer	Chemical Composition, per cent							
		C	Mn	Si	Ni	Cr	Mo	V	W
Type 410	(Various)	0.15 max	1.00 max	1.00 max	--	11.5-13.5	--	--	--
Type 419	Allegheny-Ludlum	0.25	1.00	0.20	1.00	12.0	0.50	0.40	2.90
Type 422	Crucible	0.23	0.75	0.35	0.80	12.0	1.00	0.25	1.00
12 MoV (modified Type 422)	U. S. Steel	0.20	0.50	0.50	0.65	12.0	1.00	0.30	--
Type 431	(Various)	0.20 max	1.00 max	1.00 max	2.00	16.0	--	--	--

For missile and aircraft applications, the inert-gas-shielded tungsten-arc process is the usual method of welding. Covered electrodes have been developed for use with certain of these alloys. Resistance and flash welding also may be used. In resistance welding, it is necessary to temper the weld nugget while in place between the electrodes to prevent cracking by hardening on cooling. Tempering may be done by applying a supplementary current of reduced amperage through the weld joint. This added operation is time consuming, so little use is made of resistance welding of the martensitic stainless steels in production applications.

Type 410

This steel has been used for many years by the aircraft industry both in sheet form and as castings. It has found applications in the fabrication of engine parts and of tanks for use in missile power plants. Where corrosion is a problem, some of the more corrosion-resistant alloys of this group are used or a protective coating is applied.

Welding usually is done by the inert-gas-shielded process. Covered electrodes may be used for fabricating thick sections. Filler materials are of the same composition as the base material: Type 410 filler wire and E410 covered electrodes. Rohr welds Type 410 to Type 347 stainless steel by using Type 347 filler wire with the inert-gas tungsten-arc process.

Careful attention to postheating operations is necessary to prevent cracking in the weld-metal and heat-affected zones. Although preheating may be disregarded where not convenient or in those applications where it might cause joint mismatching, for example thin sheet, postheating is essential. Allegheny-Ludlum recommends either of two treatments: (1) annealing at 1500 F followed by controlled cooling to 1100 F at 50 degrees per hour followed by air cooling, or (2) heating to 1350-1400 F followed by the same cooling cycle as in (1).(24) Ryan prevents cracking by stress relieving at

1000 F within 4 hours after welding and Aerojet-General postheats at 1200 F for 1 hour within 12 hours after welding.(25) Ryan also specifies that no working of the welded part shall take place prior to the stress-relief treatment.

Type 410 is hardened by austenitizing at 1700 to 1850 F, oil or air quenching, and tempering to the desired strength level. Welded parts of this steel may be heat treated to 160,000 to 180,000 psi ultimate tensile strength. Ryan uses some parts heat treated to 200,000 psi ultimate.

Type 419

This alloy is a standard 12 per cent chromium stainless that has been modified by the addition of carbide formers to improve the high-temperature properties of the steel. It may be welded by the inert-gas tungsten-arc process using Type 419 filler wire. Allegheny-Ludlum has reported(26) that thicknesses up to 1/2 inch may be welded without the use of preheat. However, the use of preheat is recommended for welding heavy sections or where conditions of high restraint are present. Postheating treatments similar to those used with Type 410 should be used to prevent cracking.

Hardening after welding consists of an austenitizing treatment at 1950 F followed by a quench in oil or air and a temper in the range of 800 F to 1200 F. Some means of protection to prevent decarburization during austenitizing must be used.

Sheet material (0.065 inch thick), when tempered at 1000 F, will have a yield strength of 190,000 psi and 8 per cent elongation in 2 inches. Weld-joint efficiencies of 90 to 100 per cent may be obtained.

Type 422

Type 422 stainless steel, produced by Crucible Steel Company, has been used successfully for many high-temperature applications up to about 1200 F. Typical of these are buckets and blades in compressors and steam turbines, high-temperature bolting, and compressor and turbine wheels. Being resistant to atmospheric corrosion, it has been considered for use as a skin material. Of the martensitic stainless steels, Type 422 has the best creep-rupture properties in the range of 600 to 1200 F. Directional properties are minimized by the fact that it contains essentially only tempered martensite in the heat-treated condition.

Type 422 may be successfully welded by either the inert-gas-shielded or covered-electrode processes. Filler materials recommended are Type 422 wire for inert-gas welding and Lo Cro 9 Mo covered electrodes. (Lo Cro 9 Mo is Crucible's trade mark for AISI Type 505 covered electrodes. Type 505 stainless steel contains 9 per cent chromium and 1 per cent molybdenum.) To prevent cracking, Crucible recommends(27) that a preheat of 350 to 400 F be used and that the weldment be postheated at 1200 to 1300 F for 8 hours and air cooled.

Weldments are heat treated by air cooling or oil quenching the part from the austenitizing temperature of 1900 F. Tempering at 900 F for 1 hour will produce the following properties in 0.025-inch-thick sheet: 280,000 psi ultimate strength, 213,000 psi yield strength (0.2 per cent offset), and elongation in 2 inches of 6 per cent. Tensile-test results of welded and heat-treated 0.078-inch Type 422 sheet are given in Table 16. These welds were tested both at room temperature and at elevated temperatures. Table 17 shows the stress-rupture properties of these welds tested at 1000 F.

The Martin Company(28) has investigated Type 422 as a material for use in thin-walled pressure vessels. The test specimens used were of the same design as those used to study Vascojet 1000, and are described in the section "Design, Testing, and Inspection". The specimens were welded manually using Type 422 filler wire with the tungsten-arc process. No preheat was used, but the vessels were stress relieved at 1300 F for 2 hours as soon as possible after welding, followed by air cooling. The vessels then were austenitized at 1900 F for 30 minutes, air cooled, and double tempered at various temperatures in the range of 600 to 1000 F for 2 hours. All heating operations were carried out in an argon atmosphere. Control specimens, both with and without welds, were heat treated along with the test vessels. Results of tension tests of the control specimens are given in Table 18. Pressure-vessel bursting data are given in Table 19. These data are presented graphically in Figure 4.

In general, the Type 422 pressure vessels failed in the base metal rather than in the weld metal or heat-affected zone. The maximum burst strength was obtained at a strength level lower than the maximum obtainable with this steel. At the strength level of optimum bursting strength, the ratio of calculated ultimate stress in the test vessel to the ultimate strength of the control specimens is greater than unity. Unfortunately, no crack-propagation resistance data are available for this steel for comparison. Martin concludes from these tests that Type 422 stainless steel is a good material for fabricating small, thin-walled pressure vessels. They state, though, that the performance of this steel might be somewhat different when used for fabricating larger vessels. Solar has fabricated pressure vessels from Type 422 as well as the hot-work die steels. Die steels are preferred, since they can be heat treated to higher strength levels. However, Solar did state that the ruptured test vessels of Type 422 exhibited ductile failures rather than the brittle-type failure of the vessels fabricated from the die steels.

TABLE 16. MECHANICAL PROPERTIES OF WELD JOINTS IN 0.078-INCH-THICK TYPE 422 STAINLESS STEEL(27)

The material was austenitized at 1900 F, air cooled,
and tempered at 1000 F for 1 hour.

Specimen	Welding Process	Filler Material	Testing Temperature, F	Tensile Strength, psi	Elongation in 2 Inches, per cent	Location of Failure
Sheet	--	--	Room	209,000	9	--
Weld	Covered electrode	Lo Cro 9Mo	Room	205,000	4	Weld
Weld	Automatic TIG	422	Room	212,000	8	Weld
Weld	Manual TIG	422	Room	216,000	9	Base metal
Sheet	--	--	800	176,000	9	--
Weld	Covered electrode	Lo Cro 9Mo	800	162,000	3	Weld
Weld	Automatic TIG	422	800	173,000	6	Weld
Sheet	--	--	1000	156,000	8	--
Weld	Covered electrode	Lo Cro 9Mo	1000	154,000	7	Weld
Weld	Automatic TIG	422	1000	159,000	6	Base metal
Weld	Manual TIG	422	1000	154,000	8	Base metal
Sheet	--	--	1200	61,000	17	--
Weld	Covered electrode	Lo Cro 9Mo	1200	60,000	11	Weld
Weld	Automatic TIG	422	1200	58,000	15	Base metal
Weld	Manual TIG	422	1200	62,000	13	Weld

TABLE 17. STRESS-RUPTURE PROPERTIES OF WELD JOINTS IN 0.078-INCH-THICK TYPE 422 STAINLESS STEEL AT 1000 F(27)

Filler Wire: Type 422

Material was stress relieved at 1200 F for 8 hours, austenitized at 1900 F,
air cooled, and tempered at 1000 F.

Stress, psi	Rupture Life, hours	Rupture Elongation, per cent	Location of Fracture
68,000	133	7	Weld
72,000	128	8	Base metal
75,000	73	9	Base metal
80,000	35	9	Base metal

TABLE 18. MECHANICAL PROPERTIES OF TYPE 422 CONTROL SPECIMENS PROCESSED IN THE HEAT TREATMENT OF EXPERIMENTAL PRESSURE VESSELS(28)

Tempering Temperature, F	Specimen Type	Ultimate Tensile Strength(a), psi	Yield Strength, psi	Elongation in 2 Inches, per cent
600	Weld joint	222,000	161,500	8.3
	Base metal	229,000	165,300	10.3
	Weld joint	221,000	163,700	4.5
	Base metal	227,500	165,800	8.5
800	Weld joint	241,400	188,400	6.5
	Base metal	247,900	191,300	9.5
	Weld joint	225,900	177,500	5.3
	Base metal	235,500	183,600	9.0
900	Weld joint	249,400	188,000	8.3
	Base metal	256,900	191,000	10.3
	Weld joint	245,300	187,800	9.0
	Base metal	250,100	191,400	10.8
1000	Weld joint	213,400	173,200	5.5
	Base metal	216,300	173,900	7.3
	Weld joint	207,200	166,300	5.5
	Base metal	212,000	172,300	7.8

(a) All specimens failed in the base metal.

TABLE 19. BURSTING PRESSURE OF TYPE 422 EXPERIMENTAL PRESSURE VESSELS(28)

Wall Thickness – 0.026 inch.

Tempering Temperature, F	Bursting Pressure, psi	Origin of Failure	Calculated Ultimate Stress in Cylinder at Failure, psi[a]	Ultimate Strength of Welded Control Specimens, psi	Ultimate Stress Calculated / Ultimate Strength Control
600	1550	Dome	--	222,000	--
	1660	Dome	--	221,000	--
800	1090	Dome	--	241,400	--
	1625	Cylinder	218,750	225,900	0.97
900	1380	Cylinder	185,800	249,400	0.74
	1710	Cylinder	230,200	245,300	0.94
1000	1890	Cylinder	254,400	213,400	1.20
	1900	Cylinder	255,800	207,200	1.23

(a) Calculated Stress $= \frac{\text{Bursting Pressure x Cylinder Radius}}{\text{Wall Thickness}}$.

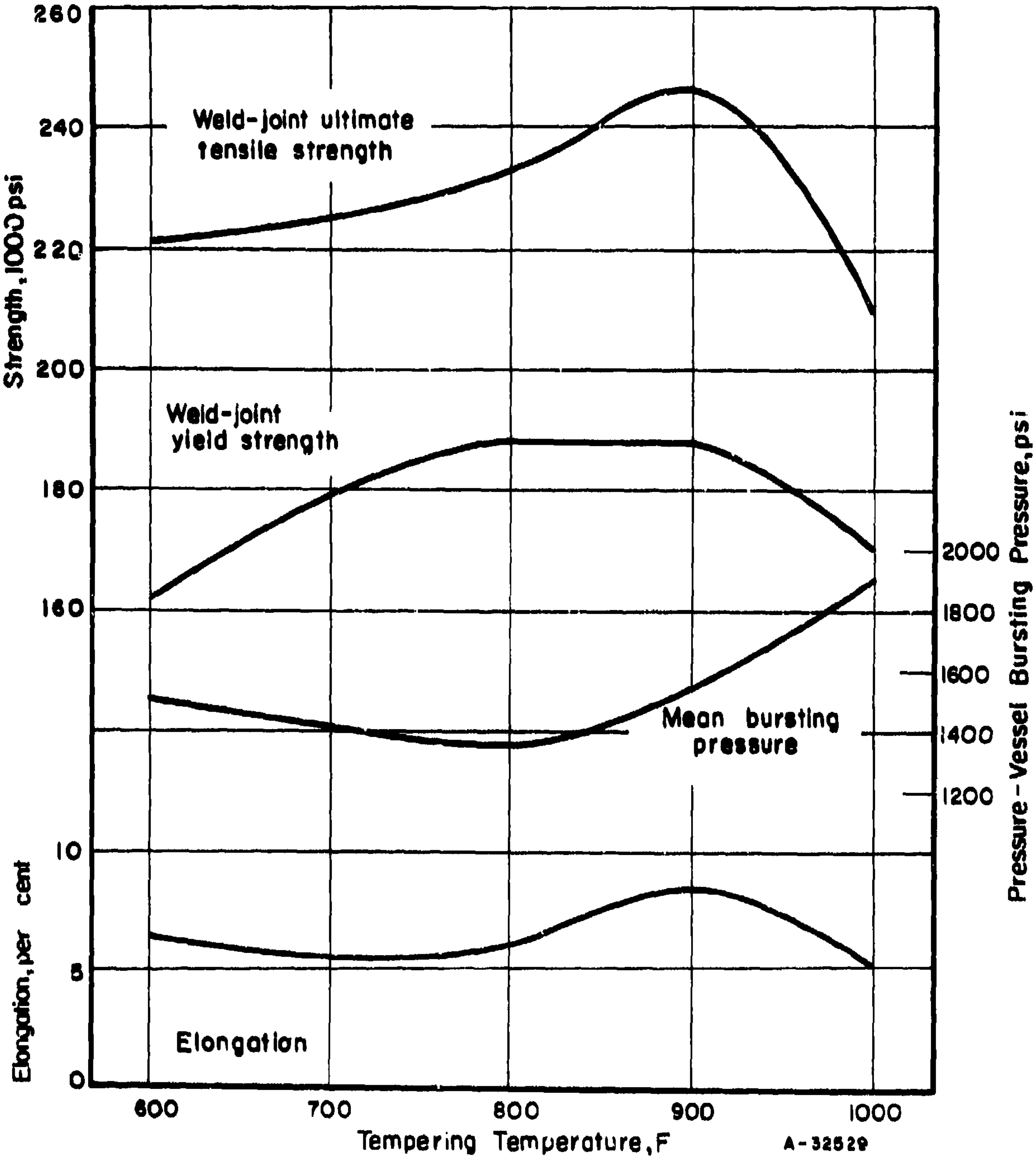

FIGURE 4. EFFECT OF TEMPERING TEMPERATURE ON WELD-JOINT TENSILE PROPERTIES AND PRESSURE-VESSEL BURSTING PRESSURE FOR TYPE 422 STAINLESS STEEL(28)

12 MoV (Modified Type 422)

This alloy, developed by the United States Steel Company, is essentially the same as the Type 422 except for the absence of tungsten in the 12 MoV alloy. This steel, like the other martensitic stainless grades, can be welded without preheat in thin gages. The inert-gas-shielded process is recommended for welding, and 12 MoV filler wire is available. Under conditions of high restraint, this steel is subject to weld-metal cracking. U. S. Steel has conducted a series of cracking tests of 12 MoV. The test pieces are placed in a restraining jig of special design during welding. To apply the restraining force, a section of fire hose is inflated with air so that it clamps the test piece against a backing plate. The restraining force may be adjusted by varying the air pressure in the hose. The results of these tests, given in Table 20, indicate that the incidence of weld-metal cracking is related to the welding speed. Two different heats of 12 MoV are indicated in this table, X18833 and X18834. The compositions of these heats are:

	C	Mn	P	S	Si	Ni	Cr	Mo	V
X18833	0.22	0.54	0.026	0.015	0.35	0.64	12.46	0.99	0.29
X18834	0.28	0.43	0.025	0.009	0.61	0.67	11.95	0.97	0.35

TABLE 20. RESULTS OF RESTRAINED WELD-METAL CRACKING TESTS OF 12 MoV STAINLESS STEEL(29)

	Welding Conditions[a]			
Sheet Thickness, inch	Travel Speed, ipm	Current, amp	Voltage, amp	Weld-Metal Cracking, per cent of weld length
0.022 (Heat X18834)	15	60	17	0
	20	80	18	0
	25	80	18	1.1
	33.5	90	18	40.7
0.050 (Heat X18834)	10	100	19	0
	12.5	100	19	2.5
	15	100	19	27.9
	32.7	135	21	100
0.050 (Heat X18833)	10	100	18	0
	15	110	18	13.7
	17.5	110	18	72.1
	20	120	18	97.3

(a) Samples were welded with inert-gas-shielded tungsten-arc process. No filler material was added.

This steel has been welded in either the quenched and tempered or annealed condition. Satisfactory joint properties may be obtained from welds in the quenched and tempered material merely by tempering the joint after welding. Such a treatment is advantageous in those applications where a quench and temper treatment after welding might cause distortion. However, the weld-joint efficiencies do not reach optimum values when this treatment is used. If 100 per cent joint efficiency is desired, the 12 MoV should be welded in the annealed condition followed by a quench and temper treatment. The data presented in Tables 21, 22, and 23 show the effect of these two postweld treatments on the weld-joint properties.

Type 431

The strength properties of this alloy are not as high as those of Type 422 and 12 MoV, although it can be heat treated to an ultimate tensile strength of about 20,000 psi higher (220,000 psi) than can the Type 410. It is used chiefly because its corrosion resistance is better than that of any of the other martensitic grades. The heat-treatment response of 431 is reported as not being uniform from heat to heat. This has forced some consumers to change to a different class of steels. Convair (San Diego), for instance, has considered the use of the precipitation-hardening, semiaustenitic and martensitic steels instead.

Welding procedures for Type 431 stainless steel are similar to those used with the other martensitic stainless. The inert-gas-shielded processes and filler wire of matching composition are used. A preheat temperature of 400 to 500 F and a 1200 F stress relief following welding are recommended.

Ultimate tensile strengths up to 220,000 psi and yield strengths up to 180,000 psi are obtained from this steel. Austenitizing temperature is in the range of 1800 to 1950 F. Since the austenite transformation is extremely sluggish in Type 431, parts may be air quenched, thus minimizing distortion.

PRECIPITATION-HARDENING STAINLESS STEELS

The precipitation-hardening stainless steels have been used extensively in the aircraft industry for many years. There also are many missile applications where these steels have been well suited. Their most desirable characteristics are good corrosion resistance and high strength. Although their heat-treated strengths are lower than those obtainable from some of the other classes of steels, they can be used for those structural applications where a corrosive environment may be encountered. In addition, the ease of fabrication of these steels is superior to that of some of the other classes of steel.

TABLE 21. TRANSVERSE TENSION PROPERTIES OF INERT-GAS TUNGSTEN-ARC WELD JOINTS IN 12 MoV STAINLESS STEEL(29)

Sheet Thickness, inch	Sheet Condition	Filler Wire	Condition of Weld	Ultimate Tensile Strength, psi	Location of Failure	Joint Efficiency, per cent
0.022 (Heat X18834)	Air cooled and tempered[(a)]	None[(b)]	Furnace tempered at 875 F for 4 hr, air cooled	208,100	Heat-affected zone	84.5
0.050 (Heat X18834)	Ditto	None[(b)]	Ditto	214,300	Heat-affected zone	85.0
0.050 (Heat X18833)	Ditto	None[(b)]	Ditto	209,000	Heat-affected zone	86.6
0.100 (Heat X18834)	Ditto	12 MoV[(c)] (Heat X18834)	Furnace tempered at 875 F for 4 hr, air cooled; weld reinforcement removed	220,600	Heat-affected zone	87.5
0.100 (Heat X18834)	Annealed	12 MoV[(c)] (Heat X18834)	1850 F for 1/4 hr, air cooled, 900 F for 4 hr, air cooled; weld reinforcement removed	269,900	Heat-affected zone	100

(a) 1850 F for 1/4 hr, air cooled, 900 F for 4 hr, air cooled.
(b) Welded automatically.
(c) Welded manually.

TABLE 22. LONGITUDINAL TENSILE PROPERTIES OF INERT-GAS TUNGSTEN-ARC WELD JOINTS IN 12 MoV STAINLESS STEEL(29)

Sheet Thickness, inch	Sheet Condition	Filler Wire	Condition of Weld	Ultimate Tensile Strength, psi	0.2 Per Cent Offset Yield Strength, psi	Elongation in 2 Inches, per cent
0.022 (Heat X18834)	Air cooled and tempered(a)	None(b)	Furnace tempered at 875 F for 4 hr, air cooled	214,100	190,800	1.0
0.050 (Heat X18833)	Ditto	None(b)	Ditto	230,500	188,200	6.0
0.100 (Heat X18834)	Ditto	12 MoV(c) (X18834)	Furnace tempered at 875 F for 4 hr, air cooled; weld reinforcement removed	239,000	186,200	10.7
0.100 (Heat X18834)	Annealed	12 MoV(c) (X18834)	1850 for 1/4 hr, air cooled, 900 F for 4 hr, air cooled, weld reinforcement removed	253,000	201,500	5.3

(a) 1850 F for 1/4 hr, air cooled, 900 F for 4 hr, air cooled.
(b) Welded automatically.
(c) Welded manually.

TABLE 23. TRANSVERSE BEND PROPERTIES OF INERT-GAS TUNGSTEN-ARC WELD JOINTS IN 12 MoV STAINLESS STEEL(29)

Sheet Thickness, inch	Sheet Condition	Filler Metal	Condition of Weld	Bend Angle at Start of Failure,(a) degrees	Location of Failure
0.022 (Heat X18834)	Air cooled(b) and tempered	None(c)	Furnace tempered at 875 F for 4 hr, air cooled	68	Weld metal
0.050 (Heat X18834)	Ditto	None(c)	Ditto	29	Weld metal
0.100 (Heat X18834)	Ditto	12 MoV(d) (X18834)	Furnace tempered at 875 F for 4 hr, air cooled; weld reinforcement removed	27	Weld metal
0.100 (Heat X18834)	Annealed	12 MoV(d) (X18834)	1850 F for 1/4 hr, air cooled, 900 F for 4 hr, air cooled; weld reinforcement removed	18	Weld metal

(a) 1/16-inch-radius mandrel.
(b) 1850 F for 1/4 hr, air cooled, 900 F for 4 hr, air cooled.
(c) Welded automatically.
(d) Welded manually.

The compositions of the precipitation-hardening stainless alloys of current interest are listed in Table 24. They can be subdivided on the basis of heat treatment and microstructure. These subdivisions are: (1) single-treatment martensitic, (2) double-treatment martensitic (sometimes called semiaustenitic), and (3) austenitic.

Single-Treatment Martensitic Steels

The 17-4PH steel is the only one of current interest that falls in the single-treatment martensitic class. Although this steel is used primarily in the form of castings, forgings, and machinings, it is available and is sometimes used in sheet form. Any of the arc-welding processes used with the regular grades of austenitic stainless steels may be used with 17-4PH. The use of preheat is not necessary since the carbon content of this alloy is so low. This low carbon content restricts the as-welded hardness of the weld metal and heat-affected zone and thus maintains sufficient ductility of these zones to overcome any tendency for cracking. Four different manufacturers (Alloy-Rods, Arcos, McKay, and Ried-Avery) currently are producing covered electrodes for welding 17-4PH. The composition of these electrodes meets the specifications released by Armco. Filler wire for use with the inert-gas-shielded processes also is available.

The composition of the filler wires and covered electrodes is slightly different from that of the base material. This is necessary to control the amount of delta ferrite present in the weld metal. A small amount of delta ferrite is desirable, since it acts as a suppressor of hot cracking. However, if too much delta ferrite is present, the weld-metal ductility is adversely affected. By adjusting the composition of the filler wire (particularly the chromium and nickel contents), the delta ferrite content of the weld metal may be controlled. The effect on the weld-metal ductility of varying chromium and nickel contents (and, correspondingly, the delta ferrite content) is shown in Table 25.

Another precaution to be observed in the chemical composition of 17-4PH with regard to its weldability is the copper content of castings. Too high a copper content will cause underbead cracking when welding these castings. To be satisfactorily weldable, the copper content of 17-4PH castings should not exceed 3 per cent.

The 17-4PH steel is quite sensitive to notch effects. Precautions must be taken in the design and fabrication of 17-4PH parts to avoid stress concentrations. Cracking is apt to occur at these stress concentrations due to high residual stresses caused by welding and hardening treatments. Armco has conducted a series of tests(30) using a maltese-cross type of specimen with the object of determining what, if any, heat treatment might reduce the

TABLE 24. NOMINAL COMPOSITION OF PRECIPITATION-HARDENING STAINLESS STEELS

		Chemical Composition, per cent								
Steel	Producer	C	Mn	Si	Ni	Cr	Mo	Cu	Al	Other
15-7Mo	Armco	0.07	0.60	0.40	7.00	15.00	2.25	--	1.15	--
17-4PH	Armco	0.04	0.60	0.40	4.00	17.00	--	4.00	--	0.3Cb + Ta
17-7PH	Armco	0.07	0.60	0.40	7.00	17.00	--	--	1.20	--
AM-350	Allegheny-Ludlum	0.10	0.75	0.30	4.20	17.00	2.75	--	--	0.10N
AM-355	Allegheny-Ludlum	0.15	0.75	0.30	4.20	15.50	2.75	--	--	0.10N
A-286	Allegheny-Ludlum, Universal Cyclops, Crucible, Carpenter	0.05	1.35	0.95	26.0	15.5	1.25	--	0.20	1.95Ti 0.30V
AF-71	Allegheny-Ludlum	0.30	18.0	0.25	--	12.5	3.00	--	--	0.80V 0.20N 0.20B
G-192	Allegheny-Ludlum	0.60	8.50	0.50	--	22.0	--	--	--	0.38N

TABLE 25. EFFECT OF WELD-METAL COMPOSITION ON TENSILE PROPERTIES OF 17-4PH STAINLESS STEEL WELD DEPOSITS(30)

								Mechanical Properties[a]			
	Chemical Composition, per cent							Ultimate Tensile Strength, psi	Yield Strength, psi	Elongation in 2 Inches, per cent	Reduction of Area, per cent
Electrode	C	Mn	Si	Cr	Ni	Cu	Cb				
Deposited With Covered Electrodes											
A	0.043	0.48	0.28	16.71	4.82	3.55	0.18	190,000	164,500	11.4	27.9
B	0.042	0.51	0.24	17.05	4.42	3.72	0.15	194,300	165,500	3.5	5.5
Deposited With Inert-Gas Consumable-Electrode Process											
C	0.032	0.44	0.43	16.83	4.87	3.52	0.19	195,500	173,500	9.6	25.0

(a) All-weld-metal specimens. After welding, specimens were annealed at 1900 F for 1/2 hr, air cooled, and hardened at 900 F for 1 hr.

notch sensitivity of this steel. Two heat treatments were found to be helpful: (1) a homogenizing treatment (2150 F for 1 hour, air cool) prior to the regular anneal, or (2) overaging the material (1150 F for 4 hours, air cool) prior to welding.

The 17-4PH steel is hardened by the following process: heat to 1900 F, air cool (annealed condition), and reheat to 900 to 1100 F for hardening. After annealing, the material has a martensitic microstructure. By aging at 900 to 1100 F, the strength and hardness of the 17-4PH steel is increased by the precipitation of submicroscopic particles, believed to be a Ni-Cu phase. After welding, two heat treatments may be applied to the weldment for hardening. Single-pass welds may be hardened simply by heating to the aging temperature. A single-pass weld cools sufficiently fast from the welding temperature that the weld metal and heat-affected zone are essentially in the annealed condition. However, in multipass welding, the continued heating and cooling cycle which occurs in the heat-affected zone and beads already deposited may result in a nonuniform response to the aging treatment. In this case, it is necessary to anneal the entire weldment after welding and then harden by aging. Northrup has found(31) that this annealing treatment, subsequent to welding, also results in the elimination of preferentially oriented ferrite stringers in the weld metal. Thus, the weld-metal structure would be more nearly the same as that of the base material. The tensile properties of weld joints in various thicknesses of material and made by various welding processes are given in Tables 26, 27, and 28. These weld joints were subjected to various heat treatments following welding. It is interesting to note the increased strength properties resulting from the subzero treatment which was given to welds in the 3/8-inch- and 1-inch-thick material. Elevated-temperature properties of welds in 17-4PH plate are shown in Figure 5.

The corrosion resistance of 17-4PH weld metal is comparable with that of the base material. However, the heat-affected zone is susceptible to intergranular attack by a corrosive hot acid solution. This attack occurs only when the weldment was hardened merely by aging. Annealing the weldment after welding and prior to aging will eliminate the sensitivity of the heat-affected zone.

Double-Treatment Martensitic Steels

In this classification of precipitation-hardening stainless steels, primary interest lies in 17-7PH and PH 15-7 Mo (also called semiaustenitic precipitation-hardening stainless steels). AM-350 and AM-355 are two other alloys in this group although they are not used quite to the extent of 17-7PH and PH 15-7 Mo.

TABLE 26. TENSILE PROPERTIES OF WELD JOINTS IN 0.188-INCH-THICK 17-4PH STAINLESS STEEL(30)

	Heat-Treated Condition of Weld Joint(a)		Mechanical Properties(b)				
					Elongation		
Welding Process	Annealing Temp, F	Aging Temp, F	Ultimate Tensile Strength, psi	Yield Strength, psi	In 2 Inches, per cent	In 1 Inch, per cent	Reduction of Area, per cent
Manual covered electrode	1900	900	200,000	185,000	6.5	13.0	28.8
	1900	950	186,000	175,000	6.0	12.0	29.7
	1900	1025	173,000	162,000	6.0	12.0	31.7
	1850	900	189,000	170,000	6.0	10.0	19.8
	1850	950	180,000	168,000	6.0	12.0	27.2
	1850	1025	163,000	154,000	6.0	12.0	39.0
Manual inert-gas tungsten arc	1900	900	202,000	187,000	7.5	13.0	29.0
	1900	950	193,000	180,000	7.2	13.5	28.5
	1900	1025	176,000	167,000	8.2	16.5	32.0
	1850	900	193,500	176,300	5.5	11.0	25.5
	1850	950	189,900	173,700	6.0	12.0	23.9
	1850	1025	169,600	154,500	6.0	12.0	26.6
Semiautomatic inert-gas tungsten arc	1900	900	199,000	183,000	9.0	17.0	34.9
	1900	950	195,500	182,000	9.0	18.0	42.4
	1900	1025	176,000	166,000	9.2	17.0	45.3
	1850	900	200,300	174,500	9.0	16.0	32.7
	1850	950	183,000	164,300	9.0	18.0	35.7
	1850	1025	170,600	160,400	9.0	18.0	40.9
Manual inert-gas consumable electrode	1900	900	202,600	181,000	7.0	14.0	
	1900	950	185,000	174,000	7.5	14.0	
	1900	1025	173,000	163,000	7.5	15.0	
	1850	900	189,200	178,300	7.0	14.0	
	1850	950	179,000	165,000	6.5	13.0	

(a) All welds were annealed and aged after welding.

(b) Tensile specimens cut transverse to weld joints.

TABLE 27. TENSILE PROPERTIES OF WELD JOINTS IN 3/8-INCH-THICK 17-4PH STAINLESS STEEL(30)

Welds deposited manually with 17-4PH covered electrodes.

Heat-Treated Condition of Weld Joint	Mechanical Properties(a) Ultimate Tensile Strength, psi	Yield Strength, psi	Elongation in 1 Inch, per cent	Reduction of Area, per cent	Location of Failure
As welded	138,000	74,000	2.0	5.0	Weld metal
Aged 900 F, 1 hr	178,000	154,000	10.0	32.0	Base metal
Aged 1000 F, 1 hr	160,000	136,000	11.0	29.0	Weld metal
Aged 1100 F, 1 hr	159,000	112,000	13.5	50.0	Base metal
Aged 1200 F, 1 hr	142,000	98,000	11.5	63.0	Base metal
Annealed 1900 F	146,000	102,000	11.0	64.0	Base metal
Annealed 1900 F, aged 900 F, 1 hr	187,000	172,000	11.0	48.0	Weld metal
Annealed 1900 F, aged 1000 F, 1 hr	170,000	161,000	12.0	48.0	Weld metal
Annealed 1900 F, aged 1100 F, 1 hr	158,000	134,000	12.0	54.0	Weld metal
Annealed 1900 F, aged 1200 F, 1 hr	144,000	105,000	16.5	64.0	Base metal
Annealed 1900 F, refrigerated -100 F, 1 hr, aged 900 F, 1 hr	204,000	189,000	11.5	44.0	Weld metal

(a) Tensile specimens cut transverse to weld joint.

TABLE 28. TENSILE PROPERTIES OF WELD JOINTS IN 1-INCH-THICK 17-4PH STAINLESS STEEL(30)

Welds deposited manually with 17-4PH covered electrodes.

Heat-Treated Condition of Weld Joint	Mechanical Properties(a) Ultimate Tensile Strength, psi	Yield Strength, psi	Elongation in 2 Inches, per cent	Reduction of Area, per cent	Location of Failure
As welded	140,000	96,000	4.5	10.5	Weld metal
Aged 900 F, 1 hr	158,000	118,000	8.0	21.0	Weld metal
Aged 1000 F, 1 hr	155,000	108,000	9.5	27.0	Weld metal
Aged 1100 F, 1 hr	158,000	111,000	7.5	18.5	Weld metal
Aged 1200 F, 1 hr	143,000	105,000	15.0	52.0	Base metal
Annealed 1900 F	145,000	91,000	10.0	46.5	Base metal
Annealed 1900 F, aged 900 F, 1 hr	186,000	163,000	9.5	36.0	Weld metal
Annealed 1900 F, aged 1000 F, 1 hr	167,000	146,000	9.5	39.0	Weld metal
Annealed 1900 F, aged 1100 F, 1 hr	158,000	129,000	11.0	38.0	Weld metal
Annealed 1900 F, aged 1200 F, 1 hr	143,000	100,000	14.0	54.0	Base metal
Annealed 1900 F, refrigerated -100 F, 1 hr, aged 900 F, 1 hr	201,000	178,000	10.0	34.0	Weld metal

(a) Tensile specimens cut transverse to weld joint.

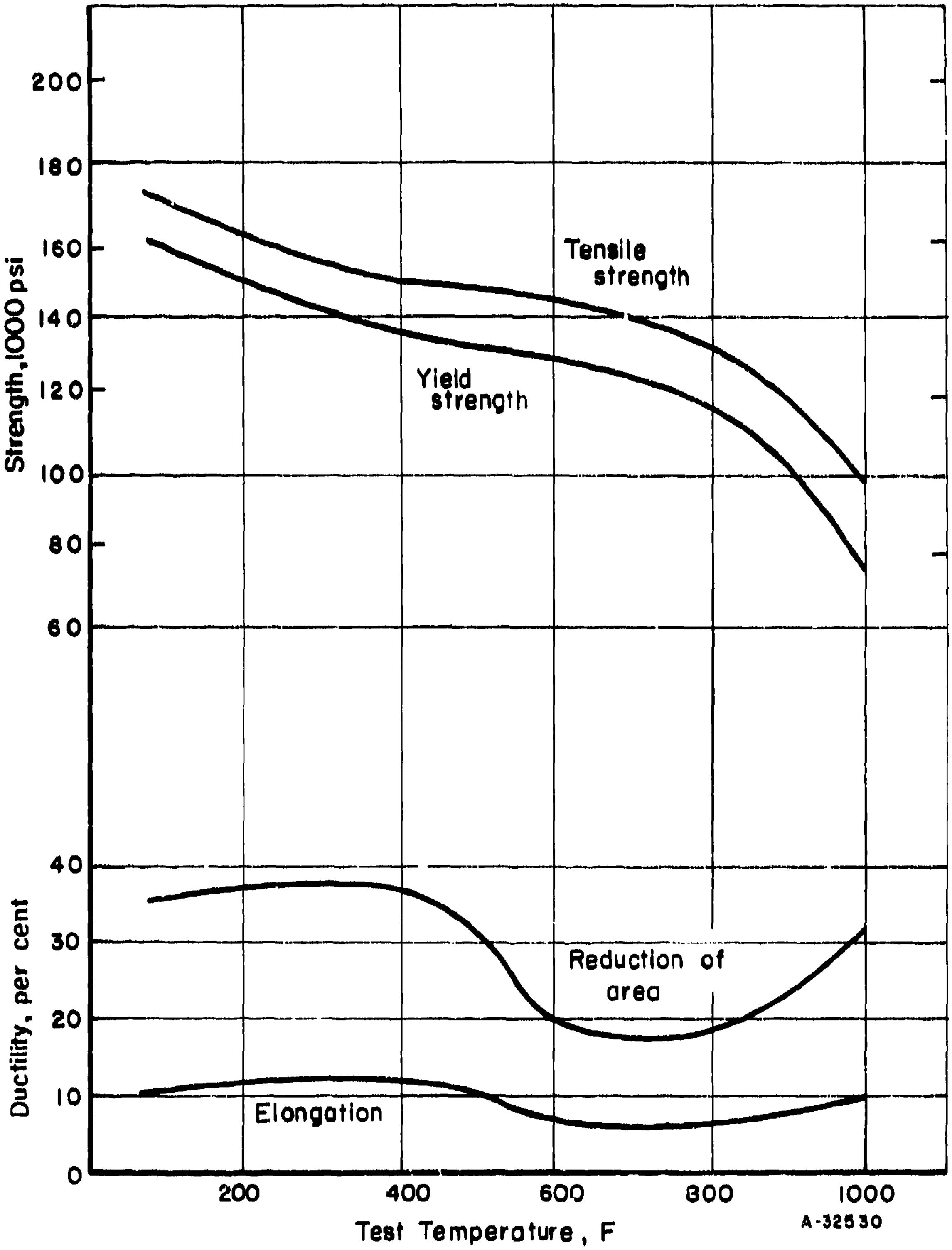

FIGURE 5. TRANSVERSE-TENSILE PROPERTIES OF INERT-GAS ARC-WELDED 1-INCH-THICK 17-4PH STAINLESS STEEL(32)

Weld joints aged at 925 F for 1 hour following welding

PH 15-7 Mo and 17-7PH

PH 15-7 Mo and 17-7PH are very similar in composition and in their welding characteristics. PH 15-7 Mo is a recent higher strength modification of the 17-7PH in which 2 per cent of the chromium content has been replaced by molybdenum. Next to some of the low-alloy martensitic steels, 17-7PH is one of the widest used high-strength steels for aircraft applications. It has been used for bulkheads, longerons, and other structural members for many years. In thin sheet form, it is finding many applications in the fabrication of missiles.

In spite of its wide usage, there have been some serious problems connected with 17-7PH. Heat-treatment response has varied from heat to heat of the steel. Dimensional changes during heat treatment have caused difficulties. Weld-metal ductility has been low. These problems have carried over into the PH 15-7 Mo alloy also. However, continued study and development work has gone a long way in solving or minimizing these problems. In many cases, by recognizing the problems related with the usage of these steels, allowances may be made in the design of parts which will tend to overcome the shortcomings.

Arc Welding. The inert-gas-shielded processes are the best ways of arc welding 17-7PH and PH 15-7 Mo. Since hardening depends on the precipitation of aluminum-nickel intermetallic compound, it is essential that the aluminum content of the weld metal be maintained during arc welding. Thus, covered-electrode welding is not recommended for these steels since it is difficult to transfer aluminum across the arc by this process. Filler wires used with the inert-gas-shielded processes are essentially of the same composition as the base material. Some modifications of the filler-metal analysis have been made, though, in an effort to improve the weld-metal ductility. As with the 17-4PH steel, ductility is related to the delta-ferrite content of the steel. The problem is compounded with 17-7PH because of its aluminum content, aluminum being a powerful ferrite former. Armco has extensively studied filler-wire compositions and has found that, by reducing the chromium and aluminum contents slightly and increasing the nickel content, the amount of delta ferrite in the weld metal is reduced and the ductility is improved.

No preheat or postheat is needed since the weld metal and heat-affected zone are austenitic in the as-welded condition and thus have sufficient ductility to resist cracking. North American has conducted restrained weld-metal cracking tests of 17-7PH(33) and found no tendency for cracking of the weld metal.

In welding these two steels by the inert-gas tungsten-arc or consumable-electrode process, the molten weld metal will be covered by a hazy film. This same effect is noted when welding aluminum. The film appearing on the steel has been identified as consisting chiefly of aluminum oxide.(34) Although this film is not detrimental to the welding of these steels, it does exert a thermionic effect which reduces the heat input into the weld. Thus, a somewhat higher welding current is necessary to obtain complete penetration. This film is most noticeable when using direct current with straight polarity. The film may be minimized by using helium as the shielding gas and is virtually eliminated by using alternating current. Ryan uses alternating current for welding all light gages but switches to direct current when welding heavier material to prevent tungsten pickup.

PH 15-7 Mo and 17-7PH may be hardened by either of three methods: a double-aging treatment, a subzero cooling treatment, or a cold-working treatment. In the first method, the mill-annealed material, which is austenitic, is heated to 1400 F for 1-1/2 hours. This treatment renders the austenite unstable so that, upon subsequent air cooling to 60 F, it transforms to martensite. Reheating to about 1000 F, depending on the properties desired, results in age hardening. This double-aging hardening treatment is designated TH, followed by the temperature of the second aging treatment, e.g., TH-1000.

The second method of hardening consists of heating the mill-annealed material to 1750 F for 10 minutes and air cooling to -100 F. During an 8-hour holding time at -100 F, the structure transforms to martensite. The material is then age hardened at around 950 F. Such treatment is denoted by RH, followed by the age-hardening temperature, e.g., RH-950.

A third method of hardening of thin sheet material is being investigated. By this method, the austenite is transformed by cold working. An age-hardening operation is applied following transformation. By using a treatment of this type, dimensional changes during the transformation are overcome. This cold-working transformation treatment results in higher strengths (265,000 psi ultimate for an aging temperature of 900 F) but the ductility is quite low (2 per cent elongation in 2 inches).

The highest joint efficiencies are obtained when the weld joint is heat treated after welding. However, when large items are to be fabricated from thin sheet (such as missile bodies), the problem of distortion due to heat treating becomes serious. One solution to this problem would be to weld after heat treatment. As would be expected, though, joint efficiencies would be much less if this technique is used. North American has conducted an extensive test program to study the properties of weld joints that have been made during various stages of the heat-treating cycle. Table 29 lists the tensile strengths of weld joints made before, during, and after the RH-950 heat treatment of 17-7PH. The tensile properties of various thicknesses of 17-7PH welded following the TH-1075 heat treatment are listed in Table 30. Similar information is given for PH 15-7 Mo welds in Table 31. The properties of the PH 15-7 Mo welds with the weld reinforcement removed are slightly lower than those with the reinforcement intact. Armco attributes this to the fact that the weld metal is not so strong as the base metal.

TABLE 29. TENSILE STRENGTHS OF WELD JOINTS IN 17-7PH STAINLESS STEEL WELDED AT VARIOUS STEPS IN RH-950 HEAT TREATMENT(35)

Welds made by inert-gas tungsten-arc process using 17-7PH filler wire.

Test Temperature, F	Sheet Thickness, inch	Ultimate Tensile Strength, psi				
		Base Metal, RH-950	Welded, RH-950	1750 F, Welded -100 F, 950 F	1750 F, -100 F Welded, 950 F	RH-950, Welded
RT	0.080	220,000	211,000	134,000	133,000	125,000
	0.032	220,000	196,000	122,000	135,000	115,000
300	0.080	200,000	194,000	85,000	88,000	82,000
	0.032	204,000	190,000	88,000	93,000	83,000
500	0.080	187,000	181,000	84,000	83,000	75,000
	0.032	190,000	176,000	83,000	84,000	75,000
800	0.080	161,000	152,000	82,000	79,000	67,000
	0.032	158,000	150,000	84,000	82,000	76,000

TABLE 30. TENSILE PROPERTIES OF WELD JOINTS IN 17-7PH STAINLESS STEEL MADE AFTER TH-1075 HEAT TREATMENT(33)

Sheet Thickness, inch	Direction of Testing	Test Temp, F	Tensile Properties			
			Parent Metal		Weld Joint	
			Ultimate Tensile Strength, psi	Elongation in 2 Inches, per cent	Ultimate Tensile Strength, psi	Elongation in 2 Inches, per cent
0.018	Transverse	RT	182,600	10.8	143,900	2.1
0.050	Transverse	RT	177,700	10.4	140,500	3.8
0.080	Transverse	RT	187,500	9.0	156,700	4.7
0.050	Longitudinal	RT	184,200	--	151,400	4.0
0.078	Longitudinal	RT	189,000	--	145,800	5.6
0.078	Longitudinal	300	175,800	9.1	96,000	4.9
0.050	Longitudinal	500	161,300	4.7	90,100	2.8
0.050	Longitudinal	700	152,400	6.5	92,300	3.0
0.050	Longitudinal	900	116,700	22.0	81,200	3.2

TABLE 31. TRANSVERSE TENSILE PROPERTIES OF WELDED JOINTS IN PH 15-7Mo STAINLESS STEEL(36)

Heat-Treated Condition of Welded Joint	Ultimate Tensile Strength, psi	Yield Strength, psi	Elongation In 2 Inches, per cent	Elongation In 1 Inch, per cent
	Weld Reinforcement Intact[a]			
Welded, TH-1050	210,000	205,000	5.0	--
Welded, TH-1100	190,000	175,000	8.0	--
Welded, RH-950	240,000	225,000	5.0	--
Welded, RH-1075	215,000	205,000	5.0	--
Welded, annealed, TH-1050	210,000	205,000	5.0	--
Welded, annealed, TH-1100	190,000	175,000	6.0	--
Welded, annealed, RH-950	235,000	215,000	4.0	--
Welded, annealed, RH-1075	210,000	205,000	4.0	--
	Weld Reinforcement Removed[b]			
Base metal TH-1050, as welded	122,000	88,000	7.0	25.0
Base metal RH-950, as welded	115,000	87,000	6.0	22.0
Welded, TH-1050	205,000	195,000	2.0	8.0
Welded, TH-1100	175,000	165,000	4.0	14.0
Welded, RH-950	230,000	215,000	2.0	8.0
Welded, RH-1075	200,000	195,000	2.5	13.0
Welded, annealed, TH-1050	210,000	205,000	2.0	9.0
Welded, annealed, TH-1100	185,000	175,000	4.0	12.0
Welded, annealed, RH-950	235,000	210,000	2.0	7.0
Welded, annealed, RH-1075	210,000	200,000	2.0	10.0

(a) All specimens failed in base metal.
(b) All specimens failed in weld metal.

North American also has found this to be true for welds in 17-7PH. Table 32 indicates that a greater reduction in joint properties occurs when the bottom reinforcement is removed than when the top reinforcement is removed. North American believes that this difference is caused by the orientation of the delta-ferrite stringers at the root of the weld joint.(33)

TABLE 32. EFFECT OF REMOVAL OF WELD-BEAD REINFORCEMENT ON TENSILE STRENGTH OF WELD JOINTS IN 0.081-INCH-THICK 17-7PH STAINLESS STEEL(33)

Weld joints heat treated TH-1075 after welding.

Weld Condition	Transverse Ultimate Tensile Strength, psi	Transverse Elongation in 2 Inches, per cent
Weld reinforcement intact	185,000	8.3
Weld reinforcement removed on top	183,400	6.5
Weld reinforcement removed on bottom	178,500	4.2
Weld reinforcement removed on both sides	177,300	4.6

The problem of increasing the ductility of weld metal in both of these steels has been a major one. North American has found that, in general, the double-aging treatment gives better ductility than the subzero treatment. Raising the aging temperature does not seem to improve the ductility. Northrup gets better ductility from 17-7PH than PH 15-7 Mo although the yield and tensile strengths are not so good. They feel that a reduction in the amount of delta ferrite in the PH 15-7 Mo weld metal would improve its ductility. Armco is developing filler wire of a composition that will reduce the delta-ferrite content of the weld metal.

Roll planishing of the weld beads improves the weld-joint properties somewhat. Northrup found that the location of tensile failures switched from the heat-affected zone to the parent metal when planishing was used. Tests were made by Boeing of welds in 0.025-inch-thick 17-7PH heat treated to RH-950 after welding. Elongation in 1 inch increased from 2 to 6 per cent when the weld bead was roll planished. Tensile and yield strengths increased about 3000 psi. The location of failure still was in the weld metal.

Resistance Welding. Both PH 15-7 Mo and 17-7PH steels may be readily spot and seam welded using a broad range of machine settings. Armco recommends, though, that the welds be left in the as-welded (austenitic) condition to obtain the best tensile and shear strengths. In a series of spot- and seam-welding tests conducted by North American, a very definite embrittlement of the weld nugget of 17-7PH and PH 15-7 Mo occurred when the transformation treatment followed welding. Some typical tensile and shear strengths for these alloys following various heat treatments are given in Tables 33 and 34. Elevated-temperature strengths of 17-7PH spot welds are shown graphically in Figure 6. Flash welding is not recommended.

TABLE 33. TENSILE AND SHEAR STRENGTHS OF SPOT-WELDED 17-7PH STAINLESS STEEL

Sheet Thickness, inch	Preweld Heat Treatment	Postweld Heat Treatment	Strength, pounds Tensile-Shear Test	Strength, pounds Cross-Tension Test	Tension-to-Shear Ratio
0.014	RH-1050	None	540	277	0.51
0.017	RH-950	None	710	400	0.56
0.025	TH-1050	None	1246	579	0.46
0.050	1750 F anneal	None	2580	1265	0.49
0.050	Ditto	TH-1075	2710	705	0.22
0.050	"	RH-950	2550	745	0.29
0.050	TH-1075	None	3130	1580	0.50
0.050	Ditto	TH-1075	2605	710	0.37
0.050	"	675 stress relief	2650	1480	0.54
0.050	RH-950	None	3045	1445	0.48
0.050	Ditto	RH-950	2845	930	0.54
0.080	TH-1075	None	--	2915	--
0.080	Ditto	RH-950	--	610	--
0.080	"	950 F aging treatment	--	3340	--
0.093	TH-1050	None	8436	3857	0.46

Note: Data for 0.050- and 0.080-inch-thick sheet were obtained from Reference 37. The balance of the data were obtained from Reference 38.

TABLE 34. TENSILE AND SHEAR STRENGTHS OF SPOT-WELDED PH 15-7 Mo STAINLESS STEEL

Sheet Thickness, inch	Preweld Heat Treatment	Postweld Heat Treatment	Strength, pounds Tensile-Shear Test	Strength, pounds Cross-Tension Test	Tension-to-Shear Ratio
0.022	RH-950	None	805	465	0.58
0.050	1750 F anneal	None	3430	2025	0.59
0.050	Ditto	RH-950	3810	575	0.15
0.050	RH-950	None	4230	1750	0.41
0.050	Ditto	RH-950	2690	583	0.21

Note: Data for 0.022-inch-thick sheet were obtained from Reference 38. Data for 0.050-inch-thick sheet were obtained from Reference 37.

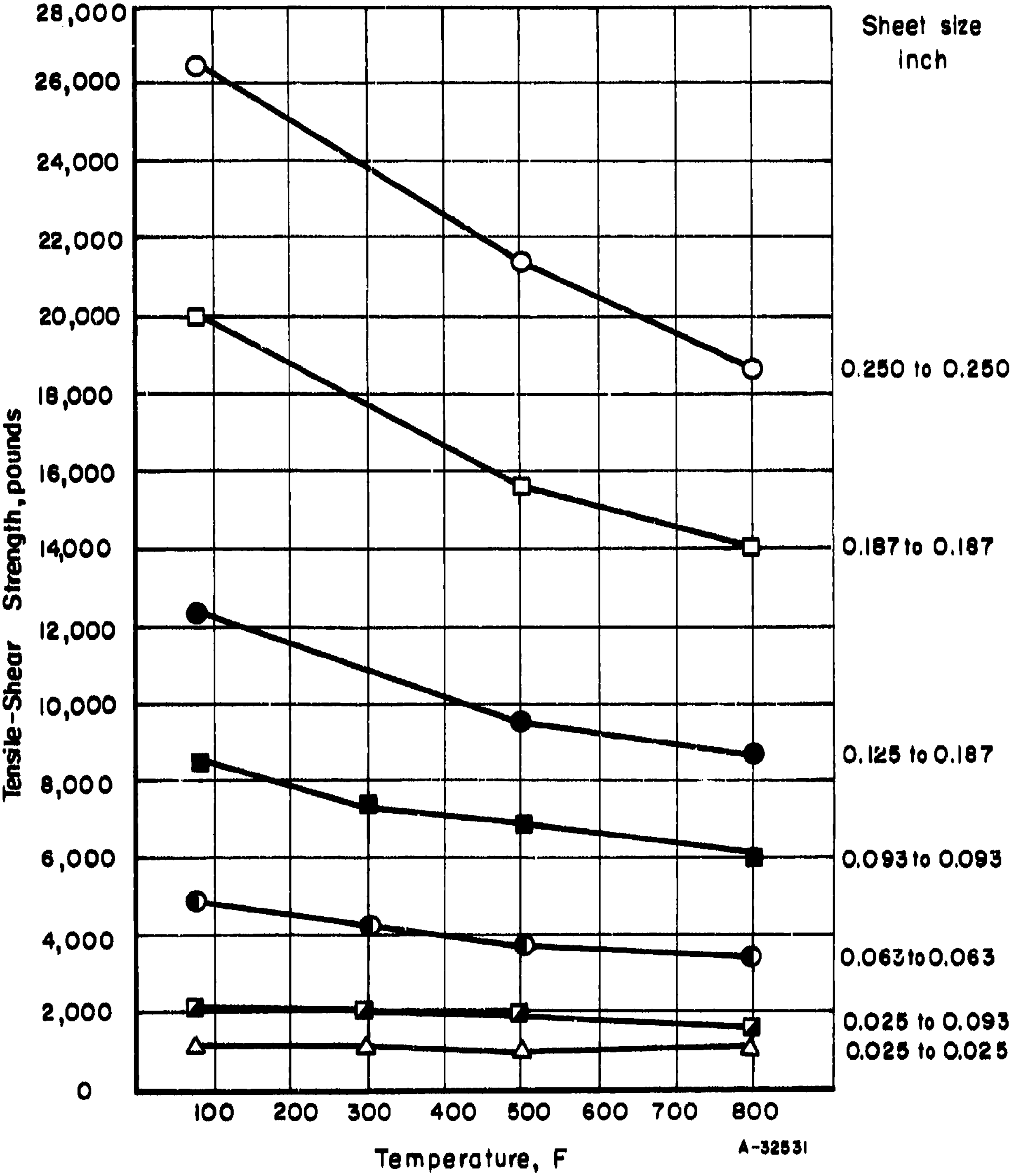

FIGURE 6. TENSILE-SHEAR STRENGTH AT ELEVATED TEMPERATURES OF SPOT-WELDED 17-7PH STAINLESS STEEL(37)

Material in RH-950 heat-treated condition prior to welding. No postweld heat treatments given.

Flash-welded parts have almost zero ductility because of the orientation of the delta-ferrite stringers in the upset metal.

The 17-7PH weld metal has poorer salt-spray corrosion resistance than the base metal.(39) If the heat treatment is conducted prior to the welding operations, somewhat better corrosion resistance is obtained. Spot welds have better corrosion resistance than fusion welds.

AM-350 and AM-355

The Allegheny-Ludlum alloys AM-350 and AM-355 also are double-treatment steels. Although these two steels are not true precipitation-hardening alloys, they are placed in this classification because they are hardened and softened by means of a similar heat-treating cycle. In composition, AM-350 and AM-355 are similar, AM-355 having a slightly higher carbon content and slightly lower chromium content. The difference in the mechanical properties of the two steels is caused by the slight change in carbon content and by the difference in delta-ferrite content.(40) AM-350 contains 10 to 20 per cent delta ferrite and AM-355 practically none. In the hardened state, the tensile and yield strengths of AM-355 are 10,000 to 15,000 psi greater than are those of AM-350.

Arc Welding. Both alloys may be welded by the covered-electrode submerged-arc, inert-gas-shielded, and resistance-welding processes. Since these steels do not contain aluminum, as do 17-7PH and PH 15-7 Mo, covered electrodes may be used. The same type of electrode is used for either steel. The deposited weld metal is of the AM-355 composition; however, satisfactory joints are produced when used with the AM-350 steel. These electrodes have been produced with either a lime or titania coating. Filler wires of the base-metal composition are used with the submerged-arc or inert-gas-shielded welding methods. Although the wire and base-metal compositions usually are matched, the AM-355 wire may be used for welding the AM-350 steel when a weld joint with slightly higher tensile strength is desired. For the most part, these steels are welded in the form of sheet, plate, bar, or forging. However, Pacific Alloy Engineering has welded AM-355 castings successfully. The same welding procedures normally followed in welding the austenitic stainless steels may be used with these two steels. No preheat or postheat is necessary to prevent cracking, since both the weld-metal and heat-affected zones are in the ductile, austenitic state.(41)

Both AM-350 and AM-355 can be welded in either the annealed or heat-treated conditions. A postweld annealing treatment at 1710 F is required for both alloys for hardening by the subzero cooling treatment.

AM-350 may be hardened by either a subzero cooling and tempering treatment (denoted SCT) or by a double-aging treatment (denoted DA). The subzero cooling treatment would consist of annealing the weldment at 1710 F, as mentioned above, and air cooling, holding 3 hours at -100 F, and tempering at the appropriate temperature for 3 hours. The double-aging treatment may be used only on material that has been welded in the annealed condition. After welding, the part is heated to 1375 F and held for 2 hours, air cooled to room temperature, and aged at 850 F for 2 hours.

The tensile properties of inert-gas tungsten-arc welds in AM-350 are shown in Table 35. The data in this table indicate the necessity for postweld annealing at 1710 F of those welds hardened by the subzero technique. They also show that this postweld annealing treatment does not have so great an effect on welds hardened by the double-aging treatment. Allegheny-Ludlum has found that it is essential that weldments being hardened by the double-aging process be cooled to room temperature or below, between the 1375 F and 850 F treatments.(41) For this reason, it recommends that the parts be water quenched in cold water to insure that room temperature has been reached. The effects of a variation in the tempering temperature used with the subzero treatment are shown in Table 36. The elevated-temperature strengths of both welded and wrought AM-350 in the SCT heat-treated condition are shown graphically in Figure 7.

The heat treatments recommended for AM-355 differ slightly from those used with AM-350. The subzero treatment consists of heating at 1375 to 1475 F for 3 hours and water quenching prior to the 1710 F annealing treatment. The addition of this "equalizing" treatment causes a more complete transformation to martensite upon the subzero cooling, thus enhancing the mechanical properties. The double-aging treatment consists of annealing at 1710 F, air cooling, reheating to 1375 F for 2 hours, air cooling, then aging 3 hours at 850 F.

The tensile properties of inert-gas tungsten-arc-welded AM-355 are shown in Table 37. The effects of several different heat treatments are indicated. Table 38 shows the tensile properties of AM-355 welded with covered AM-355 electrodes. North American Aviation (Los Angeles) has successfully welded AM-350 to 17-7PH steel by the inert-gas tungsten-arc process. Welds were made using both 17-7PH and AM-350 filler wire. The subzero cooling heat treatment was applied to these welds. However, the temperatures were modified somewhat so that a compromise in the heat treatments of the two steels was obtained. The weld joints were annealed at 1725 F, air cooled, refrigerated at -100 F, then aged at 850 F. The welds made with the 17-7PH filler wire were consistently stronger than those made with the AM-350. The tensile strengths of these welds at various temperatures are presented in Table 39.

TABLE 35. TENSILE PROPERTIES OF WELD JOINTS IN AM-350 STAINLESS STEEL[41]

Welds made by the automatic inert-gas tungsten-arc process.

Filler Wire	Heat Treatment	Ultimate Tensile Strength, psi	0.2 Per Cent Yield Strength, psi	Elongation in 2 Inches, per cent	Location of Fracture
None (base-metal test)	Annealed 1700 F	190,000	78,000	15	--
Ditto	-100 F, 2 hr, 850 F, 2 hr	195,000	172,000	15	--
"	1375 F, 1 hr, 850 F, 1 hr	185,000	160,000	15	--
	Transversely Welded 0.078-Inch Sheet				
AM-350	As welded	145,000	83,000	6.5	Weld
AM-355	As welded	136,000	62,000	12	Weld
AM-350	Welded; -100 F, 2 hr; 850 F, 2 hr	148,000	87,000	6	Weld
AM-355	Ditto	153,000	90,000	8	Weld
AM-350	Welded; 1710 F, 10 min; -100 F, 2 hr; 850 F, 2 hr	191,000	165,000	4	Weld
AM-355	Ditto	199,000	169,000	9	Base metal
AM-350	Welded; 1375 F, 1 hr; 850 F, 1 hr	178,000	153,000	9	Base metal
AM-355	Ditto	184,000	157,000	8	Base metal
AM-350	Welded; 1710 F, 10 min; 1375 F, 1 hr; 850F, 1 hr	188,000	160,000	5	Weld
AM-355	Ditto	185,000	156,000	8	Base metal
	Transversely Welded 0.180-Inch Sheet				
AM-355	As welded	156,500	75,000	10	Weld
AM-355	Welded; -100 F, 2 hr; 850 F, 1 hr	165,000	97,500	8.5	Weld
AM-355	Welded; 1710 F, 10 min; -100 F, 2 hr; 850 F, 2 hr	198,500	165,000	7	Weld
AM-355	Welded; 1375 F, 1 hr; 850 F, 1 hr	175,000	147,500	8	Weld
AM-355	Welded; 1710 F, 15 min; 1375 F, 1 hr; 850 F, 1 hr	176,000	149,500	4.5	Base metal

Note: Weld reinforcement removed prior to testing.

TABLE 36. EFFECT OF TEMPERING TEMPERATURE ON TENSILE PROPERTIES OF WELD JOINTS IN AM-350 STAINLESS STEEL(41)

Welds made by automatic inert-gas tungsten-arc process using AM-350 filler wire.

Heat Treatment[a]	Ultimate Tensile Strength, psi	0.2 Per Cent Yield Strength, psi	Elongation in 2 inches, per cent	Location of Fracture
		0.078-Inch-Thick Base Material		
A	200,700	169,900	16	--
B	186,600	160,400	12	--
C	166,300	138,000	15	--
D	205,400	158,700	13	--
		0.078-Inch-Thick Sheet, Transversely Welded		
A	203,000	172,900	6	Weld
B	175,300	158,300	8	Weld
C	163,200	140,600	9	Weld
D	200,700	162,000	10	Weld
		0.078-Inch-Thick Sheet, Longitudinally Welded		
A	203,600	171,100	4	Weld
B	172,800	152,900	14	Base metal
C	160,500	136,600	12	Weld
D	198,100	158,500	6	Weld
		0.180-Inch-Thick Sheet, Transversely Welded		
A	194,100	161,800	6	Weld
B	178,800	153,300	7	Weld
C	154,200	132,300	14	Base metal
D	192,800	159,000	6	Weld

Note: Weld reinforcement removed prior to testing.

(a)

Code	Heat Treatment
A	10 min at 1710 F, air cool, 3 hr at -100 F, 3 hr at 850 F
B	10 min at 1710 F, air cool, 3 hr at -100 F, 3 hr at 950 F
C	10 min at 1710 F, air cool, 3 hr at -100 F, 3 hr at 1050 F
D	30 min at 2000 F, 10 min at 1710 F, air cool, 3 hr at -100 F, 3 hr at 850 F.

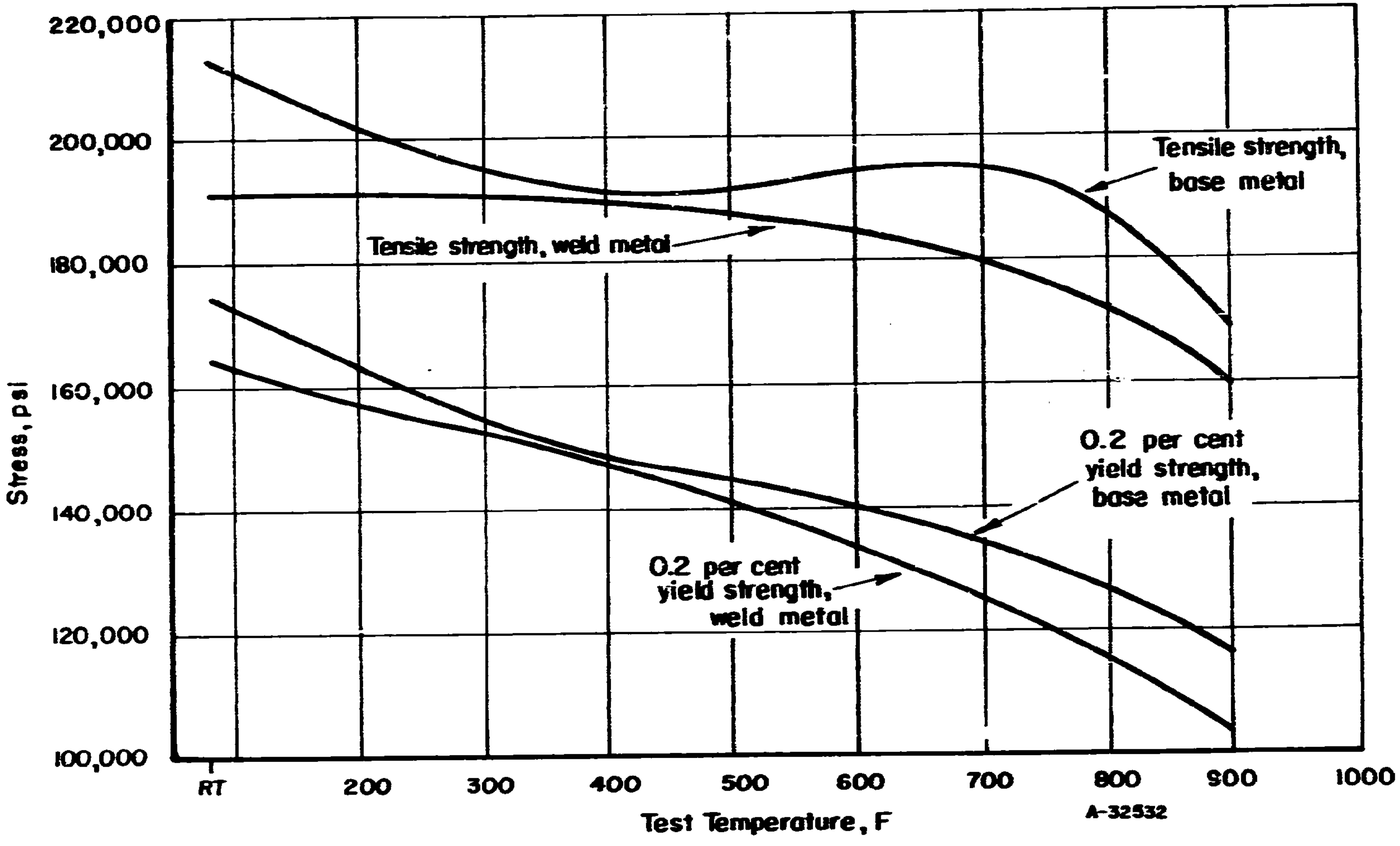

FIGURE 7. ELEVATED-TEMPERATURE TENSILE PROPERTIES OF WELDED AM-350 STAINLESS STEEL(41)

Material heat treated after welding: 15 min at 1710 F, air cool, 2 hours at -100 F, 2 hr at 850 F

TABLE 37. TENSILE PROPERTIES OF INERT-GAS TUNGSTEN-ARC WELDS IN AM-355 STAINLESS STEEL(41)

AM-355 filler wire used.

Heat Treatment(a)	Base Plate Thickness, inch	Ultimate Tensile Strength, psi	0.2 Per Cent Yield Strength, psi	Elongation in 4 T Inches, per cent	Location of Failure
		Base Metal			
A	0.5	210,000	169,500	6.0	--
	0.9	215,700	172,200	5.0	--
C	0.5	214,400	173,500	12	--
	0.9	205,000	173,500	6	--
D	0.5	201,300	172,800	14	--
E	0.5	185,400	151,000	13	--
		Transverse Weld Joints			
A	0.5	207,900	175,600	3	Weld
	0.9	212,200	173,300	4	Weld
B	0.9	199,200	164,800	8	Weld
C	0.5	205,900	178,000	6.5	Weld
	0.9	206,000	174,700	6.0	Weld
D	0.5	210,000	171,700	3.5	Weld
	0.9	198,000	169,700	9.0	Weld
E	0.5	176,500	144,100	8.5	Weld
		All-Weld-Metal Test			
A	0.9	216,300	180,900	3.0	--

(a)

Code	Heat Treatment
A	1 hr at 1710 F, water quench, 3 hr at -100 F, 3 hr at 850 F
B	1 hr at 1710 F, water quench, 3 hr at -100 F, 3 hr at 950 F
C	3 hrs at 1375 F, air cool, 1 hr at 1710 F, water quench, 3 hr at -100 F, 3 hr at 850 F
D	3 hrs at 1375 F, air cool, 1 hr at 1710 F, water quench, 3 hr at -100 F, 3 hr at 950 F
E	1 hr at 1710 F, water quench, 2 hr at 1375 F, air cool to room temperature, 2 hr at 850 F.

TABLE 38. TENSILE PROPERTIES OF COVERED-ELECTRODE WELDS IN 0.8-INCH-THICK AM-355 STAINLESS STEEL(41)

AM-355 titania-covered electrodes used.

Heat Treatment[a]	Ultimate Tensile Strength, psi	0.2 Per Cent Yield Strength, psi	Elongation in 1.4 Inches, per cent	Reduction of Area, per cent	Location of Fracture
			Base Metal		
A	209,300	175,300	12.5	31	--
B	171,600	160,000	16.0	42.5	--
			Transverse Weld Joints		
A	213,000	180,300	7.5	27	Weld
B	173,500	149,400	11.5	35	Weld

(a) Code	Heat Treatment
A	3 hrs at 1375 F, water quench, 1 hr at 1710 F, water quench, 3 hrs at -100 F, 3 hrs at 850 F
B	3 hrs at 1375 F, water quench, 1 hr at 1710 F, water quench, 3 hrs at -100 F, 3 hrs at 1000 F.

TABLE 39. TENSILE STRENGTHS AT VARIOUS TEMPERATURES OF WELD JOINTS BETWEEN 17-7PH AND AM-350 STAINLESS STEELS(35)

Welds made by inert-gas tungsten-arc process.

Test Temperature, F	Sheet Thickness, inch	Filler Wire	Ultimate Tensile Strength,[(a)] psi
75	0.080	17-7PH	201,000
		AM-350	185,000
	0.036	17-7PH	197,000
		AM-350	184,000
300	0.080	17-7PH	197,000
		AM-350	161,000
	0.036	17-7PH	178,000
		AM-350	163,000
500	0.080	17-7PH	175,000
		AM-350	150,000
	0.036	17-7PH	174,000
		AM-350	150,000
800	0.080	17-7PH	159,000
		AM-350	150,000
	0.036	17-7PH	167,000
		AM-350	135,000

(a) Transverse tension tests. All specimens heat treated as follows: solution treated at 1725 F, refrigerated at -100 F, aged at 850 F.

Resistance Welding. AM-350 and AM-355 may be resistance welded. Similar welding conditions are used as with other austenitic stainless steels. The material may be welded in either the annealed or hardened condition. Tests by North American Aviation have indicated that aging AM-350 after welding does not have so great an embrittling effect on the weld nugget as was the case with 17-7PH.(37) However, North American recommends that, to obtain tension-to-shear ratios greater than 0.25, the aging treatment precede the welding operation. Strengths of spot-welded AM-350 and AM-355 are shown in Table 40. In Table 41, the effects of various heat-treating cycles on the tension-to-shear ratio of spot-welded AM-350 is indicated. The tensile-shear strengths at elevated temperatures of various thicknesses of spot-welded AM-350 are shown in Figure 8. North American Aviation also has spot welded AM-350 to 17-7PH. The tensile-shear strengths of these welds were very similar to those in AM-350.

Austenitic Steels

Although steels in this group are hardened in a manner similar to the single-treatment martensitic steels, they are classed separately due to their microstructure. Unlike the single-treatment steels, there is no martensitic transformation in this class of steels. Hardening is caused solely by a precipitation in an austenitic matrix. The basic heat treatment for the austenitic precipitation-hardening steels is a solution anneal at around 2000 F, air cooling or oil quenching, followed by an aging treatment at 1300 to 1400 F. The room-temperature tensile properties of these steels are considerably lower than the properties of other aircraft steels. However, the austenitic precipitation-hardening steels maintain these properties at temperatures at which the other types of steels cannot be used.

A-286 is the most widely used steel in this group, although none of them are used to the extent that steels in other classifications are used. Most of these steels still are in the experimental stage, and development work is being conducted even with the A-286 alloy. AF-71 and G-192 are two other alloys in this group. Typical applications are turbine parts (wheels, casings, blades, etc.), after-burner parts, and exhaust valves for internal-combustion engines (G-192).

A-286

The A-286 alloy may be welded by the inert-gas-shielded process, by covered electrodes, or by resistance welding. A-286 filler wire has been used with inert-gas welding. However, this steel is subject to cracking both in the weld metal and in the heat-affected zone. Allegheny-Ludlum attributes this to the formation of an intermetallic compound between 2300 and 2350 F.

TABLE 40. TENSION-SHEAR STRENGTHS OF SPOT-WELDED AM-350 AND AM-355 STAINLESS STEELS(41)

Heat Treatment Condition(a)	Electrode Diameter, inch	Electrode Force, pounds	Weld Time, cycles	Welding Current, amperes	Tension-Shear Strength, pounds
		0.024-Inch-Thick AM-350			
A + welded	5/32	1200	12	8,500	1090
	1/4	1200	24	10,500	1275
B + welded	5/32	1200	12	7,500	1020
	1/4	1200	12	9,500	1440
C + welded	5/32	1200	12	7,500	1030
	1/4	1200	12	9,500	1260
		0.037-Inch-Thick AM-355			
A + welded	1/4	900	10	9,500	1810
			14	9,500	1900
B + welded	1/4	900	10	9,500	1850
			14	9,500	2500
C + welded	1/4	900	10	9,500	1410
			14	9,500	1940
Welded + D	1/4	900	10	9,500	1840
			14	9,500	2140
Welded + E	1/4	900	10	9,500	2480
			14	9,500	2080
Welded + F	1/4	900	10	9,500	1780
			14	9,500	2240

(a)

Code	Heat Treatment
A	Mill annealed at 1750 F
B	Mill annealed; -100 F for 2 hours; 850 F for 2 hours
C	Mill annealed; 1375 F for 1 hour; air cool; 850 F for 1 hour
D	-100 F for 2 hours; 850 F for 2 hours
E	1710 for 15 minutes; air cool; -100 F for 2 hours; 850 F for 2 hours
F	1375 for 1 hour; air cool; 850 F for 1 hour

TABLE 41. EFFECT OF HEAT TREATMENT ON TENSION-TO-SHEAR RATIOS OF SPOT-WELDED 0.080-INCH-THICK AM-350 STAINLESS STEEL(37)

Preweld Heat Treatment	Postweld Heat Treatment	Strength, pounds		Tension-to-Shear Ratio
		Tensile-Shear Test	Cross-Tension Test	
Anneal (1720 F)	None	7475	2575	0.34
Anneal (1720 F)	SCT	8725	2100	0.24
SCT	None	7450	3060	0.41
SCT	SCT	8710	2550	0.25

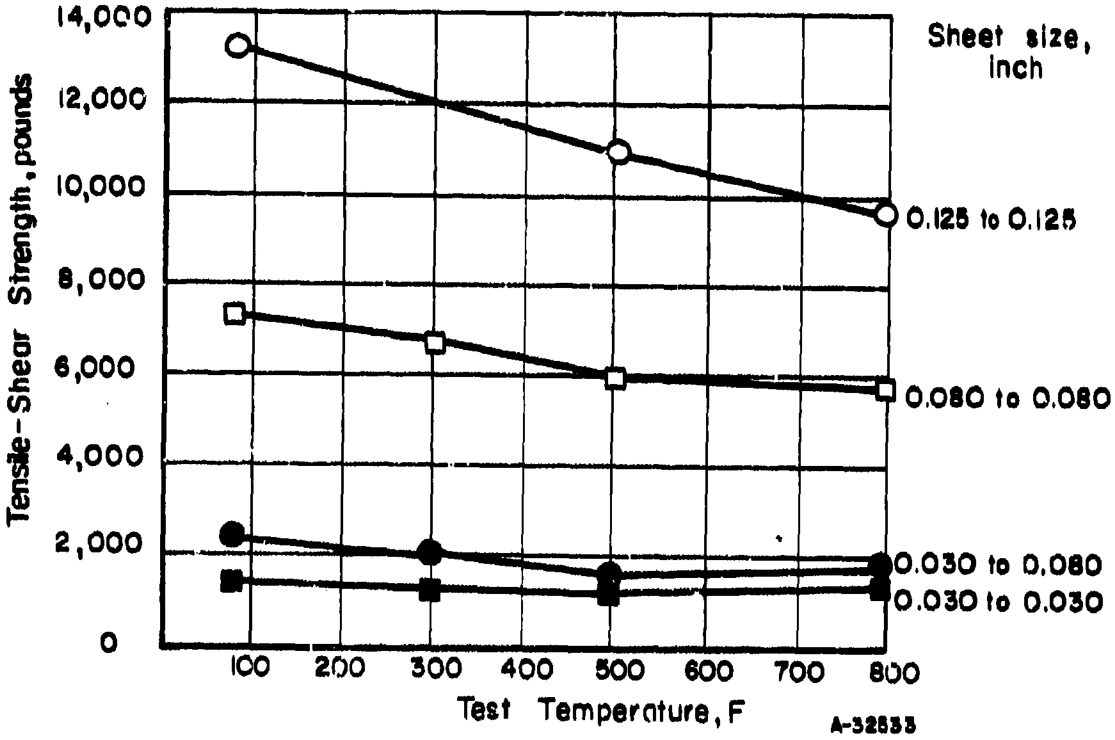

FIGURE 8. TENSILE-SHEAR STRENGTH AT ELEVATED TEMPERATURES FOR SPOT-WELDED AM-350 STAINLESS STEEL(37)

Material in SCT heat-treated condition prior to welding. No postweld heat treatments given.

This compound can be eliminated by retreatment from 1800 to 2100 F. Ryan has found that reducing the degree of restraint on the weld joint as much as possible minimizes the cracking problem. They maintain good joint fit-up as an aid in reducing the buildup of stresses during welding. When repair welding is necessary, Ryan uses Hastelloy W filler wire. An extensive range of thicknesses of A-286 is welded by Ryan with A-286 filler wire. General Electric recommends that all welding be done with Hastelloy W wire. Boeing has found that good weldability of A-286 is attained by using Hastelloy X filler wire. However, the strength of the weld joint will not be as good when the Hastelloy filler wires are used. Covered-electrode welding of A-286 may be done with Timken 16-25-6 electrodes. Tensile properties of inert-gas-shielded arc-welded joints in A-286 are given in Table 42. A limited amount of stress-rupture data are given in Table 43.

A-286 is readily resistance welded. Rohr prefers resistance welding to fusion welding, since there are no cracking problems related to resistance welding. Lockheed conducted an investigation of the spot weldability of A-286 sheet.(39) Radiographic examination of these welds failed to detect defects of any type. The strength properties of these spot welds are given in Table 44. The tensile properties of flash welds in A-286 bar stock are given in Table 45.

AF-71 and G-192

Very little information is available on the welding of AF-71 and G-192 alloys. Allegheny-Ludlum has flash welded AF-71, using special techniques, and has successfully welded G-192 by the automatic inert-gas tungsten-electrode process using G-192 filler wire. The homogeneity of the precipitate in the weld metal was increased by the use of a postweld treatment of 2100 F followed by aging at 1400 F. However, little improvement of mechanical properties was obtained.

DESIGN, TESTING, AND INSPECTION

Welds satisfactory for most purposes may be made in the steels that have been discussed, but several rather serious problems occur when such materials are used in the fabrication of highly stressed structures. The simple tensile properties of these steels and of weld joints in these steels do not correlate with the behavior of weldments subjected to multiaxial stresses. This lack of correlation seldom has been encountered with materials heat treated to relatively low strength levels or where the design factors have been higher. The current interest in large, thin-walled pressure vessels has brought this problem to the fore.

TABLE 42. TENSILE PROPERTIES OF INERT-GAS SHIELDED-ARC-WELDED JOINTS IN A-286 STAINLESS STEEL(32)

Sheet Thickness, inch	Heat-Treated Condition of Weld Joint	Test Temperature, F	Ultimate Tensile Strength, psi	0.2 Per Cent Yield Strength, psi	Elongation,(a) per cent	Reduction of Area, per cent	Location of Failure
		Base Material					
0.032	1800 F, 1 hr, oil quench, 1325 F, 16 hr	600	140,000	101,000	17	26	--
		1200	116,000	96,000	9	14	--
0.062	Ditto	1200	113,000	90,000	12	16	--
0.5	1650 F, 1 hr, oil quench	Room	143,000	101,000	26	47	--
		Inert-Gas Consumable-Electrode Welds with A-286 Filler Wire					
0.5	1325 F, 16 hr, air cool	Room	140,000	105,000	13	35	Heat-affected zone
0.5	1325 F, 16 hr, air cool, 1200 F, 20 hr, air cool	Room	140,000	109,000	11	42	Weld metal
0.5	1800 F, 1 hr, oil quench, 1325 F, 16 hr, air cool	Room	129,000	93,000	17	43	Weld metal
0.5	1800 F, 1 hr, oil quench, 1325 F, 16 hr, air cool, 1200 F, 20 hr, air cool	Room	145,000	107,000	15	36	Weld metal
0.5	Ditto	1200	113,000	96,000	6	23	Weld metal
0.5	1650 F, 1 hr, oil quench, 1325 F, 16 hr, air cool, 1200 F, 20 hr, air cool	Room	141,000	106,000	11	32	Weld metal
		Inert-Gas Tungsten-Arc Welds with No Filler Wire(b)					
0.032	1310 F, 16 hr, air cool	Room	149,000	100,000	13	14	Weld metal
0.032	Ditto	1200	103,000	92,000	3	6	Weld metal
0.062	Ditto	Room	141,000	100,000	15	24	Weld metal
0.062	Ditto	1200	103,000	86,000	5	13	Weld metal

(a) Two-inch gage length.

(b) Average of three tests.

TABLE 43. STRESS-RUPTURE STRENGTHS OF WELD JOINTS IN 1/2-INCH-THICK A-286 STAINLESS STEEL(32)

Welds made by inert-gas consumable-electrode process with A-286 filler wire.

Test Temperature, F	Heat-Treated Condition of Weld Joint	Stress, psi, for Rupture in Time Indicated	
		100 hr	1000 hr
1200	1325 F, 16 hr, air cool, 1200 F, 20 hr, air cool	52	--
		47.5	--
	1800 F, 1 hr, oil quench, 1325 F, 16 hr, air cool, 1200 F, 20 hr, air cool	58	49(a)
	1650 F, 1 hr, oil quench, 1325 F, 16 hr, air cool, 1200 F, 20 hr, air cool	49	--

(a) Extrapolated value.

TABLE 44. STRENGTH PROPERTIES OF SPOT-WELDED 0.050-INCH A-286 STAINLESS STEEL SHEET(42)

Preweld Heat Treatment	Postweld Heat Treatment	Strength, pounds		Tension-to-Shear Ratio
		Tensile-Shear Test	Cross-Tension Test	
1800 F, 1 hr, oil quench	None	2035	1840	0.90
1800 F, 1 hr, oil quench	1325 F, 16 hr	2845	1380	0.49
1800 F, 1 hr, oil quench, 1325 F, 16 hr	None	2665	1745	0.66

TABLE 45. STRENGTH PROPERTIES OF FLASH-BUTT-WELDED 3/4-INCH-DIAMETER A-286 STAINLESS STEEL BARS(32)

Heat-Treated Condition of Weld Joint	Ultimate Tensile Strength, psi	0.2 Per Cent Yield Strength, psi	Elongation,(a) per cent	Reduction of Area, per cent	Location of Failure
		Base Metal			
1800 F, 1 hr, oil quench, 1325 F, 16 hrs	148,000	101,000	26	47	--
		Weld Joints			
As welded	104,000	84,000	7	67	Weld metal
950 F, 16 hr	109,000	86,000	8	48	Weld metal
1325 F, 16 hr	147,000	99,000	22	41	Base metal

(a) Two-inch gage length.

"Low-strength level" failures of these structures have two causes. When these materials are heat treated to very high strength levels, their resistance to crack propagation becomes quite low. Failure may then be initiated at unintentional or unavoidable stress concentrations caused by such things as weld-metal cracks, incomplete penetration, poor weld-bead contour or bad structural design. Importance must be placed on the three fields: (1) the use of proper design to eliminate stress concentrations, (2) the testing of materials and welds to determine their behavior under various conditions of stress, and (3) the inspection of completed weldments to detect the presence of weld flaws that could cause stress concentrations.

Design Considerations

Design of highly stressed structures requires attention to the over-all structural design, the design of the weld joint itself, and the application of previously unexplored physical properties of the weld and base metal.

For structures that incorporate low design factors, careful consideration must be given to the elimination of areas of stress concentrations. The design strength of many of these weldments, particularly in missile cases, is nearly equal to the heat-treated strength of the material. Thus, the design of the structure must be such that the maximum stress at any point must be within the strength range of the material.

To date, difficulty has been encountered in producing weld joints in large, thin-walled missile cases that have mechanical properties equal to those of the base steel. A large number of these vessels have failed along the longitudinal weld during proof testing. Considerable effort is being expended toward the design of vessels to eliminate this longitudinal weld. Some of the methods under consideration for the fabrication of cylindrical sections are: deep drawing, explosive forming, hydrospinning, conventional spinning, various foil wrapping techniques, and even machining from a large billet. Although some of these methods become extremely expensive, they must be considered for use until some means of producing satisfactory longitudinal welds is developed.

The weld joint itself must be designed to afford uniform buildup and distribution of stresses. The weld bead must have a very uniform contour, with no undercutting or overlapping. Weld reinforcement must not be too high. Frequently, the weld reinforcement is machined or ground off. When the reinforcement is removed, the weld metal must have strength properties similar to those of the base steel. Reliance may not be put on a built-up bead for the proper strength in such a case. The joint also must be designed so that proper penetration is obtained. Lack of penetration can cause serious notch effects. There is a greater possibility for the occurrence of flaws of these types in manual welding than in automatic welding.

Parts to be welded must be properly jigged to provide good joint alignment. This is of special importance when thin sheets are to be welded, since they are much more susceptible to distortion due to the welding heat. Jigging for the production of large pressure vessels has been accomplished by the use of expanding mandrels which cold expand the cylindrical sections to some extent. It has been suggested that jigging both from the inside and outside might be necessary in order that girth welds free from distortion and/or mismatch might be made. Care should be exercised, however, in the welding of certain steels, such as A-286, which crack when welded under restraint. Jigging for these steels should position the parts, but should, if possible, apply no restraining force.

Until recently, nearly all structural and pressure-vessel designs for aircraft and missiles have been based on the yield or ultimate tensile strengths of a material, with no great emphasis given to toughness. However, pressure vessels of various sizes, heat treated to very high strength levels, often have failed at stresses below the nominal yield strength of the material. Such behavior has been attributed to the low ductility and poor resistance to crack propagation of these steels when heat treated to high strength levels. An excellent example of the low-stress failure of pressure vessels is shown in Figure 2 taken from the investigation by The Martin Company and described previously in the section "Hot-Work Die Steels". These data indicated that as the strength of Vascojet 1000 was increased through a lowering of the tempering temperature, the stress for failure of the pressure vessel decreased. From Armco's investigation of the resistance to crack propagation of this steel (also described in the "Hot-Work Die Steel" section), the same type of behavior may be noted, i.e., as the tensile strength of the material is increased above a certain point, the resistance to crack propagation decreases. From the result of these and other tests, it is becoming apparent that when the materials are heat treated to very high strength levels, the designs cannot be based simply on yield or ultimate tensile strength. Instead, some method of measurement of the notch sensitivity of the material must be used. Some members of industry feel that not enough attention is being paid to this property, and that much more emphasis must be placed on the effect of notches and flaws on the behavior of these materials. Aerojet-General (Azusa) is of the opinion that some type of notched-tensile test (to determine the crack-propagation resistance of a steel) is the first test that should be used in determining whether or not the material is satisfactory for use in thin-walled pressure vessels.

The crack-propagation properties of a steel may be used to specify the strength level to which this steel may be heat treated. Usually, the crack-propagation resistance of the high-strength steel currently in aircraft and missiles reaches an optimum value at a strength level somewhat below the maximum tensile strength obtainable in the steel. It may be advantageous to heat treat the steel to a lower strength level for best resistance to crack propagation. However, if the material must be used at its maximum heat-treated strength, all flaws in the structure must be removed. For a pressure vessel or a structure that is fabricated in the laboratory, this latter choice may be possible. However, this would require the use of so-called "jewelry techniques" to remove all of the scratches, notches, and flaws in the weldment. Very careful fabrication techniques would be needed to prevent any weld-metal flaws such as cracks. For a production run, such a procedure would be prohibitively expensive and time consuming. Since it is inevitable that some weld-metal flaws would exist in any large weldment plus small scratches and nicks that would result from normal handling, the solution to the problem depends upon the selection of a material that is not highly notch sensitive. With such a material, the flaws normally expected from production fabrication practices would not be critical.

Testing

A limited amount of specialized work has been reported in which the elevated-temperature properties of the weld metal were studied. Most of the elevated-temperature investigations have been limited to unwelded material. Conventional impact testing (such as the V-notch Charpy test) of weld metals also has been limited. Thus, the principal mechanical properties of weld joints that normally have been obtained are the ultimate tensile strength, yield strength (usually at 0.2 per cent offset), reduction of area, and elongation in various gage lengths.

New tests are being devised to determine the behavior of the material in the presence of a sharp notch or flaw. Most of the tests evaluate the material by comparing the strength of an unnotched specimen with that of a specimen in which some type of notch has been placed. From the results obtained by some of these tests, the critical crack extension force, G_c, and the critical crack length is determined for the material.

Aerojet-General (Azusa) has determined the notched-tensile strength of a wide range of steels. The specimen used in their tests is 12 inches long and approximately 3 inches wide. An internal notch, 3/4 inch long by 1/16 inch wide, is placed in the center of the specimen. An electrical-discharge technique is used to produce a crack at the ends of this notch. This crack front is reported to produce a stress concentration (ratio of stress at notch front to stress in unnotched portion of the specimen) of at least five. This test is one of the first given to a sheet material by Aerojet to ascertain its suitability for missile cases. They desire a material to have a notched fracture stress at least equal to the yield strength of the material. At fracture stresses below the yield strength, the material fails in a brittle manner. The results of this test have indicated that no present steel has good notch sensitivity when heat treated above 210,000 psi yield strength. Good reproducibility of results are obtained by Aerojet at yield strengths below 220,000 psi. Above this strength level, the properties of materials are not consistent.

For the evaluation of the toughness of sheet materials, Convair-Astronautics Division is investigating a tension-impact test. Both notched and unnotched specimens of the parent material or of a welded joint are used. The toughness is measured by the ratio of notched to unnotched results. Convair hopes that a simple test of this type can greatly reduce the amount of large-scale testing required.

The Navy Department uses several tests to evaluate materials for use in pressure vessels. Among these is the crack-propagation test developed by Messrs. Srawley and Beachem(20) at the Naval Research Laboratory, various notched-tension tests, and a drop bulge test used at the Naval Proving Grounds. In the crack-propagation test, the results of a flat-bar tension test are compared with those obtained from the tension test of a specimen containing a transverse crack. To produce the crack, a No. 56 hole is drilled in the center of the heat-treated specimen and small, sharp notches are made on the opposite sides of the hole with a jeweler's file. These notches are located normal to the loading axis. The specimen is then coated with wax except for a 1/4-inch-square area around the hole. This area is charged with hydrogen. A sharp-pointed crack is produced by slowly loading the specimen in tension to about 50 per cent of the yield strength. After cracking, the specimen is baked at the tempering temperature or 800 F (whichever is lower) to remove the hydrogen. Tension testing is then conducted of both the cracked and uncracked specimens in the conventional manner. A question has arisen as to whether all of the hydrogen can be removed by baking, so now the crack is initiated by fatigue. The results of this test give the net fracture stress and the cracked-specimen strength ratio. These are calculated from

$$\text{Net fracture stress} = F_{net} = \frac{P}{t(b-c)} ,$$

where

P = maximum load at fracture, pounds

t = specimen thickness, inches

b = specimen width, inches

c = length of initial crack, inches

and

$$\text{Cracked specimen ratio} = C = \frac{F_{net}}{F_{tu}} ,$$

where

F_{tu} = tensile strength of uncracked specimen.

The cracked-specimen ratio is said to give a measure of the crack-propagation resistance of a material for a specific heat treatment. This test has the advantage of having a crack front with a sharpness similar to that of a naturally occurring flaw in a welded structure such as a pressure vessel. The Armco Steel Corporation has used this test to evaluate a series of the high-strength steels.(21)

An internally notched tensile specimen is used by the Naval Proving Ground to determine the critical crack-extension force (G_c) of various materials.(9, 43) The 3-inch by 12-inch specimens contain an internal notch located transverse to the loading direction at the center of the specimen. Two different methods of preparing the notch have been used. A 1/2-inch-diameter hole is drilled at the center of the specimen and saw cuts are made on opposite sides of the hole. A V-notch is formed at the end of each saw cut with a sharp-edged slitting file. The length of the entire slot, including the hole, is 1 inch. In the second method, the slot, 1 inch long, is cut in the specimens by means of a 1-inch-diameter abrasive disk. Again, the ends of the slot are formed to a V-notch with a sharp-edged file. In both cases, small drops of India ink are placed in the notches during the test to mark the end of slow fracture. By proper placement of the notch, the critical crack-extension force may be determined for either the parent metal, heat-affected zone, or the weld metal itself. The critical crack-extension force may be determined from the following formula:

$$G_c = \frac{\sigma_o^2 W}{E} \tan\left(\pi \frac{a}{W}\right) ,$$

where

σ_o = nominal stress, psi

W = specimen width, inch

a = crack length, inch

E = Young's modulus, psi.

This measure of toughness has been used in the study of material involved in failures of large rocket-motor cases(9, 10), and in the evaluation of welding procedures used in fabricating such cases.(43) In addition to determining this property from the tests described above, it may be used for examination of a weldment after failure. The latter may be done if the flaw responsible for failure can be located and its size determined. Such was the case in Reference 10, wherein G_c was determined for a failed motor case without conducting tests of the material.

A G_c value numerically equal to 4000 t (t = wall thickness) has been established tentatively as the minimum requirement for rocket chambers of steel heat treated to 195,000 psi yield. Material toughness greater than this minimum value is felt to be necessary to prevent the growth under pressure of small (less than 2 t in length) "through-the-thickness" cracks. The limiting crack value of 2 t is based on the assumption that cracks of greater length can be detected by nondestructive testing. Knowing the G_c value of a material, the critical crack-length tolerance is determined by the Naval Proving Ground from

$$\text{Critical crack-length tolerance} = X = \frac{2G_c E}{\pi\sigma^2} ,$$

where

G_c = critical crack-extension force, in-lb/in.^{2}

E = Young's modulus, psi

σ = yield or actual existing stress, psi, whichever is lower.

(Crack-length tolerance is for a through-the-thickness crack.) If the critical crack-length tolerance is greater than 2 t, satisfactory performance should result, since a crack greater than the critical length could be detected and repaired.

The drop bulge test used at the Naval Research Laboratory is of rather recent development and is used as a screening test for materials for pressure vessels. The test specimen is a piece of sheet about 6 inches square. It is placed on a rubber pad and a steel die containing a 4-inch-diameter hole is placed on top. When the upper die is struck by a falling weight, the specimen is bulged upward into the die cavity by the rubber. Material may be tested either welded or unwelded. When welded material is tested, a small notch can be made in the weld metal to act as a crack starter. Specimens also may be tested either hot or cold to determine a transition from brittle to ductile type of failure. The Naval Research Laboratory is planning an extensive series of tests with this technique to evaluate a large number of materials.

The Martin Company and Solar Aircraft Company have used subsized pressure vessels to evaluate different steels for use in large rocket cases. Martin has reported on tests of both Vascojet 1000(19) and Type 422 stainless steel(28) as discussed in earlier sections of this report. The pressure vessels used in the Martin test were 7 inches in diameter by 14 inches long, with a wall thickness of 0.024 inch. The cylindrical section of the tank was rolled, and the longitudinal seam was welded. The vessels then were completed by welding on hemispherical ends. One of the ends contained a 3-inch-diameter cutout to accommodate an expanding mandrel. This mandrel served to align the ends with the cylindrical body, acted as a backup for the weld, and conducted the argon gas used to shield the underside of the weld. After the ends were welded, a 3-inch-diameter by 1/2-inch-thick plug was welded into the cutout, and then drilled and tapped to accommodate a pressure connection. All welding was done by the manual, inert-gas tungsten-arc process. After fabrication, the vessels were heat treated. Small pieces of parent metal, both welded and unwelded, were heat treated along with the vessels to serve as control specimens. The control specimens were tested by a simple tension test while the test vessels were pressurized to failure. The performance of the material was evaluated by comparing the actual bursting pressure of the vessel with the calculated bursting pressure based on the strengths of the control specimens (or calculated ultimate stress at failure of the vessel with the ultimate strengths of the control specimens). Although the details of Solar's tests are unknown, it is presumed that they are similar. Using this test, Martin has determined the heat treatment that will give the optimum bursting pressure for the vessel. With a large pressure vessel, this same heat treatment probably would give the optimum bursting pressure also. However, it is not known whether the actual bursting pressure of the two sizes of vessels would be the same.

Proof testing of the completed full-size motor cases is somewhat of a compromise. There is general agreement that the vessels should be pressurized to some level higher than anticipated in service. However, there is some difference of opinion as to the number of pressure cycles that should be used. If a series of test cycles is used, it is possible that each succeeding cycle will cause any flaws present to enlarge until a critical size is reached such that the next test cycle will cause the chamber to fail. For any limit to the number of cycles in a proof test, the possibility always exists that flaws have reached critical size and that the next cycle, which would be actual operation in this case, will cause failure. However, it is believed that a single test cycle is insufficient for proper testing. Therefore, a compromise of three proof-test cycles has been specified.

Menasco Manufacturing Company incorporates proof testing into its production of landing-gear components. After the parts are pressure welded and heat treated, they are proof tested by bending in four directions, 90 degrees apart. The bending load is calculated to load the part approximately to its yield strength. After proof testing, the parts are reheat-treated to remove residual stresses resulting from the test.

Inspection Techniques

The methods of inspection of weld joints that are used by the aircraft and missile industry include all of the common techniques, i.e., magnetic particle, dye penetrant, radiography. However, there is not complete satisfaction with the results that are being obtained. This is especially true with the fabricators of the large rocket-motor cases. In those instances where the material is heat treated to very high strength levels, the critical flaw size may be too small to detect by conventional inspection methods.

Each of the above-mentioned inspection techniques have some faults of their own. A flaw must be properly oriented to be detected by radiography or magnetic-particle inspection. The direction of the current may be altered in magnetic-particle inspection to detect cracks lying in different directions. However, a crack parallel to the surface still may not be detected. Dye-penetrant inspection may be used only to check for cracks that are open to the surface.

Although the inspection technique used may indicate the presence of a flaw, its exact size still is difficult to ascertain. A radiograph shows the length of a crack, but not its depth. The same is true of magnetic-particle and dye-penetrant inspection techniques. The surface condition of a weld also may interfere with the interpretation of the results. For example, the indication of a crack either on a radiograph or by magnetic-particle inspection may be obscured by a ripple on the surface of the weld bead. Indications of weld-metal porosity also are difficult to interpret, since little is known as to the effect of various amounts of porosity on the weldment. Lockheed, for instance, feels that a general clarification of radiographic standards, particularly on porosity, should be made which would result in an industry-wide acceptance of a single standard.

The problem of detecting all flaws larger than the critical size has two possible solutions: (1) the selection of a material with a greater resistance to crack propagation (thus having a tolerance for a greater critical flaw size) or (2) the improvement of present inspection methods or the development of new methods. Among the newer techniques that are being explored is that of ultrasonic testing. This method requires a very high degree of operator training, but has the advantage of being able to detect quite small defects. By proper usage, it is possible also to size a defect in more than one dimension. Although much development work still is being done on ultrasonic inspection, high hopes for its success are being held by some members of the industry.

HWM:REM:PJR/all

APPENDIX A

REPRESENTATIVES OF INDUSTRY INTERVIEWED IN THE COURSE OF THE SURVEY FOR THE WELDING OF HIGH-STRENGTH AIRCRAFT STEELS

APPENDIX A

REPRESENTATIVES OF INDUSTRY INTERVIEWED IN THE COURSE OF THE SURVEY FOR THE WELDING OF HIGH-STRENGTH AIRCRAFT STEELS

Aerojet-General Corporation, Azusa, California

R. D. Freymeyer
L. L. Gilbert

Aerojet-General Corporation, Sacramento, California

W. M. Boam
H. R. Fisk
E. Fyre
W. F. Tenner

Allegheny-Ludlum Steel Corporation, Brackenridge, Pennsylvania

G. Aggen
R. H. Kaltenhauser
Dr. E. Reynolds

Armco Steel Corporation, Baltimore, Maryland

Dr. A. L. Fields
G. E. Linnert

Boeing Airplane Company, Seattle, Washington

F. Baisch
L. M. Crawford
T. H. Gray
D. Lovel
S. Slosson
J. Stacy
J. Sweet
E. R. Telford
C. W. Walker

Consolidated Western Steel Company, Los Angeles, California

R. A. Brown
M. Karr
M. P. Klick
W. A. Saylor
A. J. Williams, Jr.

Convair, Division of General Dynamics Corporation, Pomona, California

H. C. Eubank
(Mrs.) R. H. Sparling

Convair, Division of General Dynamics Corporation, San Diego, California

C. W. Alesch
M. A. Ashmore
S. R. Carpenter
W. H. Schaefer
W. H. Steurer
A. Tricoli

Convair-Astronautics, Division of General Dynamics Corporation, San Diego, California

J. S. Comber
J. E. Daub
W. J. Eding
A. Hurlick
M. C. Jay
H. H. Ovalski
W. L. Rush
J. F. Watson

Crucible Steel Company of America, Pittsburgh, Pennsylvania

D. I. Dilworth

Douglas Aircraft Company, Inc., Santa Monica, California

Dr. L. Shapiro

Lockheed Aircraft Corporation, Burbank, California

G. Arnold
M. G. Childers
L. C. Cowgill
V. Dress
W. H. Edwards
P. P. Mozley
A. H. Peterson
F. Pipher
M. S. Simms
M. Tiktinsky
G. Wald

Lockheed Aircraft Corporation, Sunnyvale, California

M. Hawkes
M. Heskett
R. L. Keeney
W. R. Mayberry
J. Rojo
J. Sinnott

The Martin Company, Baltimore, Maryland

C. F. Burrows
L. L. Laux
M. Schwartz
D. Wernz

Menasco Manufacturing Company, Burbank, California

C. E. Moeller
S. S. Smith, Jr.

Norris-Thermador Corporation, Los Angeles, California

B. Baird
J. Keeling

North American Aviation, Inc., Columbus, Ohio

G. E. Martin
P. E. Ruff

North American Aviation, Inc., Los Angeles, California

V. L. Darby
L. F. Ecker
G. A. Fairbairn
F. R. Kostoch

Northrop Aircraft, Inc., Hawthorne, California

C. H. Avery
C. D. Brownfield
R. W. Chester
R. S. Collins
E. W. Crow
W. H. McCarthy
H. Smallen
H. Spector

Pacific Alloy Engineering Company, El Cajon, California

R. Kernland

Research Welding and Engineering Company, Los Angeles, California

G. Garfield
J. A. Toland

Rheem Manufacturing, Downey, California

C. W. Handova

Rohr Aircraft Corporation, Chula Vista, California

T. R. Bradley
H. M. Rush

Ryan Aeronautical Company, San Diego, California

J. R. Fullerton
A. F. Hofstatter
W. G. Hubbell
L. J. Hull

Solar Aircraft Company, San Diego, California

G. Hermanson
G. B. Pritchett

U. S. Naval Research Laboratory, Washington, D. C.

C. P. Beachem
W. S. Pellini
J. E. Srawley

United States Steel Corporation, Research Laboratory, Monroeville,
Pennsylvania

Dr. W. D. Doty H. J. Nichols

APPENDIX B

REFERENCES

APPENDIX B

REFERENCES

(1) Smith, D. C., "Ultra High Strength Weld Metal With Low-Hydrogen Electrodes", Welding Research Council Bulletin Series, Number 36 (May, 1957).

(2) Sopher, R. P., Jacobs, A. J., and Rieppel, P. J., "Investigation of Weld Metal Cracking in High-Strength Steels", Welding Journal, 34 (11), Research Supplement, 544s-552s (1955).

(3) Lowe, A. L., Jr., Sopher, R. P., and Rieppel, P. J., "Causes of Cracking in High-Strength Steel", Materials Laboratory, Wright-Patterson Air Force Base, WADC Technical Report 52-322, Part 4 (1955).

(4) Smith, D. C., "Development of Coated Arc Welding Electrodes Which Shall Produce Welded Joints Heat Treatable to Strength Levels of 220,000 to 240,000 and 260,000 to 280,000 Pounds per Square Inch", Final Report to Bureau of Aeronautics, Airborne Equipment Division, Material Branch (AE-415), Contract No. NOas-54-689-c.

(5) Mishler, H. W., and Sopher, R. P., "Development of High-Strength Filler Wires for Welding SAE 4130, 4140, and 4340 Steels", Materials Laboratory, Wright-Patterson Air Force Base, WADC Technical Report 56-550 (1956).

(6) Identification and Packaging, Welding Wire, Aeronautical Material Specification 2815.

(7) "Evaluation of High Strength Steels for Aircraft Design Manual", A. O. Smith Corporation, Report No. ARDC-TR-56-7, Part III, Contract No. AF 18(600)-1513 (June 30, 1958).

(8) "The Fatigue Strength of Uniwelded and Flashwelded Steel Tubes Heat Treated to the 220,000-240,000 and 260,000-280,000 Pounds per Square Inch Strength Ranges", Report No. 676-1 (June 6, 1955), Menasco Manufacturing Company.

(9) Romine, H. E., "Critical Crack Extension Force and Examination of Weld in Samples From Failed Engine Chamber", U. S. Naval Proving Ground, Technical Memorandum on S. P. Task Assignment No. 71402 (P. O. No. 970) (November, 1958).

(10) Kies, J. A., "Trip Report to ACF, Milton, Pa.", NRL Project 62R 19-05, Technical Memorandum No. 56, U. S. Naval Research Laboratory (December, 1958).

(11) Harnishfeger Bulletin 248, from "300-M Ultra High Strength Steel", Sands, J. W., International Nickel Company.

(12) Courtesy Cleveland Pneumatic Tool Company from "300-M Ultra High Strength Steel", Sands, J. W., International Nickel Company.

(13) "Crucible 56 Martensitic Type High Temperature Steel", Crucible Steel Company.

(14) "Crucible Steels for Aircraft and Missiles", Crucible Steel Company.

(15) "Evaluation of Weld Rod and Welding of Halcomb 218 Sheet Material", Republic Aviation Corporation, ERMR-3401.

(16) "Vascojet 1000", Vanadium-Alloys Steel Company.

(17) "Tensile Properties of Welded Vascojet 1000 Sheet", Vanadium-Alloys Steel Company.

(18) Courtesy Boeing Airplane Company.

(19) "Effect of Heat-Treatment Variations on the Bursting Strength of Thin-Walled Pressure Vessels Fabricated From Vascojet 1000 Steel", Report No. ER 10121-5, The Martin Company.

(20) Srawley, J. E., and Beachem, C. D., "Crack Propagation Tests of High-Strength Sheet Steels Using Small Specimens", NRL Report No. 5127.

(21) "New Technique for Testing Crack Propagation Resistance of High-Strength Steels", Armco Steel Corporation.

(22) Product Data Sheet, "Type Potomac A(H-11)", Allegheny-Ludlum Steel Corporation.

(23) Welty, John, "Fabrication and Mechanical Properties of Air Hardening Types of Low Alloy Steels", Solar Aircraft Company, Research Division Report No. 1056-2A.

(24) Stainless Steel Fabrication, Allegheny-Ludlum Steel Corporation.

(25) Nekervis, R. J., Lund, C. H., and Hall, A. M., "Status of High-Strength Steels for the Aircraft Industry", Titanium Metallurgical Laboratory Report No. 91 (January, 1958).

(26) Product Data Sheet, "Allegheny-Ludlum Steel Type 419", Allegheny-Ludlum Steel Corporation.

(27) "Crucible Steels for Aircraft and Missiles, Crucible 422", Crucible Steel Company.

(28) Baloga, M., and Burrows, C. F., "The Effect of Heat Treatment Variations on Bursting Strength of Thin Wall Pressure Vessels Fabricated of Crucible 422 Stainless Steel", The Martin Company, Report No. ER 10121-3.

(29) Data Sheets on USS 12 MoV Stainless Steel, United States Steel Corporation.

(30) "Welding Armco 17-4 PH Stainless Steel", Fabricating Data Bulletin, Armco Steel Corporation, Middletown, Ohio.

(31) "Fusion Welding and Heat Treating Schedule for 17-4 PH Stainless Steel Box Mechanism Assembly", Report No. NA1-58-267 (MPR 18803), June 30, 1958, Northrop Aircraft Company, Hawthorne, California.

(32) "The Elevated-Temperature Properties of Weld-Deposited Metal and Weldments", ASTM Special Technical Publication No. 226, American Society for Testing Materials, Philadelphia, Pennsylvania.

(33) "Fusion Welding of Precipitation Hardening Steels", Contract No. AF 33(600)-28469, North American Aviation, Inc., Missile Development Division.

(34) Linnert, George E., "Welding Precipitation-Hardening Stainless Steels", The Welding Journal, 36 (1), pp 9-27 (January, 1957).

(35) "Design Values for Fusion Welds in Precipitation-Hardening Stainless Steels – 17-7PH to 17-7PH and 17-7PH to AM-350", Report No. NA-57-760, North American Aviation, Inc., Los Angeles, California.

(36) "Armco PH 15-7 Mo", Armco Steel Corporation.

(37) "Summary Report on Resistance Welding of 17-7PH, AM-350 and PH 15-7 Mo Precipitation Hardening Stainless Steel Alloys", Report No. NA-57-770, North American Aviation, Inc., Los Angeles, California.

(38) Courtesy Boeing Airplane Company, Seattle, Washington.

(39) "Corrosion Resistance of Welded 17-7PH and AM-350 Stainless Steels", Report No. NA-57-728, North American Aviation, Inc., Los Angeles, California.

(40) Lula, R. A., "AM-350 and AM-355 – Properties and Heat Treatment", Metal Progress, 75 (3), pp 116-120 (March, 1959).

(41) "The Welding Properties of AM-350 and AM-355", Report No. 55-390, Project 9170-8311, Allegheny-Ludlum Steel Corporation, Brackenridge, Pennsylvania.

(42) "Spotwelding Characteristics of A-286 High Strength Heat and Corrosion Resistant Steel", Lockheed Aircraft Corporation, Production Engineering Department 72-25, Factory Coordination Investigation, No. 470.

(43) Romaine, H. E., "Critical Crack Extension Force in Second Series of Samples Representing Welding Practice With AMS 6434 and X200 Steels for Rocket Engine Chambers", U. S. Naval Proving Ground, Memorandum on S. P. Task Assignment No. 71402 (P. O. No. 970) (January, 1959).

LIST OF DMIC TECHNICAL REPORTS ISSUED

DEFENSE METALS INFORMATION CENTER

Battelle Memorial Institute

Columbus 1, Ohio

The technical reports listed below are available for distribution to Government agencies, Government contractors, subcontractors and their suppliers. Others may request copies through the Office of Technical Services, Department of Commerce, Washington 25, D. C. See PB numbers and prices in parentheses.

DMIC Report Number	Title
46D	Department of Defense Titanium Sheet-Rolling Program – Uniform Testing Procedure for Sheet Materials (PB 121649 $1.25)
46E	Department of Defense Titanium Sheet-Rolling Program – Thermal Stability of the Titanium Sheet-Rolling-Program Alloys (PB 151061 $1.25)
46F	Department of Defense Titanium Sheet-Rolling Program Status Report No. 4 (PB 151065 $2.25)
106	Beryllium for Structural Applications (PB 121648 $3.00)
107	Tensile Properties of Titanium Alloys at Low Temperatures (PB 151062 $1.25)
108	Welding and Brazing of Molybdenum (PB 151063 $1.25)
109	Coatings for Protecting Molybdenum From Oxidation at Elevated Temperature (PB 151064 $1.25)
110	The All-Beta Titanium Alloy (Ti-13V-11Cr-3Al) (PB 151066)
111	The Physical Metallurgy of Precipitation-Hardenable Stainless Steels (PB 151067)
112	Physical and Mechanical Properties of Nine Commercial Precipitation-Hardenable Stainless Steels (PB 151068 $2.25)
113	Properties of Certain Cold-Rolled Austenitic Sheet Steels (PB 151069 $1.75)
114	Ductile-Brittle Transition in the Refractory Metals (PB 151070)
115	The Fabrication of Tungsten (PB 151071)
116	Design Information for 5Cr Alloy Steels for Aircraft and Missiles (PB 151072)
117	Titanium Alloys for High-Temperature Use Strengthened by Fibers or Dispersed Particles (PB 151073)

LIST OF TML TECHNICAL REPORTS ISSUED

DEFENSE METALS INFORMATION CENTER
(PREVIOUSLY TITANIUM METALLURGICAL LABORATORY)

Battelle Memorial Institute

Columbus 1, Ohio

The technical reports listed below are available for distribution to Government agencies, Government contractors, subcontractors and their suppliers. Others may request copies through the Office of Technical Services, Department of Commerce, Washington 25, D. C. (See PB numbers and prices in parentheses.)

TML Report Number	Title
*5A	The Use of Titanium Alloy Sheet in Airframe Components (Superseded by TML Nos. 13 and 24)
*7	Survey of the Problem of Delayed Cracking in Formed Titanium Parts (PB 124562, Microfilm $3.60, Photo copy $9.30)
*8	Principles and Practical Aspects of Titanium Heat Treatment (PB 124563, Microfilm $2.70, Photo copy $4.80)
*10	A Study of the Air Contamination of Three Titanium Alloys (PB 124564, Microfilm $3.00, Photo copy $6.30)
*12	Formability Tests on Titanium Alloy Sheet (PB 124565, Microfilm $2.70, Photo copy $4.80)
13	Selection of Materials for High-Temperature Applications in Airframes (PB 111980 $1.00)
	Supplement to TML Report No. 13 (PB 121602, Microfilm $3.00, Photo copy $6.30)
**15	Engineering Properties of Commercial Titanium Alloys (PB 111981 $2.25)
*18	Analysis and Laboratory Examination of Aircraft Parts Which Failed by Delayed Cracking (PB 124567, Microfilm $3.00, Photo copy $6.30)
**19	General Summary of the Physical Metallurgy of Titanium Alloys (PB 121603 $2.25)
**20	Effect of Carbon, Oxygen, and Nitrogen on the Mechanical Properties of Titanium and Titanium Alloys (PB 111982 $2.75)
*21	The Diffusion of Interstitial and Substitutional Elements in Titanium (PB 124568, Microfilm $2.70, Photo copy $4.80)
*22	Selective Standardization and Status of Specifications for Titanium Mill Products (PB 124569, Microfilm $2.70, Photo copy $4.80)
**24	The Application of a New Structural Index to Compare Titanium Alloys With Other Materials in Airframe Structures (PB 121605 $1.00)
*25	Beta Transformation in Titanium Alloys (PB 124570, Microfilm $7.20, Photo copy $22.80)
**27	Effect of Hydrogen on the Properties of Titanium Alloys (PB 121607 $3.00)
*29	The Oxidation of Titanium and Titanium Alloys (PB 124566, Microfilm $3.90, Photo copy $10.80)
**30	Flow Properties, Deformation Textures, and Slip Systems of Titanium and Titanium Alloys (PB 121608 $2.75)
31	Welding of Titanium and Its Alloys (PB 121609 $2.25)
34	Antigalling Coating and Lubricants for Titanium (PB 121610 $1.50)
35	A Discussion of the Design of Riveted and Bolted Joints in Titanium Sheet (PB 121611 $1.00)
38	Material Properties for Design of Airframe Structures to Operate at High Temperatures (PB 121612, Microfilm $3.90, Photo copy $10.80)
**39	Survey of Physical-Property Data for Titanium and Titanium Alloys (PB 121613 $1.00)
42	Forming of Titanium Sheet (Vol. 1, PB 121917 $6.25; Vol. 2, PB 121614 $4.50)
43	An Evaluation of Compressive Testing Techniques for Determining Elevated Temperature Properties of Titanium Sheet (PB 121615 $2.00)
45	Brazing and Soldering of Titanium (PB 121616 $0.75)
46	Department of Defense Sheet-Rolling Program (PB 121617 $.75)
46A	Department of Defense Titanium Sheet-Rolling Program Status Report No. 1 (PB 121624 $1.25)
46B	Department of Defense Titanium Sheet-Rolling Program Status Report No. 2 (PB 121630)
46C	Department of Defense Titanium Sheet-Rolling Program Status Report No. 3 (PB 121642 $1.50)
48	The Engineering Properties of Precipitation-Hardenable Stainless Steels (PB 121618, Microfilm $4.80, Photo copy $13.80)
50	The Selection of Materials for High-Temperature Applications in Aircraft Gas Turbines (PB 121619 $1.00)
52	Titanium Sponge Production Methods and Present Status (PB 121620 $1.00)
53	Hot Extrusion of Titanium (PB 121621 $2.00)
55	The Measurement of the Thermal Stability of Titanium Alloys (PB 121622 $1.00)
56	The Elastic Constants in Structural Design With Particular Application to Titanium (PB 121600 $1.00)
57	The Corrosion of Titanium and Titanium Alloys (PB 121601 $4.75)
60	Production of Titanium Shaped Castings (PB 121604 $1.25)
62	A Study of Freezing Segregation in Alloy Ingots of Titanium (PB 121606 $1.00)
63	Hazards and Safety Precautions in the Production, Fabrication and Use of Titanium (PB 121623 $.75)
66	Evaluation of the Quality and Uniformity of the Titanium Mill Products Received by the Aircraft Industry During 1956 (PB 121625 $2.00)
68	An Evaluation of Bend Testing Titanium Sheet (PB 121626 $0.75)
69	Notch Sensitivity of Titanium and Titanium Alloys (PB 121627 $2.50)
72	Porosity in Formed Titanium (PB 121628, Microfilm $3.30, Photo copy $7.80)
73	The Physical Properties of Titanium and Titanium Alloys (PB 121629 $2.25)
76	Survey of Experimental Facilities for Rolling Thin, Wide, High-Strength, High-Temperature Materials for Aircraft Construction
77	An Evaluation of Fatigue Properties of Titanium and Titanium Alloys (PB 121631 $3.75)
78	Titanium Production Developments Including Metallurgy and Alloying (PB 121632 $2.75)
79	Stainless Steel and Titanium Sandwich Structures (PB 121633 $1.00)
80	Manual on the Machining and Grinding of Titanium and Titanium Alloys (PB 121644 $2.00)
82	Properties of Titanium Alloys at Elevated Temperatures (PB 121634 $6.00)
84	The Stress Corrosion and Pyrophoric Behavior of Titanium and Titanium Alloys (PB 121635 $1.50)
87	Principles and Applications of Heat Treatment for Titanium Alloys (PB 121636 $3.50)
88	The Salt Corrosion of Titanium Alloys at Elevated Temperature and Stress (PB 121637 $1.50)
89	Evaluation of Existing Vacuum-Fusion Techniques and Development of a Platinum-Flux Technique (PB 121638 $0.75)
91	Status of High-Strength Steels for the Aircraft Industry (PB 121639 $2.75)
92	The Engineering Properties of Commercial Titanium Mill Products (PB 121647 $4.00)
96	Descaling and Cleaning of Titanium and Titanium Alloys (PB 121640 $1.75)
98	The Spectrographic Determination of Oxygen in Titanium (PB 121641 $0.75)
100	Hydrogen in Titanium and Titanium Alloys (PB 121643 $2.50)
103	Metallography of Titanium Alloys (PB 121645 $2.75)
104	Adhesive Bonding of Titanium (PB 121646 $1.00)

---

*Out of print; available only as microfilm or photo copy from Library of Congress, Photoduplication Service, Publications Board Project, Washington 25, D. C.

**DMIC supply exhausted; copies may be ordered from OTS.

Battelle Memorial Institute. Defense Metals Information Center. Columbus. Ohio. **WELDING OF HIGH-STRENGTH STEELS FOR AIRCRAFT AND MISSILE APPLICATIONS**, by H. W. Mishler, R. E. Monroe, and P. J. Rieppel. 12 October 1959. [96] pp incl. illus., tables, 43 refs. (OTS PB 151074; DMIC Report No. 118) [AF 18(600)-1375] Unclassified report

This report summarizes the materials and procedures currently being used in the aircraft and missile industry to arc and resistance weld high-strength steels. The steels discussed are (1) low-alloy martensitic steels, (2) hot-work die steels, (3) martensitic stainless steels, and (4) precipitation-hardening stainless steels. For each class of steel, welding techniques and procedures are discussed, arc-welding filler materials are described, and mechanical properties of arc and resistance welds are listed. A discussion is included of design, testing, and inspection techniques as applied to weldments made from these high-strength steels.

UNCLASSIFIED

1. Steel – Welding
2. Martensite steel – Welding
3. Stainless steel – Welding
4. Tool steel – Welding
5. Aircraft – Materials
6. Guided missiles – Materials

I. Mishler, H. W.
II. Monroe, R. E.
III. Defense Metals Information Center
IV. Contract AF 18(600)-1375

UNCLASSIFIED

Battelle Memorial Institute. Defense Metals Information Center, Columbus, Ohio. WELDING OF HIGH-STRENGTH STEELS FOR AIRCRAFT AND MISSILE APPLICATIONS, by H. W. Mishler, R. E. Monroe, and P. J. Rieppel. 12 October 1959. [96] pp incl. illus., tables, 43 refs. (OTS PB 151074; DMIC Report No. 118) [AF 18(600)-1375] Unclassified report

This report summarizes the materials and procedures currently being used in the aircraft and missile industry to arc and resistance weld high-strength steels. The steels discussed are (1) low-alloy martensitic steels, (2) hot-work die steels, (3) martensitic stainless steels, and (4) precipitation-hardening stainless steels. For each class of steel, welding techniques and procedures are discussed, arc-welding filler materials are described, and mechanical properties of arc and resistance welds are listed. A discussion is included of design, testing, and inspection techniques as applied to weldments made from these high-strength steels.

UNCLASSIFIED

1. Steel – Welding
2. Martensite steel – Welding
3. Stainless steel – Welding
4. Tool steel – Welding
5. Aircraft – Materials
6. Guided missiles – Materials

I. Mishler, H. W.
II. Monroe, R. E.
III. Defense Metals Information Center
IV. Contract AF 18(600 -1375

UNCLASSIFIED

Battelle Memorial Institute. Defense Metals Information Center. Columbus. Ohio. WELDING OF HIGH-STRENGTH STEELS FOR AIRCRAFT AND MISSILE APPLICATIONS, by H. W. Mishler, R. E. Monroe, and P. J. Rieppel. 12 October 1959. [96] pp incl. illus., tables, 43 refs. (OTS PB 151074: DMIC Report No. 118) [AF 18(600)-1375] Unclassified report

This report summarizes the materials and procedures currently being used in the aircraft and missile industry to arc and resistance weld high-strength steels. The steels discussed are (1) low-alloy martensitic steels, (2) hot-work die steels, (3) martensitic stainless steels, and (4) precipitation-hardening stainless steels. For each class of steel, welding techniques and procedures are discussed, arc-welding filler materials are described, and mechanical properties of arc and resistance welds are listed. A discussion is included of design, testing, and inspection techniques as applied to weldments made from these high-strength steels.

UNCLASSIFIED

1. Steel – Welding
2. Martensite steel – Welding
3. Stainless steel – Welding
4. Tool steel – Welding
5. Aircraft – Materials
6. Guided missiles – Materials

I. Mishler, H. W.
II. Monroe, R. E.
III. Defense Metals Information Center
IV. Contract AF 18(600)-1375

UNCLASSIFIED

Battelle Memorial Institute. Defense Metals Information Center, Columbus, Ohio. WELDING OF HIGH-STRENGTH STEELS FOR AIRCRAFT AND MISSILE APPLICATIONS, by H. W. Mishler, R. E. Monroe, and P. J. Rieppel. 12 October 1959. [96] pp incl. illus., tables, 43 refs. (OTS PB 151074; DMIC Report No. 118) [AF 18(600)-1375] Unclassified report

This report summarizes the materials and procedures currently being used in the aircraft and missile industry to arc and resistance weld high-strength steels. The steels discussed are (1) low-alloy martensitic steels, (2) hot-work die steels, (3) martensitic stainless steels, and (4) precipitation-hardening stainless steels. For each class of steel, welding techniques and procedures are discussed, arc-welding filler materials are described, and mechanical properties of arc and resistance welds are listed. A discussion is included of design, testing, and inspection techniques as applied to weldments made from these high-strength steels.

UNCLASSIFIED

1. Steel – Welding
2. Martensite steel – Welding
3. Stainless steel – Welding
4. Tool steel – Welding
5. Aircraft – Materials
6. Guided missiles – Materials

I. Mishler, H. W.
II. Monroe, R. E.
III. Defense Metals Information Center
IV. Contract AF 18(600)-1375

UNCLASSIFIED

END