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DEVELOPMENT OF AUSTENITIC IRON-BASE SHEET ALLOY

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FOREWORD

This report was prepared by the Crucible Steel Company of America Research Laboratory, Harrison, New Jersey under Contract No. AF 33(616)-2047. The contract was initiated under Project No. 7351, Metallic Materials, Task No. 73512, Development of Austenitic Iron Base Sheet Alloy, formerly RDO No. 615-13-(AG) and was administered under the direction of the Materials Laboratory, Directorate of Research, Wright Air Development Center, with Capt. C. M. Hollyfield acting as project engineer.

Assistance by the Materials Laboratory with problems of testing for weldability is gratefully acknowledged.

ABSTRACT

Two types of high-phosphorus austenitic precipitation-hardening steels were investigated to determine their suitability as sheet alloys for jet engine components. One of the steels which contained approximately 0.4 C, 8.0 Mn, .2 P, 8.0 Ni, 19.5 Cr, 1.2 Mo, .2 N was tested in sheet form. This steel largely met the objectives of the investigation, in that it contained not less than 50% iron, and was stronger than N-155 at 1200, 1350, and 1500 F. Also, this steel had oxidation resistance only slightly inferior to that of N-155 at 1700 F. However, the steel was not readily weldable, and further investigation of this property would be required to properly evaluate the steel.

PUBLICATION REVIEW

This report has been reviewed and is approved.

FOR THE COMMANDER:

M. R. WHITMORE
Technical Director
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TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

Figure

I INTRODUCTION

The purpose of this investigation was the development of a precipitation hardening, austenitic steel containing not less than 50 per cent of iron and suitable for use in tail cones, pipes, after-burners, and similar components of jet engines. It was desired that such a steel should have oxidation resistance up to 2000 F equivalent to that of alloys now in use in jet engines (Types 321, 310, and N-155). Also, strength at temperatures up to 1500 F comparable to that of high strength sheet alloys, such as N-155, was desired. Ease of fabrication into sheet components and good weldability were additional required characteristics of the steel.

Work done at the Crucible Steel Company Research Laboratory prior to the issuing of the AF 33(616)-2047 Contract indicated the existence of three types of austenitic steels with properties such that these steels might be modified to meet the requirements of the Contract. The approximate compositions of these steels were as follows:

	C	Mn	P	Ni	Cr	W	Mo	N	Fe
Type I	.2	2.0	.2	21.0	19.0	5.0	6.0	--	Bal.
Type II	.5	8.0	.2	8.0	20.0	--	1.6	.2	Bal.
Type III	.6	12.0	--	--	24.0	--	--	.4	Bal.

Actual work was confined to the Types I and II steels, since modifications of the Type III steel which were made up could not be forged.

The Type I class of steels is believed to harden by precipitation of the double iron-tungsten-molybdenum carbide (M_6C) with possible additional precipitation of an iron-molybdenum compound. The Type II steels were known to harden primarily by precipitation of chromium carbide ($Cr_{23}C_6$). The function of the high phosphorus contents of the Type I and II steels is to enhance the age hardening characteristics and strength of the steels in a manner which has been described elsewhere (1).

The modifications of the Type I and II steels were evaluated by means of oxidation tests and stress-rupture tests. These evaluation tests were made on bar stock, rather than sheet, since the bar stock was the more rapidly and economically procurable of the two forms. The most promising of the steels was fabricated into sheet and tested for the required properties.

II MATERIAL

All of the experimental steels were prepared as induction melted ingots. The specified analyses of these steels are shown in Table I.

Steels AD15, 16, and 50 to 61 were made up as 30 pound

1. Numerals in parentheses refer to Bibliography appended to this report.

ingots which were rolled or forged to 5/8 inch square bars. The balance of the steels, excepting AD30 and the steels which were scrapped, were made up as 15 pound ingots and were forged to 5/8 inch square bars. Two 30 pound ingots were made under specification AD30 and were converted into 0.060 inch thick sheet.

The forgeability of these steels is referred to in this Report; this was judged, qualitatively, by the amount and soundness of the bar stock received from the forge shop.

N-155, and in two instances, Types 310 and 347 stainless steels, were used as control materials in the oxidation tests. Commercial bars of these materials were used which analyzed as follows:

	C	Mn	Si	Ni	Cr	W	Mo	Co	Cb	N	Fe
N-155	.13	1.40	.51	20.59	21.40	2.87	2.55	24.41	1.01	.12	Bal.
347	.05	1.66	.82	11.25	18.34	--	--	--	.74	--	Bal.
310	.12	.47	1.30	20.30	24.82	--	--	--	--	--	Bal.

III PROCEDURE

The general procedure followed in this investigation was to establish by means of hardness surveys whether the experimental steels would respond to age hardening treatment, if there was any doubt about such response. Except for a few of the first alloys which were studied, most of the steels age hardened, and the hardness surveys then were used only as approximate means for selecting the proper heat treatment for stress-rupture tests. Evaluation of most of the experimental alloys was made by a consideration of both oxidation and stress-rupture properties. If either oxidation resistance or stress-rupture strength of one of the alloys proved to be too low, no further work was done on that alloy.

Hardness Surveys

One half inch disks were cut from the as forged experimental steels and were solution treated in a Sentry type furnace. Aging treatments were carried out in muffle furnaces. Hardnesses were determined by means of a calibrated Rockwell hardness tester.

Oxidation Tests

Oxidation tests on the experimental steels were made on samples which had been given a treatment of 2150 F 1/2 hour, air cool. Commercial alloys were tested in the mill annealed condition. Duplicate samples 1/2 inch in diameter by 1 1/2 inches long were prepared from the forged bars. These samples were ground to a No. 120 emery finish prior to testing.

Oxidation tests on sheet were made on 2 inch square samples of the solution treated sheet having a #120 finish.

Similar sized samples of the control materials (N-155, Type 347 and Type 310) were prepared for exposure with the sheet samples.

Tests on both bar and sheet stock were made by heating the samples on special ceramic trays which permitted maximum exposure of the sample surfaces to the furnace atmosphere. Tests at 2000, 1850, and 1800 F were made in a Sentry globar type furnace in an oxidizing atmosphere. Tests at 1700 F were made in a wire-wound laboratory furnace, also in an oxidizing atmosphere. Periods of 16 hours, or longer in the furnaces were used with intermittent air cooling to room temperature. Loose scale was removed from the specimens after each of the coolings, and the trays with specimens were turned end for end prior to being reheated. This procedure was employed to minimize the effect on the test results of possible non-uniform temperature distribution in the furnaces.

The specimens were weighed before and after the total test periods and the weight losses were determined relative to the initial specimen surface areas. Final descaling of the specimens was accomplished by immersing them for a short time in molten sodium hydroxide at 1000 F, followed by a water quench.

Stress-Rupture Tests

Stress rupture tests were made on specimens of 1.40 inches gage length and 0.300 inches gage diameter which were turned from heat treated 5/8 inch square by 4-1/2 inch lengths of the forged bars.

Tests on sheet specimens were made on samples having a 0.400 inch wide by 2 inch gage section which were machined from the heat treated and sand-blasted sheet.

Standard equipment and test procedures were used for the stress-rupture tests.

The stress-rupture properties of N-155 were obtained from the literature, and some of the data so obtained are shown in Table II. One of the earliest references (2) shown in Table II indicated that a wide range of stress-rupture properties might be expected in N-155 according to the thermal and mechanical treatment which the alloy had received. The maximum values reported for stresses which would give 100 hour stress-rupture lives at 1200, 1350, and 1500 F for N-155 were used as criteria for the evaluation of the experimental alloys. Thus, stresses of 20,000 psi at 1500 F, 36,000 psi at 1350 F, and 61,000 psi at 1200 F were used for most of the tests of this investigation. Data published only recently (4, 5) indicate that N-155 in both bar and sheet form is somewhat weaker than the early data showed.

Therefore, some of the steels or heat treatments, which were rejected on the basis of the maximum stress-rupture properties of N-155 might have been satisfactory with regard to strength.

Tensile Tests

A number of tensile tests were made at elevated temperatures both on samples of the forged bars and sheet material.

Standard 0.357 inch diameter tensile specimens were machined from the heat treated bar stock. Specimens from the sheet material were prepared as described for the stress-rupture tests.

Tensile tests were also made on welded samples of the sheet material. In these tests the welded joints were transverse to the direction of tension at the center of the gage sections of the sheet type tensile specimens.

IV TESTS ON FORGED BARS-TYPE I STEELS

Analyses of the steels which were made up to the Type I steel specifications of Table I are shown in Table III.

The Type I prototype steel contained approximately:

C	Mn	P	Ni	Cr	W	Mo	Fe
.2	2.0	.2	21.0	19.0	5.0	6.0	Balance

Steels AD1 to AD7 of Table III represent an attempt to reduce the tungsten and molybdenum contents from that of the prototype analysis. Steels AD8 to AD12 are modifications which contained titanium additions. Steel AD8 was melted "off analysis" with respect to titanium and no tests were made on it.

The age hardening properties of steels AD1 to AD12 were determined as indicated in Table IV. Steels AD1 to AD7 all age hardened to some degree, but steel AD1 which contained no tungsten or molybdenum was relatively soft at temperatures over 1200 F. An increase of either tungsten or molybdenum, or both, produced increased resistance to overaging at temperatures between 1200 and 1500 F, as Table IV shows.

The steels AD9 to 12, which contained titanium, did not age harden at all in the 1200 to 1600 F temperature range. This behavior is attributed to the strong carbide forming tendency of titanium acting to "fix", as relatively insoluble TiC, the carbon which would otherwise have precipitated with the other carbide forming elements present, when the solution treated steels were aged.

Oxidation tests were made on the steels AD1 to AD7 with the results shown in Table V. None of these steels possessed good oxidation resistance at 2000 F or 1800 F relative to N-155 and no further work was, therefore, done with them.

As shown in Tables I and III, a second series of Type I steels was investigated (AD17 to AD24) in which the sum of the tungsten and molybdenum contents were higher than in the steels AD1 to AD7. Steel AD24, of Table III, represents an attempt to substitute manganese for part of the nickel of the Type I prototype steel. AD24 was made low in chromium, and an attempt to remake it, as AD24R, resulted in a heat which broke up during forging. Similar attempts to substitute manganese for nickel resulted in ingots which were scrapped during forging, as in AD25 and its remake, AD25R.

Steel AD17R was made up by mistake and was not tested. Steel AD20R was similar to AD20, except that the phosphorus content of AD20R was low.

Table V shows the result of oxidation tests made on the AD17 to AD24 series of steels. Four of the steels oxidized "catastrophically" and completely during tests at 2000 F, while the other steels had inferior oxidation resistance compared to N-155. Only one steel, AD19, of the latter series was tested at 1800 and 1700 F, since this steel had good strength at 1500 F, as shown below. The oxidation resistance of steel AD19 at 1800 F and 1700 F, as Table V shows, was comparable to that of N-155.

Stress-rupture tests were made on the steels AD17 to AD22 at 1500 F as shown in Table VI. No hardness surveys were made on these, or following, Type I steels. All were given the hardening treatment developed for the prototype Type I steel, of 2150 F 1/2 hour, water quench followed by aging at 1250 F 16 hours air cool plus 1400 F 16 hours.

Only steels AD18 and AD19 had good strength relative to N-155. Comparison of the stress-rupture and hardness results for steels AD20 and AD20R, in Table VI, illustrates the necessity for a high phosphorus content in the Type I steels.

Although the steel AD19 had good strength and fair oxidation resistance relative to N-155, the high nickel content (20%) made the steel strategically undesirable. The steels AD24R, AD25, and AD25R, which contained manganese in partial substitution for nickel and which broke up in forging, also were specified to contain about 4 per cent of tungsten. Steel AD19 contained only 1.3 per cent of tungsten. Substitution of manganese for part of the nickel in the AD19 composition was tried, in the series AD44 to AD49 of Tables I and III, in the hope that forgeable steels might result. The resulting steels AD44 to AD49 had reasonably good forgeability. The off-analysis steel, AD46, was melted high in silicon and low in chromium content.

The results of oxidation tests on steels AD44 to AD49 are shown in Table V. The best oxidation resistance was that of the high silicon steel AD46. It is expected that AD46 would have had still better oxidation resistance had it contained somewhat more chromium. None of the steels AD44 to 49 had comparable oxidation resistance to N-155 at 2000 F or 1700 F, although the steels AD44, 45, and 46 had fair resistance at the latter temperature.

As shown in Table VI, the stress-rupture properties of the steels AD44 and AD45 compared well with maximum values of Table II for N-155 at 1500 F. The low (12%) nickel modifications (AD47 and AD48) are superior in strength to N-155 sheet at 1500 F according to the data of Rush and Freeman (4), as interpolated from the data of Figure 1. (Figure 1 gives 45 hours for the life of N-155 sheet at 1500 F and 20,000 psi.)

The steels AD47 and AD48 could probably be modified further to give sufficient oxidation resistance and strength to meet the requirements for jet engine service. However, such modifications were not attempted. Work on the Type I steels was abandoned at this stage, and all effort was concentrated on the Type II steels. One final fact about the Type I steels, not so far mentioned, was that all were austenitic (non-ferromagnetic) regardless of condition or heat treatment.

V TESTS ON FORGED BARS-TYPE II STEELS

Table VII shows the analyses of the Type II steels which were made up to the specifications of Table I.

The actual analysis of the prototype of these steels was:

C	Mn	P	Si	Ni	Cr	Mo	N	Fe
.47	7.70	.23	.54	7.99	20.43	1.60	.23	Balance

Table VII shows that composition AD14 was melted close to this prototype composition and that AD13 was a lower molybdenum modification of AD14. Actually, the bars of steels AD13 and AD14 proved to be unsound and AD15 and AD16 were made up as replacements.

There was a belief, at this stage of the investigation, that the Type II steels were difficult to forge. The steels AD26, 27, 28, and AD31 to AD34 were made up, in part, to investigate the effect of composition on forgeability. The work on these steels, and on three Type II steel modifications which were made up as 150 pound ingots, demonstrated that the Type II steels had good enough forgeability to warrant consideration as commercial steels.

The age hardening properties of the Type II steels are shown in Table VIII.

Oxidation test results obtained for the Type II steels are shown in Table IX. The oxidation resistance of steels AD15, AD16, AD26, AD27, and AD28 proved to be about the same when the steels were compared at one of the three temperatures shown in Table IX. None of these steels was quite as scale resistant as N-155, although at 1700 F the experimental alloys and N-155 were not far apart in regard to this property.

Table X shows the stress-rupture properties at 1500 F and 20,000 psi of steels AD15, AD16, AD26, and AD28 for two heat treatments. Heat treatment A of Table X involved the use of a high aging temperature (1600 F) in an effort to gain good ductility in the stress-rupture tests. This treatment did not give strength equal to the maximum of N-155 shown in Table II. However, when judged by the criterion of 45 hours life at 1500 F and 20,000 psi, indicated in Figure 1, steels AD16 and AD26 were satisfactory, and AD16 had particularly good ductility.

Heat treatment C of Table X involved use of a lower aging temperature (1500 F) to gain added stress-rupture life. Steels AD16, AD27, and AD28, with treatment C lasted over 100 hours at 1500 F and 20,000 psi and, thus, were superior to N-155.

The lower molybdenum and lower carbon modifications of AD16 (AD15 and AD26, respectively) were not quite so strong as AD16, even though AD26 contained somewhat more nitrogen than AD16.

The stress-rupture properties of steels AD15, AD16, and AD28 were determined at 1200, 1350, and 1500 F as shown in Table XI. Where comparable data are shown in Table XI, it can be seen that the steels AD15, AD16, and AD28 are superior to N-155 in stress-rupture life at 1200 F and are only slightly inferior in this respect at 1350 F and 1500 F. The 0.8 Mo steel, AD15, is somewhat inferior in rupture life to the 1.8 Mo steel AD16 at the higher stress levels at 1350 F and 1500 F, as the data of Table XI seem to indicate. However, at low stress levels AD15 and AD16 appear to have comparable stress-rupture properties.

The short-time tensile properties of the AD16 steel were determined at 1200, 1350, and 1500 F, and are shown relative to those of N-155 in Table XII. The AD16 steel is superior in tensile strength to N-155 at all three test temperatures. The ductility of the AD16 in the short-time test is higher than would be expected on the basis of stress-rupture test results.

It was believed, at first, that sigma phase formed in the

AD16 steel during long heatings at 1350 and 1500 F. This belief was based on metallographic evidence, only, and has since been discounted.

On the basis of the stress-rupture data of Table XI, two 30 pound ingots were made to the specification AD30 and these were forged into slabs for conversion into sheet. The molybdenum content of the AD30 composition was specified as 1.0/1.5 instead of 1.5/2.0 to avoid the supposed formation of sigma of the higher molybdenum steel and in the belief that a decrease in molybdenum would result in improved forgeability.

Data on the properties of the AD30 sheet are given in Section VI of this Report. However, further investigation was made of modifications of the Type II steels.

Steels AD31 to AD34 which were made up with varying carbon and chromium (to investigate forgeability) forged well but had poor oxidation resistance at 2000 and 1700 F relative to N-155, as shown in Table IX. The stress-rupture properties of steels AD31 to AD34, as shown in Table X, indicate that a decrease of carbon to below 0.3 per cent, or of chromium to below 18.0 per cent, results in lowered high temperature strength at 1500 F in the Type II steels. However, the .37 C, 18.5 Cr modification (AD34) had good stress-rupture life at 1500 F.

Steels AD50 to AD55 as indicated in Table I, were vari-

-ations in nickel, molybdenum, and nitrogen of the AD16 composition. Table VII shows that steel AD50 was melted off analysis and was re-made as AD50R. The latter steel was a high nitrogen modification of AD16 but was not tested. Some of the steels of the series AD50 to AD55 had fair oxidation resistance at 1700 F relative to N-155 (Table IX) but all were inferior in stress-rupture life to AD16 and N-155, as indicated in Table X.

Steel AD56 was a Type II steel intended to be of an unusually low silicon content, as Table I indicates. As melted, AD56 contained silicon on the low side of the range specified for the Type II steels but not as low as was desired. The low silicon steel AD56 was made but was not tested.

Two attempts were made to produce a steel of the AD16 composition having a high silicon content in an effort to gain increased oxidation resistance. Both steels AD29 and AD29R, (Table I) broke up during forging.

Steels AD57 to AD62 of Table I represent another attempt to make high silicon Type II steels, both with 18 and 20 per cent chromium. Of this series, AD62 broke up in forging and the forgeability of both AD59 and AD61 was poor. Silicon additions seem, therefore, to decrease forgeability in these steels. However, the addition of 1.3 Si to the 18 Cr steel (AD58) did not adversely affect forgeability. The nitrogen content of the AD58 steel, also, was lower than that of the AD59 or AD61 steels.

The oxidation test results for steels AD57 to AD61, as shown in Table IX, show that silicon promotes resistance to oxidation in these steels to a marked degree, particularly in the 18 per cent chromium steels.

Table X shows that silicon additions apparently decrease the high temperature strength of the Type II steels. However, this behavior is probably also associated with the balance of composition of the steels to which silicon was added. Addition of 1.3 per cent of silicon to the AD60 steel produced the AD61 composition which had poor forgeability and stress-rupture properties. Additions of 1.3 per cent of silicon to the AD57 steel, however, produced the steel AD58 which had good forgeability and high temperature strength.

Steels AD57 and AD58 were tested at 1350 F, as shown in Table X, and both had fair strength relative to N-155. The stress-rupture tests on AD57 were made on samples air cooled from the solution temperature and cannot be compared directly with tests made on water quenched samples of steel AD16.

The foregoing describes the work which was done on modifications of the Type II prototype steel. None of these modifications were magnetic in any condition.

VI TESTS ON SHEET - AD30 STEEL

The 30 pound ingots from heats of the AD30 composition, of

Table VII, were forged into slabs and rolled into 0.060 inch thick sheet without difficulty. Most of the oxidation and mechanical tests to be described were made on the product of one of these 30 pound heats, while the other heat was used for welding tests.

Practical considerations in the fabrication of sheet components for jet engines apparently would require that the sheet be solution treated and descaled prior to forming and welding operations. The entire component could then be aged although this would involve some risk of distortion and scaling. Consideration of these factors governed the following series of tests.

A. Erichsen Tests and Bend Tests

Erichsen tests made on the AD30 sheet as solution treated 2150 F water quench gave values of 10.5 and 10.2 mm. Samples air cooled from 2150 F gave a value of 10.2 mm. Thus there seems to be no difference between the air cooled and water quenched AD30 sheet. These Erichsen test values obtained on the AD30 sheet correspond to those which have been obtained for Type 301 stainless. There should, therefore, be no difficulty in forming the solution treated AD30 sheet.

However, it was found that the AD30 sheet when air cooled from 2050 F gave Erichsen test values of only 7.6 mm. This be-

-havior would have to be considered if solution temperatures below 2150 F are to be used for this steel.

Since the AD30 material is a precipitation hardening steel, the possibility of intergranular corrosion during pickling of the annealed sheet exists. To test for such corrosion, a series of strips of both the water quenched and air cooled solution treated sheet were pickled in hot 50% HCl in water solution. The pickled samples were bent through an angle of 180 degrees. All samples showed signs of surface cracking at the bends. This behavior indicates that it will probably not be possible to descale the AD30 sheet by ordinary pickling, but that resort would have to be made to mechanical or molten salt descaling processes.

B. Oxidation Tests

The results of oxidation tests of the AD30 sheet are shown in Table XIII. The sheet material was less resistant, relative to N-155, than specimens made from bar stock. Table XIII shows this by comparison of results obtained on AD16 (1/2 inch diameter x 1 1/2 inch specimens) and the AD30 sheet. Evidently, tests made on the sheet specimens are more severe oxidation tests than those made on cylindrical samples.

Table XIII shows that the AD30 sheet scaled about 4 times as rapidly as N-155 at 2000 F, 40 times as rapidly at 1850 F, and

4 to 16 times as rapidly at 1700 F. The high rate of scaling at 1850 F may result from a combination of low dissolved chromium content of the austenitic matrix of the AD30 steel and high scaling test temperature. At 2000 F much of the chromium is probably in solution and thus is effective in retarding scaling. At 1700 F there is probably slightly less chromium in solution than at 1850 F, but the temperature is also lower and would be expected to result in a lower rate of scaling.

Comparison with Type 347 stainless, as in Table XIII, shows the AD30 steel to be much superior in oxidation resistance at 2000 F. At 1700 F, N-155, Type 310, and Type 347 have about the same oxidation resistance, and the AD30 steel is slightly inferior to them.

C. Stress-Rupture Tests

Sheet material is obviously best solution treated by an air cool from the solution or "annealing" temperature. Hardness surveys were, therefore, made on the sheet as air cooled from 2150 F and aged at 1500, 1550, and 1600 F for 16 hour periods. The results of the hardness surveys shown in Table XIV indicated that the AD30 sheet could be hardened to Rockwell C 37, and higher, with aging treatments between 1500 and 1550 F. Experience with the AD30 type of steel has shown that strength cannot be predicted from room temperature hardness values, except that hardnesses under Rockwell C 35 have been generally associated with inferior stress-rupture life in this steel. This does not mean that hardnesses above Rockwell C 35 will insure good stress-rupture properties, however.

Stress-rupture tests were made on the AD30 sheet as solution treated 2150 F, 1/2 hour, air cool, and aged 1500 F, 16 hours. Data for stress-rupture curves at 1500, 1350, and 1200 F were obtained, as shown in Table XV, and as plotted in Figure 1. A few stress-rupture tests were also made on the .45C, 7.76Mn, .25P, 7.62Ni, 18.98Cr, 1.18Mo, .24N heat of AD30 and this steel had about the same properties as the heat for which most of the data of Table XV were obtained.

As noted in Table XV, some of the specimens broke outside of the gage section; this fault was traced to errors in machining of the samples.

Figure 1 shows the stress-rupture properties of the AD30 sheet in relation to maximum values reported by Rush and Freeman (4) for N-155 at 1350 and 1500 F. Data for greater than 300 hours rupture life or for a test temperature of 1200 F were not reported by these authors. Figure 1 shows that the AD30 steel was superior to N-155 with respect to rupture life at 1350 and 1500 F.

Reduction of area values were difficult to measure on the sheet tensile specimens, and such data for the AD30 sheet should not be considered to be highly reliable. The low elongation values for the AD30 sheet, as shown in Table XV, caused some concern, however. Table II shows that Rush and Freeman (4) reported elongation values for N-155 sheet in stress-rupture tests at 1350 and 1500 F of 9 per cent and higher. A variety of heat treatments was, therefore, applied to the AD30 sheet in an effort to improve the elongation values at rupture. A secondary object of these tests was the modification of the heat treatment of the AD30 steel to permit use of lower solution and aging treatments. The heat treatments which were tried and their effects on the stress-rupture properties of the AD30 sheet are shown in Table XVI.

A water quench from the 2150 F solution temperature had a detrimental effect on the stress-rupture life of the AD30 sheet at 1500 F as shown in Table XVI. Aging treatments of 1600 F 2 hours, 1550 F 16 hours, or 1500 F 24 hours after a solution treatment of 2150 F, air cool, did not seriously affect the stress-rupture life of the AD30 sheet at 1500 F, but, also, did not improve the stress-rupture elongation values markedly.

A decrease of solution temperature from 2150 F produced an increase in elongation ductility of the AD30 sheet, with the 1500 F, 16 hour aging treatment.

Thus, an elongation of 8 per cent was obtained at 1500 F with a 2050 F solution treatment (Table XVI). This treatment, of 2050 F air cool plus 1500 F 16 hours, gave a satisfactory stress-rupture life at 1500 F as shown by comparison with the curves of Figure 1 for N-155 sheet (76 hours for AD30 vs 45 hours for N-155). A further decrease of solution temperature, from 2050 to 2000 F, produced inferior stress-rupture life in the AD30 sheet, as shown in Table XVI.

Unfortunately, not enough of the AD30 sheet was available for further evaluation of the effect of heat treatment than is shown in Table XVI. Only two heat treatments were evaluated at all three of the test temperatures shown in Table XVI. However, the data of Table XVI indicate that a judicious choice of solution and aging temperatures would make it possible to use lower solution treatments than 2150 F and obtain elongation values over 10 per cent with the AD30 sheet. For example, Table XVI shows that a 2000 F air cool plus 1400 F, 16 hour aging treatment gave a better stress-rupture life than that of N-155 at 1350 F (Figure 1: N-155 had a 30 hour life at 36,000 psi.) with an elongation value of 14 per cent at rupture.

Some tensile test data at various temperatures were obtained for the AD30 sheet as solution treated at 2150 F and aged at several temperatures, as shown in Table XVII. These data show the AD30 sheet to be superior in tensile strength to N-155 where such comparisons can be made in Table XVII. However, the hardened

AD30 sheet was decidedly inferior in elongation to N-155 sheet in tests made at room temperature.

D. Welding Tests

Table XVII shows the tensile test results obtained at 1500 F on two types of welded joints in the AD30 sheet. These data show tensile strengths of the welded samples only slightly inferior to those of the single-piece AD30 tensile specimens The samples which were tested had welds which appeared sound on visual inspection, but over half the welded samples were rejected because of visible cracks.

Samples of the AD30 sheet were also welded by various methods at the Materials Laboratory, Directorate of Research, Wright Air Development Center. In these tests, filler rod both of the AD30 material and of commercial welding rod steels were used with electric arc and Heliarc processes. It was found that cracks developed in the weld beads, and often in the parent metal adjacent to the beads, shortly after passage of the welding arc. Figure 2 shows a series of cracks which appeared in a three-bead weld made in the AD30 sheet without filler rod while the weld was still hot.

Electric spot welds were also made in the AD30 sheet at the Materials Laboratory. Visible cracks formed in the weld nuggets in these spot welds at all, except one or two, combinations of frequency and current of the welding apparatus.

However, subsequent radiographic examination showed cracks even in these apparently sound welds.

Metallographic examination of the welded samples from the Materials Laboratory gave no evidence as to the cause of the apparent hot shortness of the welds of the AD30 sheet.

The indication of all tests of weldability, which have so far been made, is that the AD30 material cannot be welded by the usual procedures.

E. Evaluation of Tests on AD30 Steel

Oxidation tests made on the AD30 sheet show that further improvement of the scaling resistance of the steel would be desirable. Such improvement might be possible by effecting a slight increase in the silicon content of the steel, as indicated by the data of Section V. An increase of silicon content to 0.6 to 0.8 per cent might be sufficient and probably would not decrease the forgeability or age hardening properties of the steel.

Further study of the effect of heat treatment, would also be desirable to improve ductility while maintaining the high elevated temperature strength of the AD30 steel.

The poor weldability of the AD30 steel is the only serious shortcoming with regard to its use as a sheet material for jet engines.

Phosphorus seems to be the most likely element in the

AD30 steel to blame for the apparent hot shortness of the welds. Phosphorus has generally been considered to be undesirable in austenitic weld metal (7), but no serious effort seems to have been made to find a definite cause for the hot cracking which has been associated with this element. Therefore, it is possible that some relatively simple welding procedure might be found on further investigation, for joining the high-phosphorus austenitic steels.

VII SUMMARY AND CONCLUSIONS

An attempt was made to develop a precipitation hardening austenitic sheet steel of not less than 50 per cent iron content for use in high temperature sheet components of jet engines (tail cones, pipes, afterburners, etc.). Requirements of such a steel are ease of fabrication and good weldability. High temperature strength in the range 1200 F to 1500 F and oxidation resistance up to 2000 F equal to, or better than, that of the cobalt-base alloy, N-155 were considered as additional property requirements in the investigation.

Modifications of three types of austenitic steels were investigated:

	C	Mn	P	Ni	Cr	W	Mo	N	Fe
Type I	.2	2.0	.2	21.0	19.0	5.0	6.0	--	Bal.
Type II	.5	8.0	.2	8.0	20.0	--	1.6	.2	Bal.
Type III	.6	12.0	--	--	24.0	--	--	.4	Bal.

Work on the Type III steels was stopped after a series of modifications proved to be non-forgeable.

Work on the Type I steels was carried to the point where it seemed probable that a satisfactory Type I steel of about 12 per cent nickel content might be developed. Work on the Type I steels was stopped because the Type II steels seemed to offer more promise of rapid development and had strategically a more favorable balance of composition.

Oxidation, stress-rupture, and welding tests constituted the principal methods of investigation.

Both the Type I and Type II steels were prepared and studied in the form of 5/8 inch square bar stock forged from induction melted ingots. One of the more promising of the Type II steels was processed into 0.060 inch thick sheet. This steel analyzed:

C	Mn	P	Si	Ni	Cr	Mo	N	Fe
.44	7.83	.24	.32	7.71	19.52	1.20	.20	Bal.

The stress-rupture life of this steel, as solution treated 2150 F 1/2 hour, air cool and aged 1500 F 16 hours, was superior to that reported for N-155 sheet at 1350 F and 1500 F. The stress-rupture properties were also superior to those of N-155 bar stock at 1200 F. The oxidation resistance of the experimental sheet was somewhat inferior to that of N-155 at 1700 F, 1850 F, and 2000 F. The only serious shortcoming of the experimental sheet was its poor weldability relative to commercial austenitic steels.

Other conclusions from this investigation are as follows:

1. The oxidation resistance of both the Type I and Type II steels can be improved by silicon additions.

2. A variety of heat treatments could be applied to the Type II sheet steel to modify the ductility of the steel without impairing its strength at elevated temperatures.

3. The Type II steel which was made into sheet showed such promise that it would be desirable to investigate further the weldability of this steel.

VIII BIBLIOGRAPHY

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4. A. I. Rush and J. W. Freeman, "Statistical Evaluation of the Creep-Rupture Properties of Four Heat Resistant Alloys in Sheet Form," Amer. Soc. for Testing Materials, Preprint No. 82, 1954.

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6. Metal Progress Data Sheet, Nov. 1951, p 80-B. Compiled by G. H. Boss.

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Table I

Specified Composition Ranges
(Balance of all compositions is Fe)

Steel No.	Steel Type	C	Mn	P	Si	Ni	Cr	W	Mo	Ti
AD1	I	.15/.20	1.50/2.00	.150/.200	.30/.50	20.0/21.0	18.0/19.0	--	--	--
AD2	"	"	"	"	"	"	"	2.0/2.5	--	--
AD3	"	"	"	"	"	"	"	--	2.0/2.5	--
AD4	"	"	"	"	"	"	"	2.0/2.5	"	--
AD5	"	"	"	"	"	"	"	--	3.5/4.0	--
AD6	"	"	"	"	"	"	"	1.0/1.5	"	--
AD7	"	"	"	"	"	"	"	2.0/2.5	"	--
AD8	"	"	"	"	"	"	"	--	--	1.0/1.5
AD9	"	"	"	"	"	"	"	--	2.0/2.5	"
AD10	"	"	"	"	"	"	"	1.0/1.5	"	"
AD11	"	"	"	"	"	"	"	2.0/2.5	"	"
AD12	"	"	"	"	"	"	"	"	3.5/4.0	"

Table I

Specified Composition Ranges
(Continued)

Steel No.	Steel Type	C	Mn	P	Si	Ni	Cr	W	Mo	N
AD13	II	.40/.45	7.5/8.0	.200/.250	.20/.50	7.5/8.0	20.0/21.0	--	.70/1.00	.10/.15
AD14	"	"	"	"	"	"	"	--	1.50/2.00	"
AD15	"	"	"	"	"	"	"	--	.70/1.00	"
AD16	"	"	"	"	"	"	"	--	1.50/2.00	"
AD17	I	.15/.20	1.50/2.00	.150/.200	.30/.50	20.0/21.0	18.0/19.0	4.0/4.5	5.0/5.5	--
AD18	"	"	"	"	"	"	"	2.5/3.0	"	--
AD19	"	"	"	"	"	"	"	1.0/1.5	"	--
AD20	"	"	"	"	"	"	"	4.0/4.5	4.0/4.5	--
AD21	"	"	"	"	"	"	"	2.5/3.0	"	--
AD22	"	"	"	"	"	"	"	1.0/1.5	"	--
AD23	"	"	"	"	"	18.0/19.0	"	4.0/4.5	5.0/5.5	--
AD24	"	"	4.5/5.0	"	"	15.0/16.0	"	"	"	--

Table I

Specified Composition Ranges
(Continued)

Steel No.	Steel Type	C	Mn	P	Si	Ni	Cr	V	W	Mo	N
AD25*	I	.15 .20	8.0 9.0	.150 .200	.30 .50	12.0 13.0	18.0 19.0	--	4.0 4.5	5.0 5.5	--
AD26	II	.28 .33	7.5 8.0	.200 .250	"	7.5 8.0	20.0 21.0	--	--	1.5 2.0	.10 .15
AD27	"	.35 .40	"	"	"	"	"	--	--	"	"
AD28	"	"	"	.150 .200	"	"	"	--	--	"	"
AD29*	"	.40 .45	"	.200 .250	1.50 2.00	"	"	--	--	"	"
AD30	II	.40 .45	7.5 8.0	.200 .250	.20 .50	7.5 8.0	19.5 20.5	--	--	1.0 1.5	.15 .20
AD31	"	.25 .30	7.5 8.0	.200 .250	.20 .50	7.5 8.0	16.0 17.0	--	--	1.0 1.5	.15 .25
AD32	"	.35 .40	"	"	"	"	"	--	--	"	"
AD33	"	.25 .30	"	"	"	"	18.0 19.0	--	--	"	"
AD34	"	.35 .40	"	"	"	"	"	--	--	"	"
AD35*	III	.60 .65	11.0 12.0	--	"	2.0 2.5	24.0 25.0	--	--	--	.35 .50
AD36*	"	"	"	--	"	"	"	--	--	1.0 1.5	"

* Scrapped during forging

Table I

Specified Composition Ranges
(Continued)

Steel No.	Steel Type	C	Mn	P	Si	Ni	Cr	V	W	Mo	N
AD37*	III	.60 .65	11.0 12.0	--	.20 .50	2.0 2.5	24.0 25.0	--	1.0 1.5	1.0 1.5	.35 .50
AD38*	"	"	"	--	"	"	"	.30 .50	1.0 1.5	1.0 1.5	"
AD39*	"	"	"	--	"	4.5 5.0	"	--	--	--	"
AD40*	"	"	"	--	"	"	"	--	--	"	"
AD41*	"	"	"	--	"	"	"	--	1.0 1.5	1.0 1.5	"
AD42*	"	"	"	--	"	"	"	.30 .50	1.0 1.5	1.0 1.5	"
AD43*	"	"	"	--	"	"	"	.70 1.00	1.5 2.0	2.5 3.0	"
AD44	I	.15 .20	1.5 2.0	.150 .200	.30 .50	18.0 19.0	18.0 19.0		1.0 1.5	4.5 5.0	.08 .15
AD45	"	"	"	"	"	16.0 17.0	"		"	"	"
AD46	"	"	"	"	"	14.0 15.0	"		"	"	"
AD47	"	"	"	"	"	12.0 13.0	"		"	"	"
AD48	"	"	3.5 4.0	"	"	"	"		"	"	"
AD49	"	"	5.5 6.0	"	"	"	"		"	"	"

* Scrapped during forging

Table I

Specified Composition Ranges
(Continued)

Steel No.	Steel Type	C	Mn	P	Si	Ni	Cr	Mo	N
AD50	II	.45 .50	7.5 8.5	.200 .250	.20 .25	7.5 8.0	20.5 21.5	1.0 1.5	.20 .30
AD51	"	"	"	"	"	10.0 11.0	"	"	"
AD52	"	"	"	"	"	"	"	2.0 2.5	"
AD53	"	"	"	"	"	12.5 13.5	"	"	"
AD54	"	"	"	"	"	"	"	3.0 3.5	"
AD55	"	"	"	"	"	15.0 16.0	"	"	"
AD56	"	"	"	"	.15 max.	7.5 8.0	"	1.0 1.5	"
AD57	II	.35 .40	7.5 8.5	.20 .25	.30 .60	7.5 8.5	17.0 18.0	1.0 1.5	.10 .15
AD58	"	"	"	"	1.00 1.50	"	"	"	"
AD59	"	"	"	"	2.00 2.50	"	"	"	"
AD60	"	.45 .50	"	"	.30 .60	"	20.0 21.0	"	.20 .30
AD61	"	"	"	"	1.00 1.50	"	"	"	"
AD62*	"	"	"	"	2.00 2.50	"	"	"	"

* Scrapped during forging

Table II

Published Data on Stress-Rupture

Properties of Low Carbon N-155

Condition	Test Temp., F	100 Hour Stress to Rupture, psi.	Elong. %	1000 Hour Stress to Rupture, psi.***
Hot Forged Bar (3)	1500	20,000	--	12,500
Annealed Sheet (4)	1500	18,000	*	--
Annealed Bar (5)	1500	18,000	--	13,000
Hot Forged Bar (2)	1350	36,000	11	27,500
Annealed Sheet (4)	1350	30,000	**	--
Annealed Bar (5)	1350	31,000	--	24,000
Hot-Cold Worked, 1200F (2)	1200	61,000	10	46,000
Annealed Bar (5)	1200	50,000	--	40,000

* Range: 12.5 to 23% in 80 hr.; 7 to 21% in 300 hr.
** Range: 9 to 20% in 80 hr.; 9 to 18.5% in 300 hr.
*** 1000 hour elongation values not given.

References (See details in Bibliography)

(2) Freeman, Reynolds, and White, ASTM Symposium, 1946.
(3) Metals Handbook, 1948.
(4) Rush and Freeman, ASTM Preprint No. 82, 1954.
(5) Metals Progress, July 1954.

Table III

Analyses of Type I Steels

Steel No.	C	Mn	P	Si	Ni	Cr	W	Mo	N	Ti	Fe
AD1	.18	1.74	.20	.38	20.28	18.51	--	.01	--	--	Bal.
AD2	.19	1.79	.20	.36	20.23	18.43	2.22	.01	--	--	"
AD3	.19	1.72	.19	.37	20.33	18.45	--	2.10	--	--	"
AD4	.20	1.67	.19	.35	20.18	18.37	2.09	2.17	--	--	"
AD5	.19	1.82	.21	.52	20.03	17.90	--	3.43	--	--	"
AD6	.18	1.82	.19	.33	20.48	18.13	1.17	3.55	--	--	"
AD7	.19	1.78	.19	.32	20.20	17.92	2.05	3.70	--	--	"
AD8	.19	1.73	.02	.47	30.38	19.45	--	.15	--	.15	"
AD9	.18	1.74	.19	.32	20.35	18.60	--	1.80	--	1.49	"
AD10	.15	1.44	.19	.45	20.23	18.14	1.17	2.20	--	1.34	"
AD11	.21	1.97	.19	.45	21.78	14.66	2.33	2.38	--	1.53	"
AD12	.18	1.99	.19	.46	21.40	14.77	2.45	2.92	--	1.61	"
AD17	.21	1.78	.17	.46	20.85	18.34	4.29	5.04	.06	--	"
AD17R*	.21	1.70	.16	.41	20.08	18.33	4.15	5.07	.06	--	"
AD18	.15	1.71	.17	.42	20.28	18.47	2.86	5.02	.05	--	"
AD19	.21	1.75	.18	.45	20.15	18.45	1.32	5.08	.10	--	"
AD20	.21	1.82	.18	.44	20.18	18.57	4.32	4.15	.05	--	Bal.
AD20R	.20	1.73	.01	.65	20.33	18.33	4.27	4.08	.08	--	"

* R indicates a re-make of the original specification.

Table III

Analyses of Type I Steels
(Continued)

Steel No.	C	Mn	P	Si	Ni	Cr	W	Mo	N	Fe
AD21	.20	1.84	.17	.46	20.38	18.62	2.89	4.08	.05	Bal.
AD22	.19	1.87	.17	.48	20.23	18.54	1.34	4.15	.05	Bal.
AD23	.20	1.75	.19	.34	18.43	18.22	4.27	5.15	.05	Bal.
AD24	.14	3.64	.15	.34	11.95	14.45	3.26	3.85	.04	Bal.
AD44	.21	1.98	.18	.63	18.05	18.52	1.27	4.71	.14	Bal.
AD45	.22	1.92	.17	.57	16.05	18.15	1.27	4.77	.13	Bal.
AD46	.18	1.96	.17	1.42	14.00	16.86	1.27	4.83	.16	Bal.
AD47	.18	1.79	.18	.52	12.10	18.37	1.27	4.75	.13	Bal.
AD48	.21	3.87	.18	.55	12.12	18.20	1.23	4.80	.17	Bal.
AD49	.19	5.94	.17	.55	12.15	18.43	1.25	4.77	.17	Bal.

Table IV

AGE HARDENING PROPERTIES OF TYPE I
(.2 C, .2 P, 20 Ni, 18 Cr) STEELS
VARYING IN TUNGSTEN, MOLYBDENUM, AND TITANIUM

Samples were solution treated 2150 F 1/2 hour* water quenched, and aged 48 hours at the following temperatures.

Steel No.	W	Mo	Ti	Rockwell C Hardness As Aged 1200 F	1300 F	1400 F	1500 F	1600 F
AD1	--	--	--	31	26	20.5	14	10
AD2	2.2	--	--	35.5	32.5	26	23	15
AD3	--	2.1	--	35	32	30	26	16.5
AD4	2.1	2.2	--	36	34	31	28	20
AD5	--	3.4	--	34	31	28	26	17
AD6	1.2	3.6	--	33.5	32	32	28.5	18.5
AD7	2.1	3.7	--	34	33	34	28	20
AD9	--	1.8	1.5	13	11	17	13	15
AD10	1.2	2.2	1.3	14	13	16.5	13	16
AD11	2.3	2.4	1.5	14	12	16	13	16
AD12	2.5	2.9	1.6	14.5	14	17	17	16

* Solution treated hardnesses ranged from 80 to 96 Rockwell B.

Table V

Oxidation Test Data, Type I Steels

Relative to N-155

Steel No.	Significant Analysis Variations		Oxidation Weight Loss, Grams per Square Inch			
.2 C, .2 P, 20 Ni, 18 Cr Steels			2000 F 50 hr.		1800 F 200 hr.	
	W	Mo				
AD1	--	--	2.0	2.4	1.1	1.2
AD2	2.2	--	4.4	4.6	1.3	1.3
AD3	--	2.1	3.2	3.3	0.54	0.64
AD4	2.1	2.2	1.8	2.1	1.6	1.6
AD5	--	3.4	1.3	1.5	0.30	0.41
AD6	1.2	3.6	0.90	1.2	0.97	1.4
AD7	2.1	3.7	0.74	0.75	1.4	2.4
N-155			0.25	0.30	0.12	0.12

*---

Steel No.	W	Mo	2000 F 100 hr.		1800 F 200 hr.		1700 F 200 hr.	
AD17	4.3	5.0	**		--		--	
AD18	2.9	5.0	**		--		--	
AD19	1.3	5.1	0.58	0.66	0.09	0.23	0.05	0.06

* Dashed lines separate groups of steels which constituted individual test runs.
** Specimen totally oxidized.

Table V

Oxidation Test Data, Type I Steels
(Continued)

Steel No.	Significant Analysis Variations			Oxidation Weight Loss, Grams per Square Inch					
.2 C, .2P, 20 Ni, 18 Cr Steels (Continued)				2000 F 100 hr.		1800 F 200 hr.		1700 F 200 hr.	
	W	Mo	Other						
AD20	4.3	4.2		0.55	0.64				
AD21	2.9	4.1		0.76	0.83				
AD22	1.3	4.2		0.78	0.91				
AD23	4.3	5.2	18.4 Ni	**					
AD24	("Off analysis")			**					
N-155				0.13	0.27	0.04	0.17	0.03	0.06

.2 C, .2 P, 18 Cr, 1.3 W, 5.0 Mo, .2 N Steels				2000 F 200 hr.		1700 F 200 hr.	
	Mn	Ni	Other				
AD44	2.0	18.0		1.2	1.5	0.12	0.12
AD45	2.0	16.0		0.93	1.3	0.11	0.12
AD46	2.0	14.0	1.4 Si, 17 Cr	0.67	0.73	0.15	0.15
AD47	1.8	12.1		1.1	1.6	0.09	0.20
AD48	4.0	12.1		0.94	1.3	0.21	0.21
AD49	5.9	12.2		1.2	1.8	0.15	0.22
N-155				0.28	0.31	0.07	0.06

** Specimen totally oxidized.

Table VI

Stress-Rupture Properties of Type I Steels

1500 F, 20,000 psi.

Heat Treatment: 2150 F 1 hr., water quench, aged
1250 F 16 hr. air + 1400 F 16 hr. air.

Steel No.	Significant Analysis Variations			Specimen Hardness Rc	Rupture Life, hr.	Elong. % in 1.4"	R.A. %
.2 C, .2 P, 20 Ni, 18 Cr Steels							
	W	Mo	Other				
AD17	4.3	5.0	--	34.5	65	26	52
AD18	2.9	5.0	--	35	80	10	24
AD19	1.3	5.1	--	36	117	7	12
AD20	4.3	4.2	--	35	57	17	33
AD20R	4.3	4.1	low P (.01)	23	13	40	54
AD21	2.9	4.1	--	35	35	10	20
AD22	1.3	4.2	--	34	35	8	21
.2 C, .2 P, 18 Cr, 1.3 W, 5.0 Mo, .2 N Steels							
	Mn	Ni	Other				
AD44	2.0	18.0	--	36.5	113	5	7
AD45	2.0	16.0	--	37	101	3	3
AD46	2.0	14.0	1.4 Si, 17 Cr	34.5	39	2	3
AD47	1.8	12.1	--	37	61	4	4

Table VI

Stress-Rupture Properties of Type I Steels

1500 F, 20,000 psi.
(Continued)

Steel No.	Significant Analysis Variations			Specimen Hardness Rc	Rupture Life Hr.	Elong. % in 1.4"	R.A. %
.2 C, .2 P, 18 Cr, 1.3 W, 5.0 Mo, .2 N Steels (Continued)							
	Mn	Ni	Other				
AD48	4.0	12.1	--	39	75	5	5
AD49	5.9	12.2	--	39	42	6	10

Table VII

Analyses of Type II Steels

Steel No.	C	Mn	P	Si	Ni	Cr	Mo	N	Fe
AD13	.44	7.12	.30	.37	8.11	19.44	.93	.15	Bal.
AD14	.44	7.36	.24	.28	7.67	19.87	1.79	.14	"
AD15	.46	7.97	.21	.40	7.80	20.21	.84	.11	"
AD16	.43	7.66	.21	.40	7.69	20.46	1.80	.13	"
AD26	.33	7.98	.25	.40	7.62	20.61	1.80	.19	"
AD27	.41	7.82	.25	.39	7.88	19.88	1.80	.17	"
AD28	.41	8.00	.19	.43	7.62	20.22	1.78	.21	"
AD30	.44	7.83	.24	.32	7.71	19.52	1.20	.20	"
AD30	.45	7.76	.25	.25	7.62	18.98	1.18	.24	"
AD31	.25	7.77	.24	.35	7.60	16.70	1.26	.19	"
AD32	.37	7.87	.23	.36	7.75	16.35	1.24	.20	"
AD33	.25	7.84	.25	.31	7.76	18.21	1.26	.23	"
AD34	.37	7.96	.24	.32	7.56	18.50	1.22	.21	"
AD50	.52	10.50	.22	.47	10.47	19.10	1.26	.27	"
AD50R*	.51	8.19	.23	.29	7.70	20.32	1.17	.28	"
AD51	.52	8.20	.24	.43	10.23	20.94	1.18	.33	"
AD52	.51	8.19	.24	.42	10.29	21.03	2.27	.34	"

* R indicates remake of original specification.

Table VII

Analyses of Type II Steels
(Continued)

Steel No.	C	Mn	P	Si	Ni	Cr	Mo	N	Fe
AD53	.48	8.29	.23	.57	12.67	21.23	2.27	.32	Bal.
AD54	.50	8.77	.24	.48	13.55	22.36	3.46	.34	"
AD55	.45	8.38	.22	.46	15.30	20.73	3.27	.36	"
AD56	.46	8.17	.22	.25	8.00	20.88	1.31	.31	"
AD56R	.46	8.27	.23	.12	7.82	20.41	1.26	.33	"
AD57	.41	7.90	.23	.45	8.17	17.99	1.25	.15	"
AD58	.39	7.94	.21	1.28	8.12	18.02	1.25	.12	"
AD59	.39	7.92	.21	2.38	8.02	17.47	1.22	.18	"
AD60	.48	7.71	.22	.48	8.05	20.73	1.18	.27	"
AD61	.50	7.87	.23	1.31	8.02	20.55	1.19	.27	"

Table VIII

Age Hardening Properties of Type II

Steels

Steel No.	Solution Treatment	Rockwell C Hardness As Aged 1500 F 16 Hr.	1550 F 16 Hr.	1600 F 16 Hr.
AD15	2150 F, W.Q.	38	--	31
AD16	2150 F, W.Q.	38	--	34
AD26	2150 F, W.Q.	40	--	35
AD27	2150 F, W.Q.	39	--	--
AD28	2150 F, W.Q.	37	--	34
AD31	2150 F, W.Q.	33	30.5	27
AD32	2150 F, W.Q.	38.5	37	35
AD33	2150 F, W.Q.	37	33	28
AD34	2150 F, W.Q.	40.5	38	35.5
AD50	2150 F, W.Q.	38.5	36	35
	2150 F, Air	37.5	--	--
AD51	2150 F, W.Q.	38.5	36.5	34
	2150 F, Air	37	--	--
AD52	2150 F, W.Q.	40	38	35.5
	2150 F, Air	37.5	--	--
AD53	2150 F, W.Q.	39	36	33.5
	2150 F, Air	37.5	--	--
AD54	2150 F, W.Q.	38.5	37	35
	2150 F, Air	36.5	--	--

Table VIII

Age Hardening Properties of Type II Steels
(Continued)

Steel No.	Solution Treatment	Rockwell C Hardness As Aged 1500 F 16 Hr.	1550 F 16 Hr.	1600 F 16 Hr.
AD55	2150 F, W.Q.	36.5	35	34
	2150 F, Air	35	--	--
AD56	2150 F, W.Q.	39.5	38.5	37
	2150 F, Air	41.5	--	--
AD58	2150 F, W.Q.	38	36	
	2150 F, Air	38.5	36	
AD59	2150 F, W.Q.	40	38	
	2150 F, Air	40.5	38	
AD61	2150 F, W.Q.	39	--	
	2150 F, Air	39.5	--	

Table IX

Oxidation Test Data, Type II Steels

Relative to N-155
(.4 C, 8.0 Mn, .2 P, 8.0 Ni, 20 Cr, 1.8 Mo .2 N Base Steels)

Steel No.	Significant Analysis Variations	Oxidation Weight Loss, Grams per Square Inch					
		2000 F 100 Hr.		1800 F 200 Hr.		1700 F 200 Hr.	
AD15	.8 Mo, .11 N	1.1	1.1	0.41	0.58	0.10	0.20
AD16	-- .13 N	1.1	1.1	0.27	0.31	0.04	0.11
AD26	.3 C	--	--	0.32	0.78	0.05	0.11
AD27	--	1.3	1.3	0.85	1.3	0.09	0.20
AD28	--	1.3	1.3	0.35	0.49	0.09	0.12
N-155		0.56	0.57	0.04	0.17	0.03	0.06

*---

Steel No.	Significant Analysis Variations	2000 F 100 Hr.		1700 F 200 Hr.	
AD31	.25 C, 16.7 Cr	4.4	4.5	0.67	0.71
AD32	.37 C, 16.4 Cr	5.6	5.7	0.85	0.91
AD33	.25 C, 18.2 Cr	2.1	2.1	0.51	0.70
AD34	.37 C, 18.5 Cr	2.3	2.3	0.65	0.71
N-155		0.14	0.15	0.02	0.02

*---

* Dashed lines separate groups of steels which constituted individual test runs.

Table IX

Oxidation Test Data, Type II Steels
(Continued)

Steel No.	Significant Analysis Variations	Oxidation Weight Loss, Grams per Square Inch 2000 F 200 Hr.		1700 F 200 Hr.	
AD50	.5 C, 10 Mn, 10 Ni, .3 N	3.4	3.4	0.05	0.06
AD51	.5 C, 10 Ni, 1.0 Mo, .3 N	0.74	0.79	0.04	0.18
AD52	.5 C, 10 Ni, 2.0 Mo, .3 N	0.86	0.89	0.04	0.16
AD53	.5 C, 13 Ni, 2.0 Mo, .3 N	0.65	0.73	0.04	0.12
AD54	.5 C, 14 Ni, 3.0 Mo, .3 N	0.64	0.73	0.10	0.13
AD55	.5 C, 15 Ni, 3.0 Mo, .3 N	1.3	1.3	0.11	0.15
AD56	.5 C, 1.0 Mo, .3 N	1.5	1.7	0.17	0.18
N-155		0.45	0.43	0.04	0.06
AD57	.5 Si, 18 Cr	12	12	0.40	0.94
AD58	1.3 Si, 18 Cr, .12 N	1.4	1.4	0.03	0.06
AD59	2.4 Si, 18 Cr	0.72	0.68	0.03	0.03
AD60	.5 C, .5 Si, 20 Cr, .3 N	0.77	0.84	0.19	0.68
AD61	.5 C, 1.31 Si, 20 Cr, .3 N	0.24	0.21	0.03	0.04
N-155		0.45	1.24	0.02	0.03
310		0.10	0.09	0.04	0.07

Table X

Stress-Rupture Properties of Type II Steels

(.4 C, 8.0 Mn, .2 P, 8.0 Ni, 20 Cr, 1.8 Mo, .2 N Base Steels)

Heat Treatment

A 2150 F, W.Q. + 1600 F, 16 hr.
B 2150 F, A.C. + 1550 F, 16 hr.
C 2150 F, W.Q. + 1500 F, 16 hr.
D 2150 F, A.C. + 1500 F, 16 hr.

Steel No.	Significant Analysis Variations	Heat Treat-ment	1500 F, 20,000 psi. Rupture Life, hr.	Elong. % in 1.4"	R.A. %
AD15	.8 Mo, .11 N	A	38	23	48
		C	89	8	11
AD16	-- .13 N	A	48	16	44
		C	145	9	11
AD26	.33 C	A	70	6	8
		C	89	3	3
AD27	--	C	131	5	8
AD28	--	A	43	10	24
		C	121	11	14
AD31	.25 C, 16.7 Cr	C	31	2.1	2.1
AD32	.37 C, 16.2 Cr	C	40	2.1	2.5
AD33	.25 C, 18.2 Cr	C	38	1.4	2.6
AD34	.37 C, 18.5 Cr	C	117	0.7	0.8
AD50	.5 C, 10 Mn, 10 Ni, .3 N	C	32	5	8
AD51	.5 C, 10 Ni, 1.0 Mo, .3 N	C	31	9	12

Table X

Stress-Rupture Properties of Type II Steels
(Continued)

Steel No.	Significant Analysis Variations	Heat Treat-ment	1500 F, 20,000 psi. Rupture Life, hr.	Elong. % in 1.4"	R.A. %
AD52	.5C, 10Ni, 2.0Mo, .3N	C	28	5	9
AD53	.5C, 13Ni, 2.0Mo, .3N	C	49	6	11
AD54	.5C, 14Ni, 3.0Mo, .3N	C	16	4	9
AD55	.45C, 15Ni, 3.0Mo, .3N	C	41	5	9
AD56	.46C, 1.0Mo, .3N	C	87	4	3
AD57	.5Si, 18Cr	B	75	5	9
AD58	1.3Si, 18Cr, .12N	B	98	1.3	4
AD59	2.4Si, 18Cr	B	34	7	23
		D	42	0.7	1.3
AD60	.5C, .5Si, .3N	B	68	9	13
		D	88	4	7
AD61	.5C, 1.31Si, .3N	B	38	7	4
		D	52	6	10
			1350 F, 36,000 psi.		
AD57	.5Si, 18 Cr	B	91	10	20
AD58	1.3Si, 18Cr, .12N	B	70	7	12

Table XI

STRESS-RUPTURE PROPERTIES: STEELS AD15, AD16, AD28, N-155

C Solution treated 2150 F 1 hr. W.Q. Aged 1500 F, 16 hr.
E Solution treated 2150 F 1 hr. W.Q. Aged 1550 F, 16 hr.

	C	Mn	P	Ni	Cr	Mo	N
AD15	.46	7.97	.21	7.80	20.21	.84	.11
AD16	.43	7.66	.21	7.69	20.46	1.80	.13
AD28	.41	8.00	.19	7.62	20.22	1.78	.21

Test Temp. F	Treat-ment	Load psi.	AD15 Life hr.	AD15 El. % in 1.4"	AD15 R.A. %	AD16 Life hr.	AD16 % in 1.4"	AD16 R.A. %
1500	C	24,300	--	--	--	65	2	8
	C	22,500	91	4	6	--	--	--
	C	20,000	89	8	11	145	9	11
	C	17,500	266	4	7	235	5	5
	C	15,300	--	--	--	362	4	8
	C	15,000	518	5	6	--	--	--
1350	C	42,900	--	--	--	26	3	5
	C	40,000	37	2	4	--	--	--
	C	35,000	105	2	3	112	2	1
	C	30,000	328	2	3	389	1	3
1200	C	75,000				60	8	14
	C	70,000				141	2	7
	C	65,000				258	2	4
	C	60,000				404	2	2

Test Temp. F	Treat-ment	Load psi.	N-155 Life hr.	N-155 El. % in 1.4"	N-155 R.A. %
1500	*	20,000	100	--	--
		15,000	400	--	--
1350	*	40,000	45	--	--
		30,000	475	--	--
1200	*	70,000	4	--	--
		61,000	100	--	--

* Data from Metals Handbook, A.S.M. 1948 (3) and ASTM Symposium (2)

Table XI

STRESS-RUPTURE PROPERTIES: STEELS AD15, AD16, AD28, N-155

C Solution treated 2150 F 1 hr. W.Q. Aged 1500 F, 16 hr.
E Solution treated 2150 F 1 hr. W.Q. Aged 1550 F, 16 hr.
(Continued)

Test Temp. F	Treat-ment	Load psi	AD28 Life hr.	AD28 El. % in 1.4"	AD28 R.A. %
1500	C	20,000	121	11	14
1350	C	36,000	75	7	7
	E	36,000	63	6	12
1200	C	61,000	335	5	10
	E	61,000	309	8	13

Table XII

SHORT TIME TENSILE PROPERTIES OF AD16, AND N-155

	C	Mn	P	Ni	Cr	Mo	N
AD16	.43	7.66	.21	7.69	20.46	1.80	.11

		Test Temp.F	Yield Strength (.2%) psi	Tensile Strength psi	El. %	R.A. %
AD16	(2150 F, W.Q. + 1500 F, 16 hr.)	1500	51,000	52,000	17	34
		1350	65,000	71,000	31	53
		1200	81,000	99,000	23	51
N-155*	(Hot rolled)	1500	--	45,000	24	--
		1350	--	60,000	14	--
		1200	--	80,000	--	--

* Metal Progress Data Sheet, November 1951, (6).

Table XIII

OXIDATION TESTS ON AD30 SHEET

	C	Mn	P	Ni	Cr	Mo	N
AD30	.44	7.83	.24	7.71	19.52	1.20	.20

Duplicate 2" x 2" samples of the sheet were tested together with similar sized samples of N-155, 310, and 347 in air at the indicated temperatures.

	Weight Loss, gm. per sq. in.							
Material	2000 F 100 hr.		2000 F 200 hr.		1850 F 200 hr.		1700 F 200 hr.	
AD30	1.09	1.24	2.26	2.24	1.74	1.75	0.65	0.68
N-155	0.10	0.10	0.51	0.57	0.05	0.03	0.05	0.04
Type 310	0.08	0.08	--	--	0.04	0.05	0.04	0.04
Type 347	--	--	7.30	6.86	--	--	--	--
							1700 F 200 hr.**	
AD30			--	--			0.13	0.14
N-155			.56*	.57*			0.04	0.04
Type 347			--	--			0.07	0.03
AD16			1.07*	1.07*			0.11*	0.04*

* Data from Table IX(Specimens 1/2 inch dia. x 1 1/2 inches.)

** Second test run at 1700 F.

Table XIV

EFFECT OF HEAT TREATMENT ON HARDNESS OF AD30 SHEET

Samples 1 x 1 x 0.060 in. were heat treated as shown and checked for hardness.

Solution Treatment	Aging Time, hr.	Rockwell C Hardness as Aged,		
		1500 F	1550 F	1600 F
2150 F 1/2 hr. air cool	0	20	--	--
2150 F 1/2 hr. air cool	1	39.5	38	36
2150 F 1/2 hr. air cool	2	39.5	37.5	35
2150 F 1/2 hr. air cool	4	40.5	38.5	--
2150 F 1/2 hr. air cool	8	40	38	--
2150 F 1/2 hr. air cool	16	39	37.5	34.5

Table XV

Stress-Rupture Properties of

AD30 Sheet

Solution treated 2150 F, 1/2 hour, air cool
aged 1500 F, 16 hours.

Composition:	C	Mn	P	Ni	Cr	Mo	N
	.44	7.83	.24	7.71	19.52	1.20	.20

Test Temp., F	Stress psi.	Rupture Life, Hr.	Elong. % in. 1.4"	R.A. %
1500	23,500	36	1.3	0.8
1500	20,000	138	2.9	0.8
1500	17,000	323	1.4	1.6
1500	15,000	408	1.8	1.3
1500	13,500	542	Broke outside gage section	
1500	13,500	224	" " " "	
1350	45,000	22	6.0	7.5
1350	36,000	87	2.7	0.8
1350	31,000	123	Broke outside gage section	
1350	31,000	249	0.8	1.1
1350	26,000	379	Broke outside gage section	
1350	21,000	1080	0.5	1.7
1200	80,000	8	7.6	10.
1200	70,000	76	4.9	7.5
1200	66,000	85	5.4	5.1
1200	61,000	217	3.6	5.8
1200	55,000	436	0.9	0.3
1200	50,000	848	1.8	3.6

Table XV

Stress-Rupture Properties of AD30 Sheet
(Continued)

Composition:	C	Mn	P	Ni	Cr	Mo	N
	.45	7.76	.25	7.62	18.98	1.18	.24

Test Temp., F	Stress, psi.	Rupture Life, hr.	Elong. % in 1.4"	R. A. %
1500	20,000	60	Broke outside gage section	
1500	20,000	86	1.4	1.8
1500*	20,000	90	3.1	10.
1350*	36,000	99	4.6	6.7
1200	61,000	164	1.8	6.2

* Solution treated in 31" x 24" sized sheet by commercial heat treater.

Table XVI

Effect of Heat Treatment on Stress-Rupture

Properties of AD30 Sheet

Composition:	C	Mn	P	Ni	Cr	Mo	N
	.44	7.83	.24	7.71	19.52	1.20	.20

Solution Treatment*	Aging Treatment	Rupture Life, hr.	Elong. % in 1.4"	R.A. %	Hardness Rc
	Tested at 1500 F, 20,000 psi.				
2150 F, W.Q.	1500 F, 16 hr.	41	1.9	2.9	38.5
2150 F, W.Q.	1500 F, 16 hr.	23	1.9	0.8	37.5
2150 F, A.C.	1600 F, 2 hr.	82	3.1	0.3	35.
2150 F, A.C.	1550 F, 16 hr.	144	3.0	1.9	36
2150 F, A.C.	1550 F, 16 hr.	136	4.2	0.5	37
2150 F, A.C.	1500 F, 24 hr.	79	1.4	2.7	38
2150 F, A.C.	1400 F, 16 hr.	28	Broke outside gage section		
2125 F, A.C.	1550 F, 16 hr.	85	2.7	6.2	34
2100 F, A.C.	1500 F, 16 hr.	97	4.5	7.0	37
2050 F, A.C.	1500 F, 16 hr.	76	8.0	12.	30
2050 F, A.C.	1400 F, 16 hr.	49	Broke outside gage section		
2050 F, A.C.	1400 F, 16 hr.	90	6.2	10.5	37
2050 F, A.C.	1300 F, 16 hr.	104	5.6	1.7	
2000 F, A.C.	1500 F, 16 hr.	23	21.	25.	

* Times at solution temperature were 1/2 hr. for 2150, 2125, and 2100 F and 3/4 hr. for 2050 and 2000 F.

Table XVI

Effect of Heat Treatment on Stress-Rupture

Properties of AD30 Sheet
(Continued)

Solution Treatment	Aging Treatment	Rupture Life, Hr.	Elong. % in 1.4"	R.A. %	Hard-ness Rc
	Tested at 1350 F, 36,000 psi.				
2150 F, A.C.	1400 F, 16 hr.	28	Broke outside gage section		
2125 F, A.C.	1550 F, 16 hr.	83	6.2	10.	37
2100 F, A.C.	1400 F, 16 hr.	118	1.8	4.7	40.5
2050 F, A.C.	1400 F, 16 hr.	98	5.1	7.0	38.5
2050 F, A.C.	1300 F, 16 hr.	70	Broke outside gage section		
2000 F, A.C.	1400 F, 16 hr.	53	14	8.7	36.5
	Tested at 1200 F, 61,000 psi.				
2125 F, A.C.	1550 F, 16 hr.	136	7.0	8.7	37
2100 F, A.C.	1500 F, 16 hr.	159	3.3	4.6	39
2050 F, A.C.	1300 F, 16 hr.	149	3.6	0.8	41

Table XVII

SHORT TIME TENSILE TESTS ON AD30 SHEET AND WELDS

All samples were solution treated 2150 F, 1/2 hr. prior to aging.

Cool from Solution Temperature	Aging Treatment	Test Temp. F	Tensile Strength psi.	El. % in 2 in.	R. A. %
Water	1600 F, 16 hr.	1500	42,000	21.0	
	1550 F, 16 hr.	1500	43,000	21.5	
	1550 F, 16 hr.	1500	47,000	18.0	
Air	1600 F, 16 hr.	1500	42,000	23.5	
	1600 F, 2 hr.	1500	49,000	16.5	
	1550 F, 16 hr.	1500	44,000	22.0	
	1550 F, 4 hr.	1500	48,000	15.0	
	1500 F, 16 hr.	1200	101,000	12.0	14.2
	1500 F, 16 hr.	1300	86,000	14.0	25.1
	1500 F, 16 hr.	1500	52,000	9.0	--
	1500 F, 16 hr.	1600	44,000	6.5	12.5
	1500 F, 16 hr.	1700	36,000	5.5	7.2
	1500 F, 16 hr.	80	162,000*	4.0	4.0
	Not Aged	80	125,000*	35.0	29.3
Electric Flash Butt Welded Samples					
Air	1500 F, 16 hr.	1500	41,000	1.5	
	1500 F, 16 hr.	1500	45,000	1.0	
Heliarc Welded Samples AD30 Filler Rod					
Air	1500 F, 16 hr.	1500	50,000	5.5	
	1500 F, 16 hr.	1500	57,000	4.0	
N-155 Hot Rolled**		1500	45,000	24	
		1350	60,000	14	
		1200	80,000	--	
N-155 Annealed Sheet***					
		80	119,000	54	

*0.2% yield strength: 64,000 psi as S.T.; 134,000 psi as S.T. and aged.
**Metal Progress Data Sheet November 1951 (6)
***Rush and Freeman (4), Average value. (0.2% Y.S.: 122,000 psi)

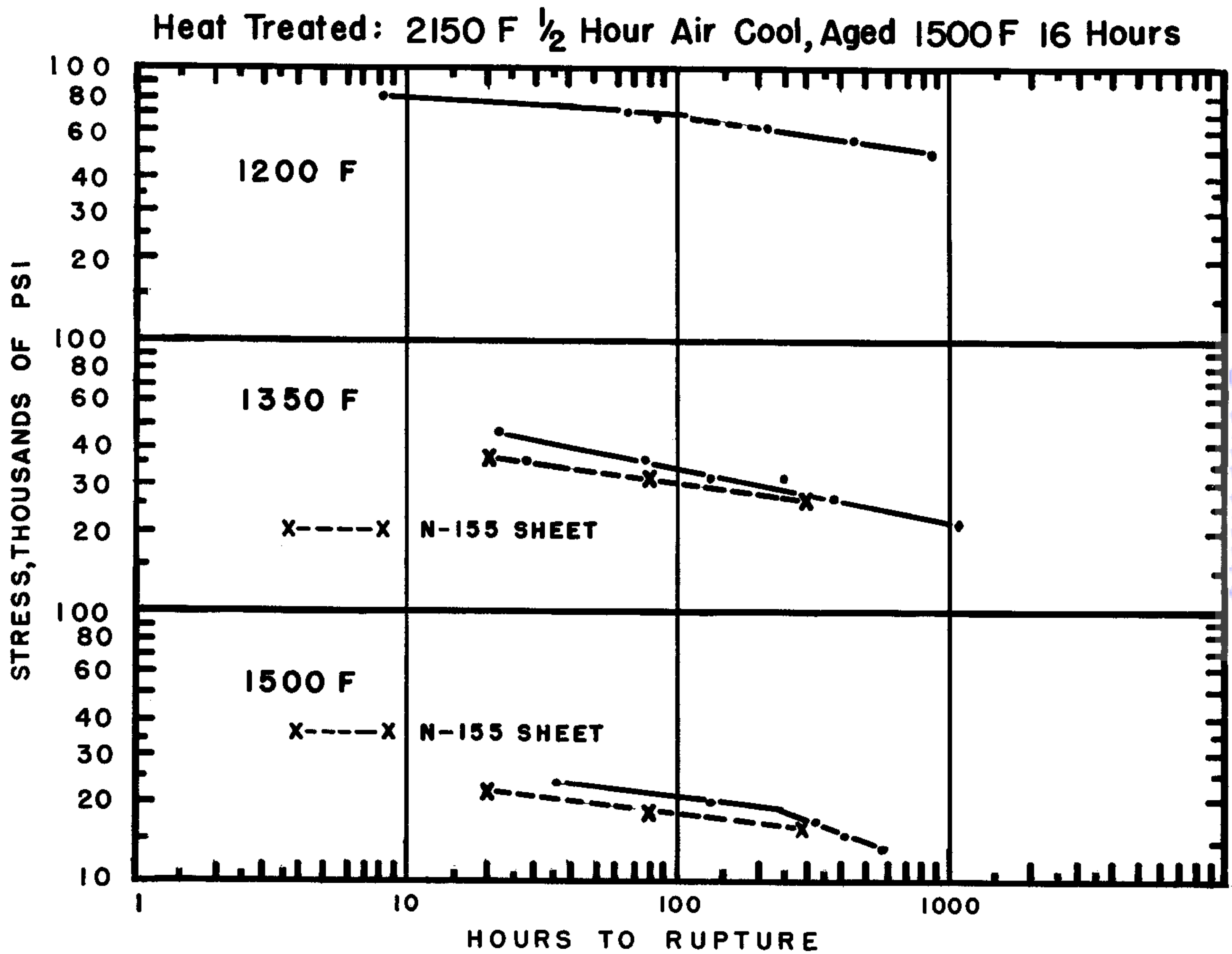

Figure 1 Stress - Rupture Properties of AD 30 Sheet

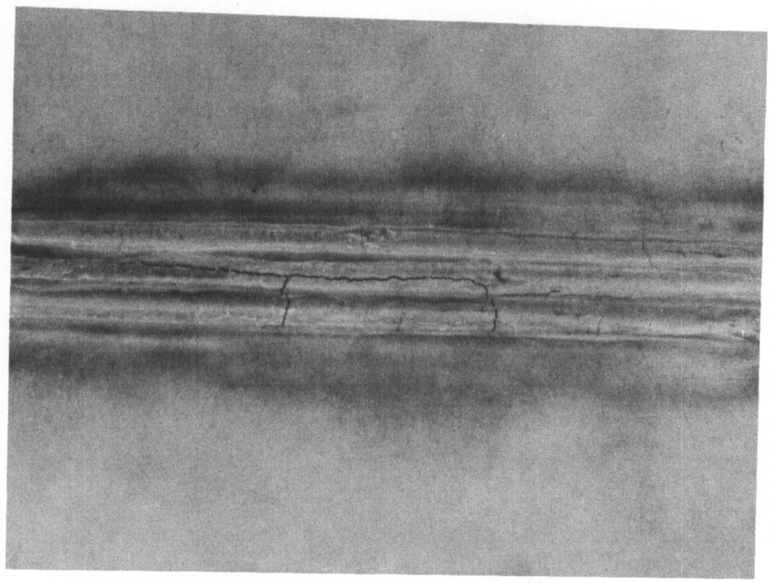

Figure 2. Three bead weld in AD30 steel sheet. Electric arc method, no filler rod. 2/3 actual size.

Weld made at Materials Laboratory, Wright Air Development Center.