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TO

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WRIGHT AIR DEVELOPMENT CENTER

ON

AN INVESTIGATION OF THREE FERRITIC STEELS FOR HIGH-TEMPERATURE APPLICATION

by

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SUMMARY

This report presents the progress made in an investigation of the elevated-temperature properties of three low-alloy steels for use in jet engines and air frames. The work period covered by the report was from June 1, 1955 to December 15, 1955.

Data are presented which were obtained during a study of the effect of hardness level on the properties of several typical microstructures. The steels being studied are SAE 4340 (Ni-Cr-Mo Steel), "17-22-A"S (1.25Cr-0.75Si-0.5Mo-0.25V Steel), and "17-22-A"V (1.25Cr-0.75Si-0.5Mo-0.8V Steel).

Survey creep and rupture tests were run on several structures which were tempered to a nominal hardness of 350 BHN so that comparisons could be made with the results of previous work on the same structures tempered to a 300 BHN hardness level. The incomplete data do not permit any final generalizations at this time; hence, only the apparent trends are reported for each steel and structure.

INTRODUCTION

This is the first progress report issued under Air Force Contract No. AF 33(616)-3239, covering work done from September 15, 1955 to December 15, 1955. (Work done between June 1, 1955, and September 15, 1955 under Contract No. AF 33(038)-13496, Supplemental Agreement No. S12(55-1510), is also included in this report because it was not ready to be included in the Final Report dated September 15, 1955.)

The present investigation is related to previous work done at the University of Michigan for Wright Air Development Center concerning the metallurgical factors involved in the use of low-alloy steels at elevated temperatures in jet engines.

Initially, the high temperature properties of four low-alloy steels in the form of rotor wheels for gas turbines of jet engines were determined following various heat treatments. The results of this work were published as WADC Technical Report 53-277, Part I (1).* A concurrent investigation was conducted to determine the relationships between types of microstructure and the properties of the steels. Microstructures were controlled by means of isothermal transformations in the pearlitic and bainitic temperature ranges, as well as by oil quenching and tempering and normalizing and tempering. A final report covering the results of this study and correlating the results with the rotor wheel data was published as WADC Technical Report 53-277, Part II (2). A third phase of the over-all investigation involved a study of the effect of austenitizing temperature and rate of continuous cooling on microstructure and the resulting elevated-temperature properties. These results were given in the Final Report dated September 15, 1955, under Contract No. AF 33(038)-13496 (proposed WADC Technical Report 55-388).

* References are given at the end of the report.

The current phase of the investigation involves a Ni-Cr-Mo (SAE 4340) Steel, a 1.25Cr-0.75Si-0.5Mo-0.25V ("17-22-A"S) Steel, and a 1.25Cr-0.75Si-0.5Mo-0.8V ("17-22-A"V) Steel. Included in the study are: (1) completion of work initiated under the previous contract on the effect of higher hardness level on several typical structures, (2) a general survey of the relationship between properties of the new, higher strength "17-22-A"V steel , (3) step-wise isothermal transformations in the upper bainitic region, (4) an evaluation of the effect of a prior homogenization normalize, and (5) a study of the effect of various double heat treatments.

All effort thus far has been concentrated on the completion of the work at the higher hardness level. The "17-22-A"V steel has not yet been received; hence, only the results for the SAE 4340 and "17-22-A"S steels can be reported at this time.

TEST MATERIALS

The chemical compositions of the steels involved in this study were reported by the manufacturers to be as follows:

Steel	Heat	C	Mn	Si	Cr	Ni	Mo	V
SAE 4340	19053	0.40	0.70	0.30	0.78	1.75	0.26	--
"17-22-A"S	10420	0.29	0.61	0.67	1.30	0.18	0.47	0.26

PROCEDURE

In previous work done on the relationship between microstructure and elevated temperature properties, all structures were tempered to the 300 BHN (± 20 BHN) hardness level before testing. Because there is extensive need for materials at a higher hardness level in jet engine and air frame parts, it was decided to attempt to define the properties of structures at the 350 BHN (± 10 BHN) hardness level. It appears that there is extensive need for information defining high temperature properties of low-alloyed steels better than by hardness alone at these higher hardness levels.

For some heat treatments, the hardness of the steel was less than 350 BHN before tempering, making it impossible to include these structures in the higher hardness study. Those structures which had a sufficiently high initial hardness and were thus included in the 350 BHN study were:

SAE 4340	"17-22-A"S	
1. Oil Quenched	1. Oil Quenched	4. Upper Bainite
2. Normalized	2. Normalized	5. Middle Bainite
3. Lower Bainite	3. Lower Pearlite	6. Lower Bainite

Heat Treatment

The heat treatments used to produce the various structures at 350 BHN were the same as those used in the previous 300 BHN program, except that the tempering conditions were less severe. The details of the heat treatments are given in Table I.

For the oil-quenching and the normalizing treatments, 1-inch bar stock was rough machined to 0.8-inch rounds before heat treating. Smaller samples (0.4-inch rounds) were used for the isothermal transformation treatments so that rapid cooling to the isotherm could be attained. All austenitizing was done in electrical resistance furnaces in an air atmosphere, and all isothermal transformations were carried out in agitated molten salt baths.

The appropriate tempering conditions to give a final hardness of 350 BHN were determined for each structure by trial and error, using slugs cut from a representative heat-treated bar. A recirculating air furnace was used for tempering to ensure uniform temperature distribution throughout the bars.

Evaluation of Elevated-Temperature Properties

The bases adopted for the evaluation of the elevated temperature properties were the same as those used for the previous studies at 300 BHN, except that the 1100°F tests for SAE 4340 and the 1200°F tests for "17-22-A"S were eliminated. Very briefly, the bases of evaluation were (1) creep rate and total deformation data at 700° and 900°F for both steels, and (2) total deformation and short- and long-time rupture data at 1000°F for 4340 and at 1100°F for "17-22-A"S. These data were obtained from a minimum number of survey tests -- one test per heat treatment at 700° and 900°F, and two tests per heat treatment at 1000°F for SAE 4340 and the same for "17-22-A"S at 1100°F.

The creep and rupture tests were conducted in accordance with ASTM Specifications. Most of the specimens were loaded into a cold furnace and brought up to within 100°F of the testing temperature on the evening before the day the test was begun. However, in the few instances where the testing temperature was equal to or higher than the tempering temperature, the specimen was loaded into a furnace already at the testing temperature, and the test was started as soon as the proper thermal equilibrium and distribution were attained.

RESULTS

The data for "17-22-A"S and SAE 4340 available at this time are presented in Table II. It seems advisable to wait until the data are complete before making any generalizations regarding the effect of hardness level. The apparent trends indicated by the present data are as follows:

"17-22-A"S Steel

Oil Quenched and Tempered:

1. At 1100°F the short-time rupture strength was higher for the 350 BHN material, with a rather sharp decrease in ductility.

2. The long-time (800-900 hours) rupture strength at 1100°F was slightly lower at the 350 BHN level, and the ductility was also a little lower for the harder structure.

3. The creep rates at 19,000 psi and 1100°F were equal, but the times to reach a specified total deformation were somewhat longer at the higher hardness level.

Normalized and Tempered:

1. At 115,000 psi and 700°F, the higher hardness material had superior creep properties.

2. Both tests run at 70,000 psi and 900°F were discontinued before rupture. The creep and total deformation data, however, clearly pointed to the 350 BHN structure as being superior.

3. At 1100°F, there was a slight trend in the rupture data toward lower strengths at short times and higher strengths at long times as the hardness was increased. A small decrease in ductility with increased hardness was observed in all cases.

4. The creep strength at 1100°F was higher for the harder material, while the total deformation strengths of the 350 BHN material were superior or inferior, depending on which deformation the strength is based on.

Lower Pearlite (Tempered):

1. At 70,000 psi and 900°F, the creep and total deformation properties were both superior for the harder material.

2. The present data indicate that at 1100°F the 350 BHN structure is superior with respect to rupture, creep, and total deformation characteristics, but inferior with respect to ductility.

Upper Bainite (Tempered):

1. At all temperatures the harder structure had somewhat superior creep, rupture, and total deformation strengths, with the only possible exception being

the creep strength at 1100°F which was slightly lower for the 350 BHN structure.

Middle Bainite (Tempered):

1. The higher hardness level yielded somewhat superior creep and total deformation strengths at all temperatures.

2. The only rupture data are for tests run at 1100°F and they indicate very little or no effect of hardness at 41,000 psi, while at 19,000 psi they show the harder structure to be a little superior. The 350 BHN material exhibited inferior ductility as usual.

Lower Bainite (Tempered):

1. At all temperatures the harder material had superior creep, rupture, and total deformation characteristics. The degree of superiority was greater at 700° and 900°F than it was at 1100°F.

Ni-Cr-Mo (SAE 4340) Steel

Oil Quenched and Tempered:

1. At 700° and 900°F, the 350 BHN structure had the better creep and total deformation strengths.

2. At 1000°F, the data indicated that the 300 BHN rather than the 350 BHN material was stronger with respect to creep, rupture, and total deformation.

3. The ductility of the harder structure was superior at 1000°F.

Normalized and Tempered:

1. Insufficient data are available for comparisons of properties at 700° and 900°F.

2. At 1000°F, one test at 31,000 psi indicated that the harder material had inferior short-time rupture strength, better ductility, and inferior creep and total deformation strengths.

Lower Bainite (Tempered):

1. The material at the higher hardness level apparently has the lower creep and total deformation strengths at 700°F.

2. At 900°F, the harder structure appeared to have the higher creep strength, but a somewhat lower total deformation strength.

3. The only available direct comparison at 1000°F indicates that this structure has somewhat superior short-time rupture and creep strengths at the higher (350 BHN) level of hardness, but it may be slightly weaker with respect to total deformation characteristics.

DISCUSSION

It is to be emphasized that the results reported above are merely trends which the incomplete data seem to suggest at this time.

One factor which was ignored in the presentation of the results above may or may not prove to be important. That is, that two heats of "17-22-A"S were involved in the hardness level study. Because additional "17-22-A"S stock from the old heat (No. 24797) was unavailable, new stock from Heat No. 10420 was used in the last few tests at 300 BHN and all the tests at 350 BHN. Variations in chemical composition between the two heats were small, and spot checks indicated that both heats had practically identical isothermal transformation diagrams. Also, the data of Table II indicate that, as might be expected, the 350 BHN structures (new heat) are sometimes stronger and sometimes weaker than the 300 BHN structures (old heat). Since the same pattern exists for SAE 4340 where only one heat is involved, it seems reasonable to assume that the heat-to-heat variations in the "17-22-A"S are not large enough to defeat the purpose of this study.

Another variable which will deserve prime consideration in the final interpretation of the data is the degree of temper. It is unfortunate that for certain structures (specifically, the normalized and the "lower bainite" structures of

SAE 4340, very wide differences in the degree of tempering were necessary in order to meet the 300 and the 350 BHN specifications. For example, the 4340 normalized structure with an initial hardness of 385 BHN was tempered 1 hour at 1100°F to obtain a final hardness of 300 BHN, while a temper of no more than 0.5 hour at 900°F could be given the same structure and still retain a final hardness of 350 BHN. It is quite certain that the structure at 350 BHN would have less metallurgical stability (i.e., greater tendency for microstructural changes during testing) than it would have if it were tempered to the 300 BHN level. Microstructural changes during creep-rupture testing usually have a weakening effect. However, in the final analysis it will be necessary to adjust this generality to the several cases where the harder structures are proving to have better long-time strength properties.

The low tempering temperature used for the normalized and the "lower bainite" structures of SAE 4340 at 350 BHN presented still another problem (although basically the same problem of structural changes during testing). Two tests for the normalized structure and three for the "lower bainite" structure were run at 1000°F. Since this testing temperature was 100°F higher than the tempering temperature, the significance of the data from these tests is to some extent uncertain. It is expected, however, that such tests will better clarify the accepted rule that tempering should always be done above the service temperature.

It is believed that when the testing is completed for this study of the effect of hardness level, and the data can be analyzed as a whole, the limitations of the data due to the variables discussed above will be at least a little more clearly defined.

FUTURE WORK

The present work on the effect of hardness on properties is expected to be complete for SAE 4340 and "17-22-A"S by the end of January, 1956. The same study will be extended to include the new steel, "17-22-A"V, after the preliminary survey is made of its general heat-treating characteristics.

Detailed experimental procedures are being worked out for the other phases of this year's investigation.

REFERENCES

(1) A. Zonder, A. I. Rush, and J. W. Freeman, "High Temperature Properties of Four Low-Alloy Steels for Jet-Engine Turbine Wheels", Wright Air Development Center Technical Report 53-277, Part I (November, 1953).

(2) A. I. Rush and J. W. Freeman, "High-Temperature Properties of Four Low-Alloy Steels for Jet-Engine Turbine Wheels", Wright Air Development Center Technical Report 53-277, Part II (February, 1955).

TABLE I

Structures and Heat Treatments Used in the Study of the Effect of Hardness on Properties of SAE 4340 and "17-22-A"S Steels

Structure	Initial Heat Treatment	Average Hardness Before Tempering (BHN)	Tempering Conditions 300 BHN	350 BHN
	SAE 4340 Steel			
Oil Quenched (100% Martensite)	1 Hour at 1750°F, Oil Quenched (0.8 in. round)	585	10 hrs. at 1100°F	1.5 hrs. at 1000°F
Normalized (65% Bainite + 35% Martensite)	1 Hour at 1750°F, Air Cooled (0.8 in. round)	385	1 hr. at 1100°F	0.5 hr at 900°F
Lower Bainite (100% Fine Bainite)	1 Hour at 1750°F, Isothermally Transformed 1.5 hrs. at 650°F, Water Quenched (0.4 in. round)	430	1.25 hrs. at 1100°F	0.5 hr at 900°F
	"17-22-A"S Steel*			
Oil Quenched (100% Martensite)	1 Hour at 1750°F, Oil Quenched (0.8 in. round)	525	1 hr. at 1300°F	3 hrs. at 1200°F
Normalized (85% Bainite + 15% Martensite)	1 Hour at 1750°F, Air Cooled (0.8 in. round)	355	10 hrs. at 1200°F	15 hrs. at 1100°F
Lower Pearlite (40% Pearlite + 60% Ferrite)	1 Hour at 1750°F, Isothermally Transformed 10 hours at 1150°F, Water Quenched (0.4 in. round)	375	12 hrs. at 1200°F	3 hrs. at 1100°F
Upper Bainite (60% Bainite + 40% Martensite)	1 Hour at 1750°F, Isothermally Transformed 2 hrs. at 900°F, Water Quenched (0.4 in. round)	465	16 hrs. at 1200°F	12 hrs. at 1100°F
Middle Bainite (97% Bainite + 3% Martensite)	1 Hour at 1750°F, Isothermally Transformed 0.5 hr. at 800°F, Water Quenched (0.4 in. round)	360	4 hrs. at 1200°F	8 hrs. at 1100°F
Lower Bainite (100% Fine Bainite)	1 Hour at 1750°F, Isothermally Transformed 0.2 hr. at 700°F, Water Quenched (0.4 in. round)	365	12 hrs. at 1200°F	12 hrs. at 1100°F

* All values given are for Heat No. 10420.

TABLE II

Comparison of Rupture, Creep, and Total Deformation Data at the 300 and 350 BHN Hardness Levels for "17-22-A"S and SAE 4340 Steels Tested in the Range of 700° to 1100°F

Structure	Test Temp. (°F)	Stress (psi)	Rupture Time (hrs)		Elongation (% in 4D)		Reduction of Area (%)		Def. on Loading (%)		Min. Creep Rate (%/Hr)		Time to Reach Specified Total Deformation (Hours): 0.2 Percent		0.5 Percent		1.0 Percent	
			300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN	300 BHN	350 BHN
"17-22-A"S																		
Oil Quenched (Tempered)	700	115,000	289.0 a		19.8		63.3		0.6700	0.538	0.00950		b	b	b	b	1.0	
	900	70,000	756.0 a		30.3		64.0		0.3780	0.365	0.00384	(0.00028)	b	b	3.0	30.0	50.0	
	1100	41,000	23.4 a	52.7	28.0	5.5	27.5	10.0	0.1730	0.224	0.00650	c	c	b	b	~4.0	c	24.0
	1100	19,000	850.0 a e	712.7	4.0	2.0	-	5.5	0.1050	0.102	0.00152	0.00150	17.0	30.0	170.0	220.0	420.0	492.0
Normalized (Tempered)	700	115,000	132.0 a	>1205.0	21.0	-	61.9	-	0.6600	0.623	0.0220	0.000047	b	b	b	b	1.0	>>1205.0
	900	70,000	>1482.0 a	>1205.0	-	-	-	-	0.3350	0.352	0.0003	0.000079	b	b	24.0	175.0	1400.0	>>1205.0
	1100	41,000	112.0 a	92.8	2.5	2.0	3.1	2.4	0.2120	0.1980	0.00614	0.00420	b	~0.1	26.0	~10.0	-	60.0
	1100	19,000	900.0 a e	1211.4	2.0	1.0	-	0.8	0.0850	0.096	0.00063	0.00050	80.0	55.0	580.0	500.0	800.0	1050.0
Lower Pearlite (Tempered)	700	115,000	a d	>1296.0	19.0	-	61.0	-	-	0.843	-	0.000540	b	b	b	b	b	<0.5
	900	70,000	>1205.0 a	>1176.0	-	-	-	-	0.4060	0.279	0.00223	0.000385	b	b	2.0	60.0	53.0	1180.0
	1100	41,000	42.0	49.1	8.5	5.5	8.7	5.1	0.2260	0.231	c	c	b	b	4.0	-	12.0	
	1100	19,000	f	677.2	-	4.5	-	3.5	-	0.0780	-	0.00178	-	22.0	-	185.0	-	385.0
	1100	15,000	652.0 a		15.5		17.1		0.0650	0.0580	0.00340	0.00068	54.0	72.0	107.0	500.0	218.0	
Upper Bainite (Tempered)	700	115,000	147.0 a		20.2		62.0		0.7100	0.414	0.0180	(0.00011)	b	b	b	~10.0	<1.0	
	900	70,000	686.0 a	>2376.7	30.0	-	59.5	-	0.3550	0.3900	0.00504	0.000064	b	b	1.0	70.0	50.0	>>2376.0
	1100	41,000	51.5	58.9	7.2	5.0	8.6	7.1	0.2690	0.2700	c	0.0224	b	b	4.0	5.0	13.0	24.0
	1100	19,000	796.0 a	851.2	5.8	3.0	6.6	4.1	0.1100	0.087	0.00140	0.00155	8.0	65.0	177.0	230.0	447.0	490.0
Middle Bainite (Tempered)	700	115,000	>1827.0 a	>2544.2	-	-	-	-	0.6100	0.513	0.00029	<0.00001	b	b	b	b	45.0	>>2544.0
	900	70,000	>1648.0 a	>2448.6	-	-	-	-	0.3230	0.309	0.00014	0.000052	b	b	65.0	510.0	2500 e	>>2448.0
	1100	41,000	88.2 a	83.6	5.1	2.5	4.9	3.3	0.2170	0.232	c	c	b	b	6.0	9.0	19.0	40.0
	1100	19,000	815.0 a	938.1	4.0	~1.0	3.0	~1.0	0.0960	0.105	0.0015	0.00081	30.0	35.0	222.0	360.0	575.0	735.0
Lower Bainite (Tempered)	700	115,000	59.4 a	>1298.0	18.8	-	66.7	-	0.8150	0.5110	0.0452	0.000047	b	b	b	b	<1.0	>>1298.0
	900	70,000	1456.0 a	>1200.0	24.0	-	56.2	-	0.3500	0.3480	0.00115	0.000072	b	b	12.0	550.0	362.0	>>1200.0
	1100	41,000	92.8	119.1	5.0	2.0	4.0	2.5	0.2520	0.2400	0.0165	0.0090	b	b	9.0	22.0	32.0	64.0
	1100	21,000	889.0 a	f	2.0	-	5.6	-	0.1740	-	0.00113	-	6.0	-	198.0	-	604.0	-
	1100	19,000	f	1278.9	-	4.0	-	4.7	-	0.0940	-	0.00085	-	60.0	-	375.0	-	855.0
SAE 4340																		
Oil Quenched (Tempered)	700	90,000	>1350.0		-		-		0.430	0.342	0.00027	0.000138	b	b	2.0	350.0	675.0	
	900	55,000	381.0		19.5		39.5		0.269	0.292	0.01480	0.00546	b	b	2.0	~2.0	13.0	20.0
	1000	31,000	160.0 e	143.1	11.0	12.5	15.0	17.0	0.149	0.376	0.02500	c	~1.0		3.5		16.0	
	1000	20,000	780.0 e	693.9	12.0	21.5	15.0	23.0	0.099	0.113	0.00380	0.0060	7.0	~2.0	47.0	15.0	190.0	72.0
Normalized (Tempered)	700	90,000	>1294.0		-		-		0.467		0.00016		b		1.0		1000.0	
	900	55,000	842.0		12.0		22.3		0.260	0.381	0.00414		b	b	8.0	<1.0	64.0	~5.0
	1000	31,000	371.0	268.1	5.5	12.5	7.4	13.5	0.126	0.164	0.00505	0.01260	~5.0	<1.0	50.0	10.0	145.0	40.0
	1000	20,000	1392.0		5.0		4.0		0.090	0.106	0.00114	0.00213	20.0	~5.0	228.0	55.0	650.0	275.0
Lower Bainite (Tempered)	700	90,000	>1485.0		-		-		0.440	0.482	0.00016	0.00030	b	b	~1.0		2000 e	575.0
	900	55,000	897.0		18.5		15.4		0.250	0.298	0.00530	0.0020	b	b	8.0	~5.0	51.0	35.0
	1000	55,000	f	13.5	-	19.0	-	34.8	-	0.350	-	c	-	b	-	c	-	c
	1000	31,000	210.0	263.7	9.4	10.0	17.0	10.1	0.161	0.220	0.01790	0.00188	~1.0	~1.0	~6.0	~6.0	26.0	20.0
	1000	20,000	f		-		-		-	0.161	-	0.00244	-	~2.0	-	18.0	-	123.0
	1000	13,000	>1035.0		-		-		0.055		0.00053		32.0		300.0		1100 e	

a Heat No. 24797; all others from Heat No. 10420
b Value exceeded on loading
c Unavailable because of insufficient data
d Ruptured on loading
e Extrapolated or interpolated value
f No test run under these conditions
> Greater than (test was discontinued at this time)
>> Much greater than
< Less than
~ Approximately
( ) Tentative value -- test still in progress
Blank spaces indicate that the value is unavailable because the test is still in progress