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Goel, Virendra Singh.

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OF CONVENTIONAL AND AUSFORM STEELS**

Virendra Singh Goel

(Ph.D. Thesis)

January 1965

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ELEVATED TEMPERATURE STRAIN AGING
OF CONVENTIONAL AND AUSFORM STEELS

Virendra Singh Goel

Inorganic Materials Research Division
Lawrence Radiation Laboratory
Department of Metallurgy
School of Engineering
University of California
Berkeley, California

January 1965

ABSTRACT

The strain-aging behavior of conventional H-11 and ausform H-11 steel was investigated by variation of prestrain temperature, prestrain rate and post-tempering temperature. The temperature during prestrain was varied from 300°F to 900°F, the strain rate was varied from $1.35 \times 10^{-5} \text{ sec}^{-1}$ to $1.35 \times 10^{-3} \text{ sec}^{-1}$, and the post-tempering temperature was varied from 300°F to 900°F.

An increase in yield stress from 240,000 psi to 310,000 psi - i.e., a gain of 70,000 psi - was observed for conventional H-11 steel. Yield stress for ausform H-11 steel increased from 275,000 psi to 400,000 psi - i.e., a gain of 125,000 psi. There was no significant loss in ductility, and the ultimate tensile stress was slightly increased in both conventional and ausform steels.

I. INTRODUCTION

The phenomenon of strain-aging in steel has been extensively studied.^{1,2} It is thought that strain-aging is due to the formation of carbon and nitrogen atmospheres around dislocations and/or precipitation of carbides that pin dislocations.³

A model for solute segregation was first proposed by Cottrell and Bilby⁶ and later modified by Harper.⁷ The kinetics of precipitation of carbon has been studied by various methods, including internal friction.^{4,5}

In alloy steels the secondary hardening peak is believed to be due to the precipitation of coherent alloy carbides.^{8,9,10} By strain-enhanced diffusion it may be possible to bring these carbides out at a lower temperature.

Recently there has been great interest in the strain-aging behavior of high-strength alloy steels¹¹ due to their great engineering importance. Cohen et al.¹² have noted an increase in yield stress of 80,000 psi in ausbainformed H-11 by strain-aging, without significant loss of ductility. Irish and Rosenberg¹¹ obtained an increase of 60,000 psi in yield stress in M-763 steel. [Yield stress increased from 260,000 psi to 320,000 psi, when the specimens were stressed at 600°F for 1000 hours (strain $\approx$ 2%) and then cooled and tested at room temperature.] Steigerwald and Hanna¹³ have tried to correlate strain-aging (indicated by increase in ultimate tensile strength) in high strength steels, with notch brittleness during tensile tests at elevated temperatures. Young¹⁴ obtained an increase of 50,000 psi in yield stress of H-11 with mar-straining, without significant loss of ductility.

The previous studies^{15,16,17,18} have been conducted with only a limited number of prestrain-tempering variations. This suggested the need for an investigation to determine whether an optimum prestrain-rate, prestrain-temperature, and post-tempering temperature combination could be obtained, to get maximum strength without appreciable loss in ductility. Accordingly, in the present work the effect of the above variables have been studied with respect to yield stress, ultimate tensile stress, elongation, reduction in area, and hardness.

In Cohen's work¹⁹ on prestraining and retempering of alloy steel, the lowest pretempering temperatures gave the best results. Consequently the lowest possible pretempering temperatures that would still provide ductility were chosen in the present investigation.

It is expected that the maximum amount of carbon and alloy carbide formers are retained and would still be in solution and available for clustering or precipitation during treatment.

Mechanical properties of a material depend on precipitate distribution in the matrix.

Diffusivity of the substitutional alloying elements is one of the major factors controlling the formation of clusters or precipitates during straining. Self diffusion and diffusion of substitutional solute atoms are both largely dependent on vacancy concentration in a material, and so it may be expected that the diffusivity of substitutional atoms will show an increase in vacancy concentration.

Cohen et al.²⁰ have shown that the self-diffusivity in α iron is enhanced in proportion to the strain rate and that this dependence increases with decreasing temperature. Strain rates from 0 to 2×10^{-3} sec⁻¹ were investigated by them. An increase in diffusivity of up to 3×10^3

times in the temperature range of 742°C to 885°C was obtained at lower temperatures.

Because of strain-enhanced diffusion, alloy carbides may be expected to precipitate at a lower temperature during prestrain than under tempering conditions. With this in mind a prestrain temperature range from room temperature to 900°F was chosen.

Since increase in strain rate can enhance diffusivity by a factor of a thousand or more, strain rates differing by two orders of magnitude were chosen for study ($1.35 \times 10^{-3} \text{ sec}^{-1}$ and $1.35 \times 10^{-5} \text{ sec}^{-1}$).

All samples were given a post-tempering treatment in an effort to develop greater ductility.

In this investigation an effort was made to develop a thermomechanical treatment for superstrength alloys. The steels chosen were hot die steels (conventional and ausform H-11) which have a high base strength and are readily amenable to ausforming. In addition, a great deal of work has been done on the microstructure and defect structure of this steel in the ausform state.²¹⁻²³

Zackay et al.²¹ examined the relation of structure to mechanical properties of these materials with emphasis on the factors of strain hardening of the austenite, microstructural anisotropy, austenite and martensite grain size, carbon content, and tempering.

The conventional and ausform H-11 steels used were of the same chemical composition but of different microstructure. Ausform steel has a finer distribution of martensite plates and a higher dislocation density²² due to severe deformation ($\sim 80\%$) around 1000°F than conventional H-11 steel. The two different microstructures were used to determine the effect of the same thermal treatment on the mechanical properties.

II. EXPERIMENT

A. Variables

Ten variables were considered in this experiment; six were kept constant and four were varied (these are summarized in Table I).

B. Procedure

1. Specimen Material

Alloy steel generally known as Vascojet 1000 or H-11 of the following composition was obtained in the ausformed and conventional state.

Composition of H-11 Steel

	<u>C</u>	<u>Si</u>	<u>Mn</u>	<u>S</u>	<u>P</u>	<u>W</u>	<u>Cr</u>	<u>V</u>	<u>Mo</u>
Conventional	.40	.85	.33	.015	.011		5.06	.5	1.28
Ausformed	.40	1.00	.25	.0083	.011		5.09	.5	1.4

The material was ausformed by Ford Laboratories and then given a double pretemper at 500°F before being shipped to Berkeley. The steel was in the shape of half-inch rolled rods. The conventional H-11 steel was also in the shape of half-inch rods.

2. Specimen Preparation

Ausformed H-11 rods were precision ground to $.113 \pm .001$ " diameter and 1.125 ± 0.001 " length, as illustrated in Fig. 1. These specimens were ground very carefully, keeping the size of each cut below .001" in each pass, to minimize heating during the grinding operation. Copious flow of coolant was maintained during the grinding operation.

Conventional H-11 steel rod was cut to 2" lengths and austenitized at 1850°F for half an hour. The material was encapsulated in evacuated quartz tubes with argon at one-seventh atmospheric pressure. Specimens

MU-34743

Fig. 1

TABLE I

Variables kept constant throughout entire investigation		Variables varied one at a time when all the others were held constant for measurement of yield stress, ultimate tensile stress, elongation, reduction in area, and yield drop	
	Process Variable	Conditions Chosen	Number of Conditions
Austenitizing temperature	Material	Ausform H-11 steel, conventional H-11 steel	2
Quench rate and quenching temperature	Prestrain temperature	300°F, 450°F, 600°F, 750°F, 900°F	5
Pretemper time and temperature	Prestrain rate	$1.35 \times 10^{-3} \text{ sec}^{-1}$, $1.35 \times 10^{-4} \text{ sec}^{-1}$, $1.35 \times 10^{-5} \text{ sec}^{-1}$	3
Amount of strain	Post tempering temperature	350°F, 500°F, 600°F, 700°F, 900°F	5
Strain rate for final test			
Time for post-tempering			

were air-cooled after austenitization, to room temperature. The rods were then tempered at 900°F for one hour. Tempering temperature was maintained within an accuracy of $\pm 5^\circ\text{F}$. These rods were then ground the same way as the ausformed rods, as illustrated in Fig. 2.

3. Tensile Tests

Specimens were mounted in the hot-testing jig as illustrated in Figs. 2 and 3. The system was pumped down by a mechanical pump and flushed three times with helium, before helium was finally introduced to a pressure of one atmosphere. The oven was preheated to the desired temperature and the jig was lowered into the oven by a block-and-tackle arrangement. It took about two hours for the specimen to come to temperature. The temperature at both the lower and upper grip was monitored by chromelalumel thermocouples and a chart recorder. The temperature difference between the upper and lower grip was maintained within $\pm 4^\circ\text{F}$.

Specimens were strained at an elevated temperature, with different strain rates. Strain rates used were 1.35×10^{-3} , $1.35 \times 10^{-4} \text{ sec}^{-1}$, and $1.35 \times 10^{-5} \text{ sec}^{-1}$. Elongation of the specimen was sensed directly at the ends of the specimen by a combination of a mechanical micrometer and a differential transformer. This eliminated the possible errors due to thermal and mechanical expansion of the extension rods. After prestrain at elevated temperature, the specimens were air-cooled by a blower. Then these specimens were given a post-temper in a furnace where temperature was maintained to within $\pm 5^\circ\text{F}$. After post-tempering treatment, specimens were precision-honed to uniform diameter. Specimens were then finally pulled to destruction at room temperature, giving the final stress-strain curve.

ZN-4369

Fig. 2

ZN-4368

Fig. 3

4. Hardness Tests

Some hardness tests were run to determine the optimum post-tempering temperature for maximum strength. In these tests, specimens were pre-strained a specific amount at an elevated temperature, air-cooled in an air blast; then were sliced by using a thin cutoff wheel and copious flow of coolant. These were then post-tempered at different temperatures ranging from 200°F to 900°F. After tempering, the cut sections were carefully hand-ground and polished, yielding parallel flat surfaces at the ends. Then hardness measurements were taken on the C scale of the Rockwell hardness tester.

5. Replica Work

After the final room-temperature test, specimens were sliced at right angles to the longitudinal axis with a cutoff wheel, using a copious flow of coolant. These were then polished on the cross-section face, and a carbon film was deposited under vacuum by sputtering graphite rods. Carbon extraction replicas were floated off the surface of the specimen by placing them in a dilute acid bath. No carbides were detected in these replicas.

III. RESULTS

Table II shows a comparison of the variables used in Figs. 6-18, and helps to locate the variations of mechanical properties under particular conditions.

Figures 6-18 show the effect on mechanical properties of variation of the parameters. (These variables are as previously summarized in Table I,)

Experimental results are summarized in Tables III and IV.

The shape of stress-strain curves obtained during the final room temperature tests are interesting in many cases, because of the good work hardening rate exhibited after the yield point, so autographic records of the final tests are reproduced in the Appendix.

A. Conventional H-11 Steel

1. Prestrain Temperature

Samples were: austenitized at 1850°F, air cooled, tempered at 900°F, prestrained at several temperatures (ref. Fig. 4), post-tempered at 900°F, and then finally pulled to destruction at room temperature. The effect of varying prestrain temperature on the physical properties is shown with the aid of two sequences of plots in Figs. 6 and 7. Prestrain rates of $1.35 \times 10^{-5} \text{ sec}^{-1}$ (Fig. 6) and $1.35 \times 10^{-3} \text{ sec}^{-1}$ (Fig. 7) were used.

a. Prestrain rate of $1.35 \times 10^{-5} \text{ sec}^{-1}$. Figure 6 shows that the stress at 2% yield during elevated temperature prestrain tests decreases monotonically from 300,000 psi at room temperature to 240,000 psi at 900°F. This behavior of decreasing flow stress with increasing temperature is as expected. The yield stress curve starts out with a high value at room temperature, shows a minimum at 300°F, increases to a maximum between

TABLE II Summary of Variables Used in Figs. 3-15

Graph No.	Material ^a	Prestrain Temperature °F	Prestrain Rate $\times 10^{-3} \text{ sec}^{-1}$	Post-temper Temperature in °F	
6	C	Varies	10^{-5}	900	
7	C	Varies	10^{-3}	900	
8	C	70,300, 450,600, 750,900	Varies	900	
9	C	750	10^{-4}	Varies	
10	C	Varies	$10^{-3}, 10^{-5}$	900	Yield drop effect
11	A.F.	Varies	10^{-5}	900	
12	A.F.	Varies	10^{-3}	900	
13	A.F.	300,450, 525,750, 900	Varies	900	6,7 superposed
14	A.F.	300	10^{-4}	Varies	
15	A.F.	450	10^{-4}	Varies	
16	A.F.	Varies	10^{-4}	350,500, 600,750, 900	9,10 superposed
17	A.F.	Varies	$10^{-3}, 10^{-5}$	900	y. point effect
18a	C	900	10^{-4}	Varies	
18b	A.F.	150	10^{-5}	Varies	hardness
18c	A.F.	300	10^{-4}	Varies	curves
18d	A.F.	450	10^{-4}	Varies	

^a C indicates conventional H-11 steel, A.F. indicates ausformed H-11 steel.

TABLE III

Post Tempering Temperature		900°F				750°F				500°F	350°F
Strain Rate	Temperature	Yield stress 1000's psi	U.T.S. 1000 psi	Elongation, %	Reduction in Area, %	Yield Stress 1000's psi	U.T.S. 1000's psi	Elongation, %	Reduction in Area, %		
10 ⁻³	70°F	330	330	1.78	12.0						
	300°F	299	322	4.9	10.2						
	450°F	312	318	4.4	8.8						
	600°F	328	328	4.8	12.8						
	750°F	321	327	5.5	9.4						
	900°F	296	323	7.6	14.0						
10 ⁻⁴	70°F										
	300°F										
	450°F										
	600°F	312	312	2.40	21.2						
	750°F					336	336	2.86	31.0		
	900°F										
10 ⁻⁵	70°F	332	332	1.9	15.0						
	300°F	308	316	8.3	13.4						
	450°F	326	326	3.6	12.6						
	600°F	323	323	2.7	15.5						
	750°F	319	322	7.8	14.6						
	900°F	289	330	5.8	18.3						

TABLE IV
AUSFORM H-11

Post Tempering Temperature	900°F	750°F	600°F	500°F	350°F
Strain Rate/ 1.35 sec ⁻¹	Yield Stress 1000's psi U.T.S. 1000's psi Elongation % Reduction in Area	Yield Stress 1000's psi U.T.S. 1000's psi Elongation % Reduction in Area	Yield Stress 1000's psi U.T.S. 1000's psi Elongation % Reduction in Area	Yield Stress 1000's psi U.T.S. 1000's psi Elongation % Reduction in Area	Yield Stress 1000's psi U.T.S. 1000's psi Elongation % Reduction in Area
10 ⁻³	300°F	353 381 11.1 20.2			
	450°F	362 375 10.8 23.2			
	525°F	359 379 12.1 18.5			
	600°F	361 377 10.8 19.0			
	750°F	340 386 10.9 19.0			
10 ⁻⁴	900°F	311 393 8.2 32.0			
	300°F		398 398 5.35 33.	410 410 2.6 19	397 397 9.9 30.0
	450°F	350 378 10.0 19.5	399 399 3.3 25.	402 402 9.5 21.0	396 396 9.5 28.0
	525°F	362 375 9.5 13.5			
	600°F	361 376 11.1 26.0			
10 ⁻⁵	750°F				
	900°F				
	300°F	349 381 8.1 12.4			
	450°F	370 374 9.6 18.7			
	525°F	390 390 12.7 27.0			
10 ⁻⁵	600°F	358 375 11.7 27.8			
	750°F	326 386 11.6 37.0			
	900°F	347 380 8.3 40.0			

MU-34805

Fig. 4

MU-34806

Fig. 5

MU-34807

Fig. 6

MU-34808

Fig. 7

MU-34809

Fig. 8

MU-34811

Fig. 9

MU-34810

Fig. 10

MU-34812

Fig. 11

MU-34813

Fig. 12

MU-34814

Fig. 13

MU-34815

Fig. 14

MU-34816

Fig. 15

MU-34817

Fig. 16

MU-34818

Fig. 17

MU-34819

Fig. 18

450°F and 750°F, and then decreases again at 900°F. The tensile stress curve also starts out high, shows a minimum at 300°F, a second minor dip at 750°F, and finally the value increases slightly at 900°F. The elongation curve shows two peaks, one at 300°F and the other at 750°F. These coincide with the minimum values in the yield stress curve as expected. The reduction in area shows a minimum at 450°F near the minimum in the elongation, and then increases up to 18% at 900°F.

b. Prestrain rate of $1.35 \times 10^{-3} \text{ sec}^{-1}$. Figure 7 shows that the stress at 2% yield during prestrain decreases with increase in temperature as expected. The yield stress curve starts high as in the previous case, dips again at 300°F, shows a sharper maximum at 600°F, and then drops down in value at 900°F. The tensile stress curve also starts high and shows a minimum at 450°F instead of 300°F, as in the previous case. Then the value slightly increases and stays approximately constant until about 900°F. Elongation is very low at room temperature coincident with a high value of yield strength. As the temperature increases elongation values improve right up to 900°F. A very slight maximum is observed at 300°F along with a minimum in the yield stress curve. Reduction in area curve shows two minima, one at 450°F and the other at 750°F. These do not seem to correlate with any other physical property investigated here.

2. Prestrain Rate Effect

Figure 8 shows variation of physical properties with slow and fast strain rate, $1.35 \times 10^{-5} \text{ sec}^{-1}$ and $1.35 \times 10^{-3} \text{ sec}^{-1}$, respectively. Values of stress at 2% yield during prestrain are almost coincident in the entire temperature range. The yield stress values follow a very similar pattern only they are slightly higher for slow strain rate at temperatures between 300°F-500°F and again at 900°F. The elongation curve with

slow strain rate has pronounced maximum at 300°F and 750°F. There is a slight maximum at 300°F with fast rate; however, the second maximum observed with the slow rate at 750°F is not observed at this rate.

Reduction in area curves run parallel for both rates.

Values with the slow rate are always approximately 30% higher; e.g., at 300°F, 10% reduction in area is obtained with the fast rate, 13.5% with the slow rate.

3. Post tempering temperature

Figure 9 shows the strain aging behavior of conventional H-11 steel, austenitized at 1850°F, air cooled, pretempered at 900°F, prestrained 2% at 750°F, and post tempered at various temperatures.

As post tempering temperature is increased, values of yield stress and ultimate tensile stress continuously decrease. Elongation stays constant at about 3% to 700°F and then improves to 7% at 900°F with a slight fall in the values of yield and tensile stress. Reduction in area decreases with increase in temperature. At 900°F reduction in area has dropped to 10% from 30% though elongation has increased to about 7% from 3%. Generally, high ductility means good elongation and large reduction in area. Here, as elongation increases, reduction in area decreases. This unusual effect is brought about because of a high work-hardening rate, which results in a more uniform elongation, hence a small reduction in area, and a favorable stress-strain curve.

4. The yield drop

Figure 10 shows the yield drop (upper yield stress minus the lower yield stress) behavior of conventional H-11 steel, with varying prestrain temperature, along with the yield strength and hardening rate during prestrain. The yield drop with slow strain rate is always higher than

with fast strain rate. Both curves show a peak at 600°F. The yield drop peak at 600°F with fast rate is accompanied with a minimum in hardening rate. Such a correlation does not exhibit itself with slow rate. Hardening rate is high at room temperature, it shows a minimum at 300°F for both fast and slow prestrain rate. A second minimum for fast strain rate occurs at 600°F; the value with slow rate goes down at 900°F. A clear second minimum with slow rate is not exhibited within the temperature range investigated.

5. Hardness

The hardness variation of conventional H-11 steel, prestrained 2% at 750°F, is shown in Fig. 18.

Hardness shows a maximum at 350°F. The overall variation of hardness is small with post-tempering temperature up to 900°F.

B. Ausform H-11 Steel

1. Prestrain Temperature

The material was austenitized at 2100°F, deformed 87% at 1050°F, air cooled, double tempered at 500°F, prestrained at several temperatures (Fig. 5), post-tempered at 900°F, and then finally tested to destruction at room temperature. The effect of varying prestrain temperature on the mechanical properties is shown with the aid of two sequences of plots in Figs. 11 and 12. Prestrain rates of $1.35 \times 10^{-5} \text{ sec}^{-1}$ (Fig. 11), and $1.35 \times 10^{-3} \text{ sec}^{-1}$ (Fig. 12) were used, the same as with conventional H-11 steel.

a. Prestrain rate of $1.35 \times 10^{-5} \text{ sec}^{-1}$. Figure 11 shows that the stress at 2% yield during elevated temperature prestrain tests decreases from 410,000 psi at 300°F to 270,000 psi at 900°F. The decrease of stress in this case is more than twice of that of conventional H-11, under similar

test conditions. The yield stress curve shows a maximum at 525°F. (Conventional H-11 also showed a maximum close to the same temperature, though the peak of the curve was less pronounced.) The curve shows a minimum at 750°F, and the value of the yield stress again increases by about 20,000 psi at 900°F. Tensile stress also shows a minimum at 525°F, as did the yield stress curve. Strangely enough it has a maximum at 750°F where the yield stress exhibits a minimum. The value of tensile stress drops by about 6,000 psi, while that of yield stress rises by 20,000 psi from 750° to 900°F. Elongation exhibits a maximum at 525°F which coincides with the maximum in yield stress, tensile stress, and reduction in area. This high elongation with high yield and tensile stress value is unusual. The stress strain curve at this temperature also looks good, as it does not decrease continuously after the yield drop; rather, the stress value increases constantly almost to the end of the elongation curve. Elongation values stay about 11% to 750°F then fall to 8% at 900°F. Reduction in area starts at 11% at 300°F and goes up to 40% at 900°F.

b. Prestrain rate of 1.35×10^{-3} sec⁻¹. Figure 12 shows at 2% yield during prestrain starts with a value of 381,000 psi which stays about constant to 700°F and then increases to 393,000 psi at 900°F. Elongation shows a maximum at 525°F, where a minimum is observed in yield stress. This is as usually expected, but at higher temperatures of 750°F and 900°F, yield stress decreases from 340,000 psi to 311,000 psi. Normally, the elongation would be expected to increase but instead it decreases, from 10.9% to 8.2%. Reduction in area stays at about 20% between 300°F and 750°F; it increases to 32% at 900°F. Increase in reduction of area between 300°F to 450°F is unusual, since in this range yield stress increases.

2. Prestrain Rate Effect

Figure 13 shows variation of mechanical properties with slow and fast strain rate, $1.35 \times 10^{-5} \text{ sec}^{-1}$ and $1.35 \times 10^{-3} \text{ sec}^{-1}$, respectively. The value of stress at 2% yield decreases with slow rate in the entire temperature range without exhibiting a minimum at 525°F, as the fast rate did. With slow prestrain rate, at 525°F, a maximum is seen in the yield stress curve, and slope of stress at 2% yield is even. These characteristics are not shared by fast prestrain rate. At 525°F and 900°F the yield stress with slow rate is higher, and is not much different in the rest of the temperature zone. Maxima are seen in both elongation curves at 525°F, and they run approximately parallel between 525°F to 900°F. The curve with slow prestrain rate shows a slightly higher value in this range. At 300°F elongation obtained with the fast rate is about 30% higher. Reduction in area obtained with slow prestrain rate is higher between 525°F to 900°F, and lower between 450°F to 300°F. This is as expected because the elongation curve also exhibits similar behavior. Between 750°F and 900°F elongation values decrease and reduction in area increases, for both slow and fast rates. This is unusual and is probably brought about by a higher work-hardening rate at 900°F.

3. Post-Tempering Temperature

Figures 14 and 15 show the strain-aging behavior of ausform H-11 steel, austenitized at 2100°F, deformed 87% at 1050°F, air-cooled, double-tempered at 500°F, prestrained 2% at both 300°F and 450°F, and post-tempered at various temperatures.

a. Prestrained at 300°F. Figure 14 shows variation of mechanical properties with post-tempering temperature. Yield and ultimate tensile strength values overlap in the temperature range investigated, i.e.,

from 350°F to 750°F. With increase of post-tempering temperature from 350°F to 600°F, a very slight increase in yield strength from 398,000 psi to 410,000 psi is obtained. Elongation is above 9% up to 500°F, it shows a minimum at 600°F, and then improves to 5% at 750°F. Reduction in area is about 30% at 300°F and 750°F, and shows a minimum of 19% at 600°F.

b. Prestrained at 450°F. Figure 15 is similar to Fig. 14. Yield and ultimate tensile strength values overlap from 350°F to 750°F, separate out at 900°F, and at this temperature show a difference of 28,000 psi. A favorable stress-strain curve is obtained at this temperature without a yield drop. Elongation is above 9% at 300°F and 900°F; it shows a minimum around 600°F. Reduction in area shows a maximum of 30% at 500°F and then decreases to 19.5% at 900°F.

c. Prestrain temperature. Figure 16 shows a variation of physical properties with prestrain temperatures of 300°F and 450°F. Better yield strength is obtained with 300°F prestrain than with 450°F. Both prestrain temperatures show a minimum in the elongation curve at about 600°F. A maximum in reduction of area is obtained at 500°F with 450°F prestrain temperature and at 750°F with 300°F prestrain temperature.

4. Yield Drop

Figure 14 shows the yield drop behavior of ausform H-11 steel, with varying prestrain temperature, along with the yield strength and hardening rate during prestrain. The yield drop with slow rate is always equal to or higher than with fast strain rate. Both curves show a peak between 500°F and 600°F. At 525°F, the difference in yield drop between fast and slow strain rate is maximum, the yield drop obtained with slow rate being almost six times that obtained with fast rate. With slow rate, the yield drop maximum obtained at 525°F coincides with the maximum in

yield stress. The hardening rate with slow and fast prestrain is about the same between 525°F and 900°F, but is much higher for slow prestrain below 525°F.

5. Hardness

The hardness variation of ausform H-11 steel, prestrained 2% (at 150°F, 300°F, and 450°F), is shown in Fig. 18.

a. Prestrain at 150°F. Hardness shows very little variation, with post-tempering from room temperature to 900°F.

b. Prestrain at 300°F. Hardness shows a minimum at 500°F, and two maxima at 350°F and about 650°F. The overall variation of hardness is small with post-tempering temperature up to 900°F.

c. Prestrain at 450°F. Hardness shows a minimum at 750°F and a maximum at 500°F. The amount of variation in hardness observed with this prestrain temperature is higher than that obtained with the 150°F and 300°F prestrain temperatures.

IV. DISCUSSION

A. Elevated Temperature Prestrain

According to Thomas et al.²² the most obvious and important change that occurs during ausforming is an increase in dislocation density; the higher density leads to a greater number of interactions of dislocations creating sites for precipitation of carbides during tempering. All this survives during transformation to martensite leading to an increase in strength. It has been shown that dislocation arrays in the form of sub-boundaries can be inherited by martensite.²⁴ Here it is anticipated that the process of prestraining the samples at elevated temperature, during the strain-aging treatment, would be in some ways analogous to ausforming and would give similar or better results in terms of increase of yield strength and ductility. In both cases the matrix is expected to be supersaturated with carbide forming substitutional solute atoms, and dislocation density is expected to rise during deformation. The higher density of dislocations and dislocation interactions could, here, also create sites for precipitation of carbides during subsequent tempering. BCC structure of tempered martensite and ferrite is "more open" than FCC lattice of austenite, this leads to easier diffusion of solute atoms. From this it was expected that the optimum temperature of deformation for the BCC lattice would be lower than that for FCC lattice. It was found in this investigation that for 900°F post-temper treatment the optimum prestrain temperature was around 525°F for ausform H-11, and around 600°F for conventional H-11 steel. Optimum ausforming temperatures run around 1000°F.

In strain-aging treatments, the prestraining is done mostly at room

temperature and the material is subsequently tempered to develop greater strength, but this generally reduces the ductility. When in the wake of moving dislocations tangled networks and loops are left behind, such regions are known to form nuclei for precipitation, and a large number of nucleation sites result.

In the strain-aging of ausform H-11, where the results have been most promising, it is seen that yield strength of elevated temperatures ($\approx 525^{\circ}\text{F}$) prestrained material is considerably higher ($\approx 40,000$ psi) than that for room temperature prestrained material. The elongation also shows a peak around the same temperature of prestrain. In the case of conventional H-11, though the yield strength obtained by elevated temperature prestraining remains about the same, the elongation shows considerable improvement (increases $\approx 50\%$).

These results indicate that elevated temperature prestraining produces a better combination of strength and ductility than can be obtained by room temperature prestraining.

B. Ausform Vs. Conventional H-11

Under the most favorable conditions, the strength of conventional H-11 was increased from 240,000 to 310,000 psi, i.e., a gain of 29% (70,000 psi) in strength, whereas the strength of ausform H-11 steel increased from 275,000 to 400,000 psi, i.e., a gain of 45% (125,000 psi) was found. The chemical compositions were identical, and so the difference in response could be attributed to the difference in microstructure. Ausform steel always has a finer distribution of martensite plates.²¹

Thus there are more large angle (grain) boundaries, as well as small angle dislocation boundaries that can act as dislocation sources during the prestraining operation. A larger number of dislocation sources

would mean that a larger number of dislocations would be participating during the prestrain deformation in the case of the ausform H-11 steel. The larger number of mobile dislocations interact to a greater extent, leaving more "debris" in the crystals. These highly distorted regions could serve as nucleation sites for the precipitate formed during the strain-aging treatment.

From this it would appear that elevated temperature strain-aging should be more beneficial for ausformed than conventional H-11 steel, and this is consistent with the experimental results.

C. Strain Rate

An increase in self-diffusivity to 3×10^3 times in α iron for variation of strain rate from 0 to $2 \times 10^{-3} \text{ sec}^{-1}$ was observed by Cohen et al.²⁰ Thus it might be expected that strain rate variations would influence the strain-aging behavior. From Figs. 8 and 13 we notice that the value of stress at 2% plastic deformation during prestrain remains the same irrespective of strain rate. Had the amount of precipitation during elevated temperature prestrain been strongly dependent on strain-rate, the strength increase during prestrain would have been strongly strain-rate dependent also.

However no strain-rate effect was observed either in the case of ausform or conventional H-11 steel when the strain rate was varied by a factor of 100. This is evident from the results shown in Figs. 8 and 13.

V. CONCLUSIONS

From this investigation it is concluded that the strength of conventional H-11 and ausform H-11 steel may be considerably increased by suitable strain-aging treatment, without significant loss of ductility. Optimum increase of yield strength in conventional H-11 steel was obtained by prestraining 2% at 750°F with a 1.35×10^{-5} sec⁻¹ strain rate, and post-tempering at 900°F. The yield strength increased from 240,000 psi to 310,000 psi, the elongation decreased from 9.7% to 7.8%, and the reduction-in-area remained constant. A favorable stress-strain curve, i.e., with positive work hardening after the yield drop, was obtained at room temperature (Appendix, Fig. C-900-2-750-5-900).

In ausform H-11 steel, optimum increase of mechanical properties was obtained by prestraining 2% at 300°F with a 1.35×10^{-4} sec⁻¹ rate, and post-tempering at 500°F. The yield strength increased from 275,000 psi to 400,000 psi, the elongation decreased from 11% to 9.5%, and the reduction-in-area remained constant.

During strain-aging the prestrain temperature, prestrain rate, and post-tempering temperature have a marked influence on the final physical properties of the material at room temperature. By a suitable combination of the process variables, desirable mechanical properties can be developed.

As illustrated in Tables III and IV only a few of the possible combinations of process variables were investigated.

These results indicate that the elevated temperature prestraining produces a better combination of strength and ductility than can be obtained by room temperature prestraining. The process is more beneficial for ausformed than conventional H-11 steel, and the strain aging in these steels is insensitive to strain rate.

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APPENDIX

STRESS-STRAIN CURVES

The following tabulation is for use with the group of curves that follow. These show stress-strain autographic records obtained on the Instron machine during the final room-temperature tests.

TABLE A-1

Identifying Numeral or Letter	Position Within Identification	Explanation
A	First	Ausform H-11 Steel
C		Conventional H-11 Steel
900	Second	Material pretempered at 900°F for one hour.
500		Material pretempered at 500°F for one hour, quenched again, then tempered again at 500°F for one hour.
2 4 8	Third	Amount of strain given to material at an elevated temperature in percent before post temper and final pull.
70 300 450 600 750 900	Fourth	Temperature in degree Fahrenheit at which material was prestrained.
3		Strain rate during prestrain = $1.35 \times 10^{-3} \text{sec}^{-1}$.
4	Fifth	Strain rate during prestrain = $1.35 \times 10^{-4} \text{sec}^{-1}$.
5		Strain rate during prestrain = $1.35 \times 10^{-5} \text{sec}^{-1}$.
300 500 600 700 900	Sixth	Temperature in °F at which material was post-tempered for one hour after prestrain and before final room-temperature test.
0		No post-tempering.

For example, A-500/2-300-3/900 would indicate ausformed H-11 steel double tempered at 500°F, strained 2% at 300°F at a strain rate of $1.35 \times 10^{-3} \text{sec}^{-1}$, cooled and post-tempered at 900°F before final room-temperature test.

46 C 900 2 450 3 900

44 C 900 2 450 5 900

45 C 900 0 450 0 900

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FIGURE CAPTIONS

- Fig. 1 Sketch of tensile specimen for conventional H-11 and ausform H-11 steel.
- Fig. 2 Tensile-testing-jig for prestraining specimens at elevated temperature.
- Fig. 3 Assembly of tensile-testing-jig with furnace as mounted on the Instron testing machine.
- Fig. 4 Schematic representation of the sequence of operations performed on conventional H-11 steel.
- Fig. 5 Schematic representation of the sequence of operations performed on ausformed H-11 steel.
- Fig. 6 Strain-aging behavior of conventional H-11 steel pretempered at 900°F, prestrained 2% at different elevated temperatures with a strain rate of $1.35 \times 10^{-5} \text{ sec}^{-1}$, and then post tempered at 900°F.

a) Yield Stress. ($\Delta \dots$) and ultimate tensile ($\bigcirc \text{ ---}$) at room temperature versus prestrain temperature.

b) Reduction in area versus prestrain temperature.

Properties of conventional H-11 without prestrain, tempered at 900°F:

Yield Stress = 236,000 psi

Ultimate Tensile Stress = 306,000 psi

Elongation = 9.7%

Reduction in area = 15%

Stress at 2% yield = 290,000 psi

- c) Stress at 2% yield during prestrain versus prestrain temperature.
- d) Elongation at room temperature versus prestrain temperature.

Fig. 7 Strain-aging behavior of conventional H-11 steel tempered at 900°F, prestrained 2% at different elevated temperatures with a strain rate of $1.35 \times 10^{-3} \text{ sec}^{-1}$, and then post-tempered at 900°F.

- a) Yield stress (Δ ....) and ultimate tensile stress ($\emptyset$ —) at room temperature versus prestrain temperature.
- b) Stress at 2% yield during prestrain versus prestrain temperature.
- c) Elongation at room temperature versus prestrain temperature.
- d) Reduction in area versus prestrain temperature.

Properties of conventional H-11 without prestrain, tempered at 900°F:

Yield Stress	= 236,000 psi
Ultimate Tensile Stress	= 306,000 psi
Elongation	= 9.7%
Reduction in Area	= 15%
Stress at 2% Yield	= 290,000 psi

Fig. 8 Comparison of strain-aging behavior of conventional H-11 steel prestrained at $1.35 \times 10^{-5} \text{ sec}^{-1}$ ($\emptyset$ —) and $1.35 \times 10^{-3} \text{ sec}^{-1}$ (Δ ....). Specimens were: pretempered at 900°F, prestrained 2% at different elevated temperatures with two strain rates as mentioned above, and then post-tempered at 900°F.

- a) Yield stress at room temperature versus prestrain temperature.

- b) Stress at 2% yield during prestrain versus prestrain temperature.
- c) Elongation at room temperature versus prestrain temperature.
- d) Reduction in area at room temperature versus prestrain temperature.

Fig. 9 Strain-aging behavior of conventional H-11 steel pretempered at 900°F, prestrained 2% at 750°F with a strain rate of $1.35 \times 10^{-4} \text{ sec}^{-1}$, and then post-tempered at different temperatures.

- a) Yield and ultimate tensile stress versus post-tempering temperature.
- b) Elongation at room temperature versus post-tempering temperature.
- c) Reduction in area at room temperature versus prestrain temperature.

Fig. 10 Yield drop behavior of conventional H-11 steel during room temperature tests, after the samples had been pretempered at 900°F, prestrained 2% at different elevated temperatures with strain rates of $1.35 \times 10^{-5} \text{ sec}^{-1}$ ($\circ$ —), $1.35 \times 10^{-3} \text{ sec}^{-1}$ (Δ ...), and then post-tempered at 900°F.

- a) Yield stress at room temperature versus prestrain temperature.
- b) Yield drop at room temperature versus prestrain temperature.
- c) Hardening rate during prestrain (at 1% yield) versus prestrain temperature.

Fig. 11 Strain-aging behavior of ausform H-11 steel double tempered at 500°F, prestrained 2% at different elevated temperatures with a strain rate of $1.35 \times 10^{-5} \text{ sec}^{-1}$, and then post tempered at 900°F.

- a) Yield stress ($\Delta \dots$) and ultimate tensile stress ($\circ \text{ ---}$) at room temperature versus prestrain temperature.
- b) Stress at 2% yield during prestrain versus prestrain temperature.
- c) Elongation at room temperature versus prestrain temperature.
- d) Reduction in area from room temperature test versus prestrain temperature.

Properties of Ausform H-11 without prestrain, tempered at 900°F:

Yield Stress	= 275,000 psi
Ultimate Tensile Stress	= 385,000 psi
Elongation	= 11%
Reduction in Area	= 19%
Stress at 2% Strain	= 340,000 psi

Fig. 12 Strain-aging behavior of ausform H-11 steel double tempered at 500°F, prestrained 2% at different elevated temperatures with a strain rate of $1.35 \times 10^{-3} \text{ sec}^{-1}$, and then post-tempered at 900°F.

- a) Yield stress ($\Delta \dots$) and ultimate tensile stress ($\circ \text{ ---}$) at room temperature versus prestrain temperature.
- b) Stress at 2% yield during prestrain versus prestrain temperature.
- c) Elongation at room temperature versus prestrain temperature.

- d) Reduction in area at room temperature versus prestrain temperature.

Properties of ausform H-11 steel without prestrain, tempered at 900°F.

Yield Stress	275,000 psi
Ultimate Tensile Stress	385,000 psi
Elongation	11%
Reduction in Area	19%
Stress at 2% Strain	340,000 psi

Fig. 13 Comparison of strain-aging behavior of ausform H-11 steel prestrained at $1.35 \times 10^{-5} \text{ sec}^{-1}$ (O —) and $1.35 \times 10^{-3} \text{ sec}^{-1}$ (Δ ...). Specimens were double tempered at 500°F, prestrained 2% at different elevated temperatures with two strain rates as mentioned above, and then post-tempered at 900°F.

- Yield stress at room temperature versus prestrain temperature.
- Stress at 2% yield during prestrain versus prestrain temperature.
- Elongation at room temperature versus prestrain temperature.
- Reduction in area at room temperature versus prestrain temperature.

Fig. 14 Strain-aging behavior of ausform H-11 steel, double tempered at 500°F, prestrained 2% at 300°F with a strain rate of $1.35 \times 10^{-4} \text{ sec}^{-1}$, and then post-tempered at different temperatures.

- Yield stress and ultimate tensile stress versus post-tempering temperature.

- b) Elongation at room temperature versus post-tempering temperature.
- c) Reduction in area at room temperature versus prestrain temperature.

Fig. 15 Strain-aging behavior of ausformed H-11 steel double tempered at 500°F, prestrained 2% at 450°F with a strain rate of $1.35 \times 10^{-4} \text{ sec}^{-1}$, and then post-tempered at different temperatures.

- a) Yield stress and ultimate tensile stress versus post-tempering temperature.
- b) Elongation at room temperature versus post-tempering temperature.
- c) Reduction in area versus post-tempering temperature.

Fig. 16 Comparison of strain-aging behavior of ausform H-11 steel prestrained at 300°F ($\Delta \dots$) and 450°F ($\circ \text{ ---}$). Specimens were: double tempered at 500°F, prestrained 2% with a strain rate of $1.35 \times 10^{-4} \text{ sec}^{-1}$ at above temperatures and then post-tempered at different temperatures.

- a) Yield strength versus post-tempering temperature.
- b) Elongation versus post-tempering temperature.
- c) Reduction in area versus post-tempering temperature.

Fig. 17 Yield drop behavior of ausform H-11 steel during room temperature tests, after the samples had been double tempered at 500°F, prestrained 2% at different elevated temperatures with strain rates of $1.35 \times 10^{-5} \text{ sec}^{-1}$ ($\circ \text{ ---}$), $1.35 \times 10^{-3} \text{ sec}^{-1}$ ($\Delta \dots$), and then post-tempered at 900°F.

- a) Yield stress at room temperature versus prestrain temperature.

- b) Yield drop at room temperature versus prestrain temperature.
- c) Hardening rate during prestrain (at 1% yield) versus prestrain temperature.

Fig. 18

- a) Hardness increases as a function of post-tempering temperature for conventional H-11 steel austenitized at 1850°F, aircooled, pretempered at 900°F, prestrained 2% at 750°F with a strain rate of $1.35 \times 10^{-4} \text{ sec}^{-1}$, and then post-tempered at different temperatures for one hour.
- b) Hardness increases as a function of post-tempering temperature for ausform H-11 steel double tempered at 500°F, prestrained 2% at 150°, and post-tempered at different temperatures.
- c) Hardness increase as a function of post-tempering temperature for ausform H-11 steel double tempered at 500°F, prestrained 2% at 300°F, and post-tempered at different temperatures.
- d) Hardness increase as a function of post-tempering temperature for ausform H-11 steel double tempered at 500°F, prestrained 2% at 450°F, and post-tempered at different temperatures.

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