FABRICATION EFFECTS UPON THE STRUCTURE AND PROPERTIES OF SOLID SOLUTION STRENGTHENED HIGH TEMPERATURE ALLOYS

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ABSTRACT

Samples from production sheets of several solid-solution strengthened high temperature alloys were strained by 10 percent and 20 percent and then heat treated at 1040°C (1900°F) and 1120°C(2050°F) to simulate conditions experienced during the manufacture of hardware items. The alloys used in the study were HASTELLOY® alloy X, HAYNES® alloy No. 230, HAYNES alloy No. 188 and INCONEL® alloy 617. Mechanical properties were measured and compared to those of solution annealed material. The microstructure associated with each fabrication cycle was characterized based upon optical microscopy. The variations observed are reported herein.

INTRODUCTION

The widespread use of solid-solution strengthened alloys for high temperature applications is based largely upon the combination of several attractive characteristics, including environmental resistance, strength, and comparative ease of fabrication. However, wrought high temperature alloys are usually supplied by the manufacturer in the solution annealed condition with characteristic microstructures and corresponding properties. Subsequent fabrication and heat treatment processes involved in the production of hardware items can significantly alter these initial mechanical properties. Therefore, potential property changes resulting from production steps should be an important consideration in the alloy selection process or when assessing material performance. This paper presents the results of an effort to investigate the effects of various thermal and mechanical treatments on the microstructure and mechanical properties of several solid-solution strengthened high temperature alloys.

TEST PROCEDURES

The four high temperature sheet alloys that were used in this investigation have the nominal compositions given in Table I. Specimens were obtained from 1.3mm (0.050 in.) thick commercially produced sheet. Alloys X, 188 and 230 were produced by Cabot Corporation while the alloy 617 was produced by Huntington Alloys, Inc. Recommended solution heat treatment temperatures are 1175°C (2150°F) for alloys X, 188 and 617 and 1230°C (2250°F) for alloy 230. All materials were received in the solution annealed condition and possessed the room temperature tensile properties listed in Table II.

In order to simulate strain introduced by fabrication steps, sheet samples were elongated by 10 percent and 20 percent using a stretcher leveling device. (Note however, that while preparing the specimens with 20 percent strain, samples from HAYNES alloy No. 188 began to exhibit edge cracking at 14.6 percent elongation at which point the stretching was terminated). After straining, test specimens were removed from the strained sheets. Since both post weld (or post forming) stress relieving and brazing cycles are often accomplished well below the recommended solutioning temperatures, the effect of these lower temperature excursions on the strained material was examined. For each level of strain, samples from each alloy were annealed for 15 minutes at both 1040°C (1900°F) and 1120°C (2050°F) in an air atmosphere furnace followed by an air cool. For comparison purposes, specimens in the as received condition were also subjected to these annealing cycles. Optical microscopy was used to characterize the resulting microstructures. Room temperature tensile and creep testing was conducted on as-annealed material; no attempt was made to remove the thin oxide layer.

Transverse weld tensile specimens were machined from as-received sheets which had been butt welded together using manual Gas Tungsten Arc Welding (GTAW) and matching composition filler metal. Cylindrical all weld metal pins were machined longitudinally from 15mm (5/8 in.) thick GTAW weld joints in order to obtain weld metal tensile properties.

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® INCONEL is a registered trademark of Inco Family of Companies

TABLE I

Nominal Compositions of Test Materials

Alloy	Ni	Co	Cr	Mo	W	Fe	Si	Mn	C	Al	Others
HASTELLOY alloy X	BAL	1.5	22	9	0.6	18.5	1.0*	1.0*	0.10	--	--
HAYNES alloy No. 188	22	BAL	22	--	14.0	3.0*	0.35	1.25*	0.10	--	0.04 La
HAYNES alloy No. 230	BAL	3.0*	22	2	14.0	3.0*	0.40	0.50	0.10	0.30	0.03 La
INCONEL alloy 617	BAL	12.5	22	9	--	1.5	0.50	0.50	0.07	1.20	0.3 Ti

* Maximum

TABLE II

Room Temperature Tensile Properties of As-Received Material

	0.2% Y.S.		U.T.S.		% Elongation
Alloy	MPa	(ksi)	MPa	(ksi)	in 50mm (2 in)
X	380	(55)	765	(111)	44
188	480	(70)	950	(138)	53
230	385	(56)	870	(126)	48
617	335	(49)	740	(107)	60

RESULTS AND DISCUSSION

Microstructural Features

Changes in grain size as a result of the cold work plus annealing sequences are shown in Table III. Grain sizes of the as received plus annealed (no cold work) specimens remained virtually unchanged.

At the lower annealing temperature of 1040°C (1900°F), microstructural features of the four alloys were similar. Recrystallization was not observed for any of the specimens tested. Only slight increases in grain size were observed for the specimens with prior cold work. However, extensive carbide precipitation was found on twin and grain boundaries as shown in Figure 1 for alloy X. Bending of twin boundaries indicated some residual strain.

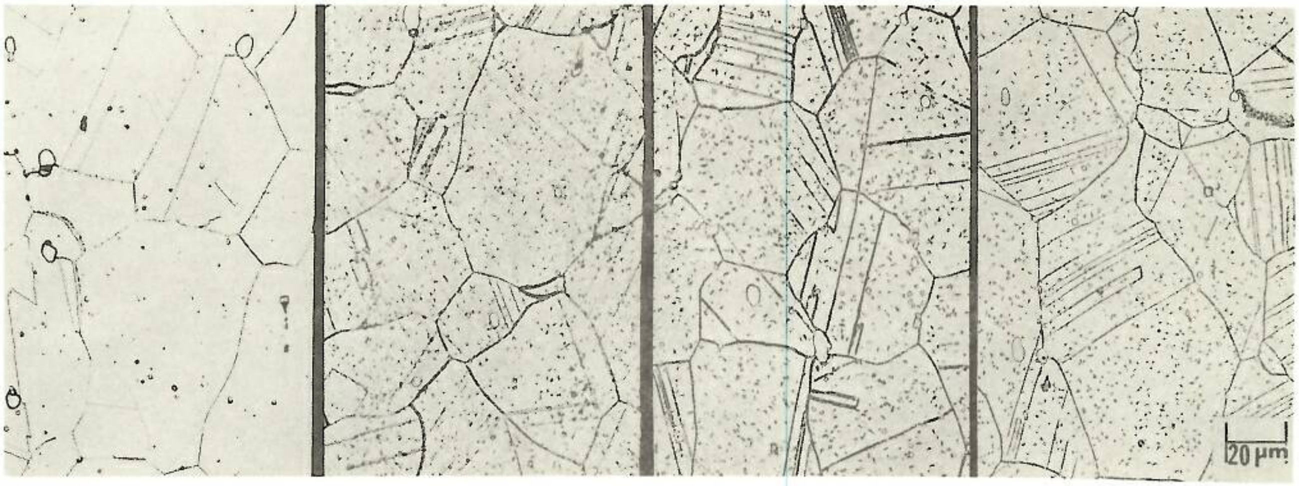
TABLE III

Effect of Cold Work Plus Anneal Upon Sheet Structure

ASTM Grain Size

		1040°C Anneal Following		1120°C Anneal Following	
Alloy	As Received	10% Cold Work	20% Cold Work	10% Cold Work	20% Cold Work
X	5 - 6	5 - 6 (No ReX)	5 - 6 (No ReX)	5 (Partial ReX)	5-1/2 - 7
188	5-1/2 - 6	6 (No ReX)	6* (No ReX)	6 (No ReX)	6* (No ReX)
230	5 - 6	6 (No ReX)	6 (No ReX)	6 (No ReX)	7 - 8
617	3 - 4	2 - 4 (No ReX)	2 - 4 (No ReX)	2 - 4 (No ReX)	2 - 7 (Duplex ReX)

* Alloy 188 acquired only 14.6% Cold Work



As Received 0% Cold Work 10% Cold Work 20% Cold Work

Plus 1040°C Anneal

Figure 1: HASTELLOY alloy X Microstructures

Specimens annealed at the higher temperature (1120°C/ 2050°F) exhibited a range of behaviors. With 10 percent cold work, alloy X showed partial recrystallization while the other alloys remained essentially unrecrystallized. At the higher strain level, all but alloy 188 recrystallized. These differences are clearly seen by comparing the series of microstructures for alloy X (Figure 2) with those for alloy 188 shown in Figure 3. The recrystallized materials were seen to have clean grain boundaries with extensive carbide networks along prior twin and grain boundaries.

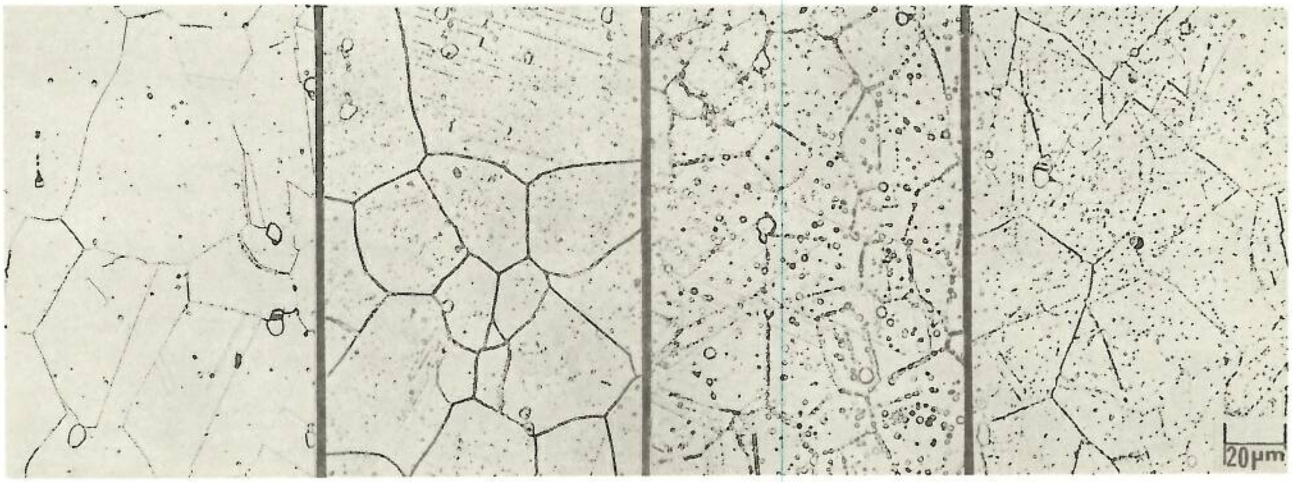
Mechanical Properties

The room temperature tensile properties are listed in Table IV; yield strengths are also compared graphically in Figure 4. Both the yield strengths and the ultimate strengths incresed for each alloy when cold work was followed by the lower temperature anneal. When the 1120°C anneal followed the cold working operation, tensile strengths returned to approximately the as-received values. For this higher annealing temperature, recovery occurred in each case regardless of whether or not recrystallization had taken place.

These results are particularly significant when compared to the values obtained on non-strained samples. Both of the annealing cycles caused varying amounts of carbide precipitation, resulting in a reduction in the amount of carbon (and Cr, etc.) in solution. Any precipitation strengthening effect was greatly overshadowed by the loss of solid solution strengthening. The high temperature anneal caused a reduction of the yield strength in each alloy, while the lower temperature excursion decreased the yield strength in all except alloy 617.

The ductility values followed a similar trend with a decrease in elongation seen after cold work and the 1040°C anneal. Values comparable to as-received properties were found for cold worked specimens which had undergone the higher temperature anneal. Interestingly, the unstrained specimens also exhibited this drop in ductility following the low temperature anneal despite having reduced strength levels, while the 1120°C anneal had little impact on ductility.

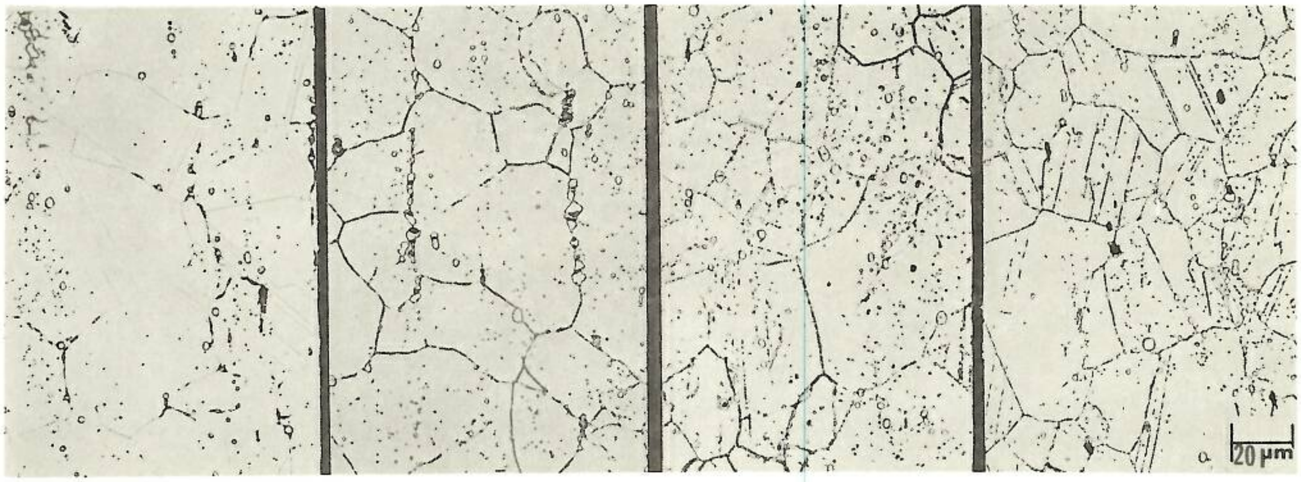
Creep test results are presented in Table V. Those cold worked specimens annealed at 1040°C (1900°F) all had considerably higher creep lives than the as-received



As Received 0% Cold Work 10% Cold Work 20% Cold Work

Plus 1120°C Anneal

Figure 2: HASTELLOY alloy X Microstructures



As Received 0% Cold Work 10% Cold Work 14.6% Cold Work

Plus 1120°C Anneal

Figure 3: HAYNES alloy No. 188 Microstructures

specimens. At 1120°C (2050°F), their creep lives were generally of about the same magnitude as those for the as-received material with the exception of alloy 188. It appears that these creep properties are strongly affected by recrystallization. In the absence of recrystallized stress-free grains, the residual cold work is seen to extend creep life. It has previously been observed for an aluminum alloy(1) and Type 316 stainless steel(2) that pre-straining specimens can extend creep life. The precipitation of secondary M_6C-type carbides in alloys X and 188 or $M_{23}C_6$-type carbides in alloys 230 and 617 appears to be of secondary significance compared to the residual stress level. In the absence of cold work, exposure to temperatures in this carbide precipitation range (prior to creep testing) depletes carbon from the supersaturated matrix. Creep life is thereby reduced(3) since less carbon is available to pin dislocation motion during subsequent creep testing. Recrystallized specimens, which contain secondary carbide precipitation aligned with prior grain boundaries and slip systems, would be expected to have creep lives at least as low as the as-received material. The recrystallized structures were indeed seen to behave in this manner except for the anamolous behavior of alloy 617 at 20 percent cold work and 1120°C anneal.

Finally, the tensile properties of GTAW weld metal and transverse GTAW butt welded specimens are compared to those of the base metal in Table VI. Note that in every case, the yield strength of the weld metal is considerably greater than that of the base metal, while weld metal ductility is significantly lower. In a transverse tensile test, this results in most of the strain being channelled to the wrought structure. Consequently the measured tensile properties of the transverse specimens closely approximate those of the base metal. However, a welded component exposed to tensile stresses can clearly deform non-uniformly.

TABLE IV

Effect of Cold Work Plus Anneal Upon
Room Temperature Tensile Properties

			1040°C Anneal Following			1120°C Anneal Following		
Alloy	Property	As Received	0% Cold Work	10% Cold Work	20% Cold Work	0% Cold Work	10% Cold Work	20% Cold Work
X	0.2% Y.S.(MPa)	401	338	460	474	337	328	328
	U.T.S. (MPa)	792	798	850	842	798	788	793
	% Elong.	43	40	33	33	42	42	42
188	0.2% Y.S.	465	437	616	587*	436	441	441*
	U.T.S.	931	950	1031	1015*	967	978	978*
	% Elong.	53	48	38	39*	50	48	49*
230	0.2% Y.S.	385	360	525	581	344	363	385
	U.T.S.	873	865	943	970	847	853	878
	% Elong.	47	41	33	29	43	37	40
617	0.2% Y.S.	351	357	467	564	321	375	361
	U.T.S.	754	789	857	909	754	785	785
	% Elong.	59	50	40	34	58	48	51

* Alloy 188 acquired only 14.6% Cold Work

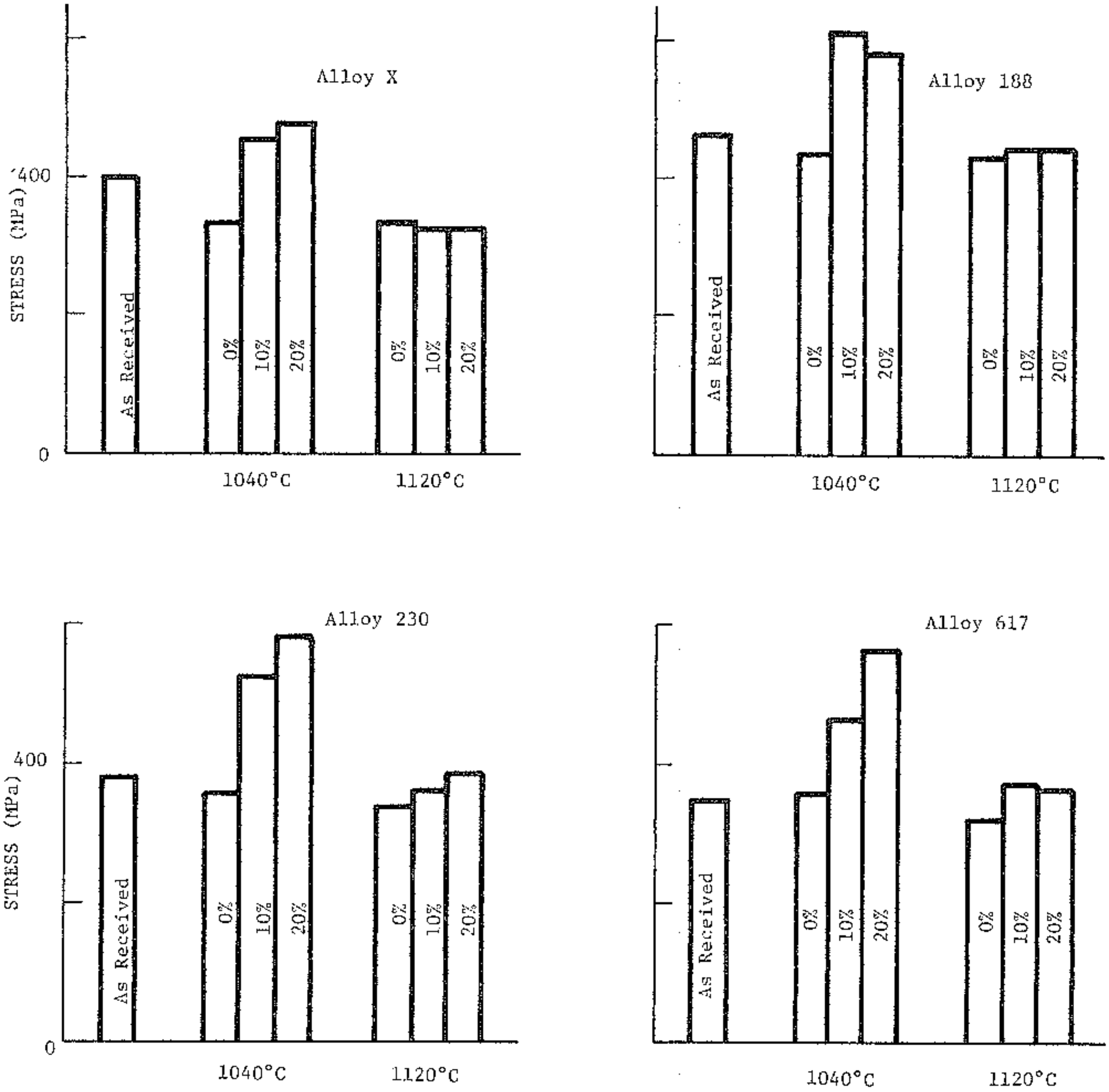


Figure 4: Effect of Cold Work Plus Anneal on Room Temperature 0.2% Yield Strength

CONCLUSIONS

It was found that thermal and mechanical processing of solid-solution strengthened superalloys during component fabrication can induce microstructural changes with corresponding alterations of mechanical properties. While the response to these simulated fabrication cycles was not identical for each alloy, some general tendencies were observed. Most of the mechanical property changes could be explained and even predicted from optical microstructural examination. The exposure of fabricated components which possess localized distributions of residual stress to intermediate annealing temperatures can result in a considerable non-uniformity of mechanical properties. Even the mechanical properties of a "stress-free" structure subjected to a rapid thermal cycle (such as a brazing operation) can be altered considerably. It is concluded that these differences in both structure and properties compared to the solution annealed material can have important implications concerning performance of fabricated components.

TABLE V

Effect of Cold Work Plus Anneal Upon 870°C (1600°F)/48 MPa (7 ksi) Creep Properties

Time to 0.5% Creep Strain, Hours

		1040°C Anneal Following			1120°C Anneal Following		
Alloy	As Received	0% Cold Work	10% Cold Work	20% Cold Work	0% Cold Work	10% Cold Work	20% Cold Work
X	13	7	93	84	6	5	6
188	162	68	575	590*	72	680	622*
230	88	23	1035	352	9	50	12
617	66	28	840	535	8	49	240

* Alloy 188 acquired only 14.6% Cold Work

TABLE VI

Comparison of Weld Metal, Base Metal, and Transverse Welded Tensile Properties

		Room Temperature				
		0.2% Y.S.		U.T.S.		Elongation
Alloy	Material	MPa	(ksi)	MPa	(ksi)	%
X	Base Metal	379	55	739	107	45
	Welded	356	52	760	110	46
	All Weld Metal	503	73	752	109	28
188	Base Metal	476	69	957	139	53
	Welded	461	67	969	141	57
	All Weld Metal	547	79	806	117	39
230	Base Metal	385	56	874	127	45
	Welded	379	55	887	129	46
	All Weld Metal	541	78	676	98	20
617	Base Metal	323	47	727	106	62
	Welded	328	48	741	108	61
	All Weld Metal	515	75	796	116	27

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