SOME EFFECTS OF HOT WORKING PRACTICE
ON WASPALOY'S STRUCTURE AND TENSILE PROPERTIES

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Abstract

In order to gain a pragmatic understanding of the influence of hot working variables on Waspaloy's tensile properties, an experimental hot rolling program was executed in which the effects of preheat temperature, percent reduction and finish temperature were investigated.

Slabs were rolled following preheats at temperatures ranging from 2050F to 2250F. Slabs rolled from 2125F were reduced with heavy (49%), medium (33%) and light (18%) reductions. Also, slabs rolled from 2125F receiving 33% reduction were finish deformed at 1760F, 1900F, and 1940F.

The mechanical property results revealed that (a) tensile strength is strongly dependent upon finish temperature and moderately dependent upon reduction, and (b) tensile ductility is strongly dependent on reduction and slightly dependent on finish temperature. Moreover, preheat temperature, in the range studied, is relatively unimportant, provided proper reductions with a satisfactory finish deformation temperature are employed.

A generally finer grain size accounted for the somewhat higher tensile strengths of (a) the slab rolled from 2050F and (b) the slab that received a heavy reduction. However, rather large tensile strength variations were found with little difference in grain size. The specimen intentionally finish deformed at 1940F, which displayed the lowest tensile strength, possessed a γ' and dislocation structure considerably different from the specimen finish deformed at 1760F, which exhibited the highest tensile strength. In addition, the specimen experiencing the heavy reduction schedule showed the best tensile ductility, presumably due to the low concentration of grain boundary phases.

Although Waspaloy is categorized as a γ' precipitation strengthened superalloy, its tensile strength is markedly influenced by the dislocation structure generated via thermal-deformation processing.

Introduction

Waspaloy is a wrought nickel-base superalloy which has faithfully served for many years in jet engines as turbine blades and as turbine and compressor discs. In turbine blade applications, creep and stress rupture properties are paramount, so the first stage of the heat treatment is above the γ' solvus temperature within the 1950F to 1975F range. However, in disc applications where tensile and low cycle fatigue properties are of greatest concern, the first stage of the heat treatment is below but near the γ' solvus temperature; i.e., in the 1825F to 1875F range.

Hot working practice is known to have a marked effect on Waspaloy's structure and mechanical properties; however, there is a dearth of systematic information available on the effects of preheat temperature, reduction and finish temperature upon the microstructure and mechanical properties of Waspaloy⁽¹⁾ and other superalloys^(2,3,4,5). Donachie et al⁽¹⁾ published an enlightening paper on the effect of hot work on

Waspaloy's properties, but they were concerned with turbine blade applications for which the first stage of the heat treatment is ordinarily 1975F/4hrs.

The purpose of the present investigation was to determine the influence of hot working practice on Waspaloy's structure and tensile properties transverse to the direction of metal flow when the alloy is used in disc applications. The aim was to assist the forgers in hot working Waspaloy to produce consistently good room temperature and 1000F tensile properties. Throughout this study the first stage of the heat treatment was 1865F/4hrs/Oil Quench. The effort concentrated on room temperature tensile properties, especially as they were related to optical and electron microstructures.

Experimental Procedure

The test slabs, which had been cut from a 10-inch round billet converted from a 20-inch VIC ingot, were 2-inches thick x 6-inches wide x 10-inches long. The chemical analysis of this particular Waspaloy heat is recorded in Table 1.

The relatively large test slab size was used to provide sufficient test material and to allow considerable heat reduction during rolling. Hot rolling of the test slabs was carried out at roll speed of 16 in/sec on a pilot plant Birdsboro hot mill which has 15-inch diameter rolls. Thermodots, which operate on infrared radiation, were mounted on each side of the mill to monitor the surface temperature of the slab. The finish temperatures, which were measured by the thermodots, should be regarded as relative values ($\pm 20F$) and not as precise readings.

The hot rolling program consisted of three sections as follows:

Effect of Preheat Temperature: Seven test slabs were soaked two hours at the following preheat temperatures: 2050F, 2125F, 2150F, 2175F, 2200F, 2225F, and 2250F. After this single heating, the slabs were transferred to the rolling mill and rolled from a thickness of about 2.15-inches to 1.44-inches in five passes as follows: 2.15-inches $\rightarrow$ 1.97-inches (8.4%) $\rightarrow$ 1.80-inches (8.6%) $\rightarrow$ 1.67-inches (7.2%) $\rightarrow$ 1.55-inches (7.2%) $\rightarrow$ 1.44-inches (6.7%). The rolling sequence produced a total reduction of approximately 33% following a single heating. Finish or off-mill temperature varied considerably but the aim was the 1900F to 1850F range.

Effect of Finish Temperature: Two test slabs were soaked at 2125F for two hours and rolled with the same pass schedule as described in the previous paragraph, but the deformation-temperature sequences were adjusted to aim for a 1950F finish on one slab and a 1750F finish on the other slab. This was accomplished through proper timing of the pass schedule coordinated with the thermodot readings. The finish temperature of the former slab was measured as 1940F and of the latter slab was 1760F. A screeching sound was emitted by the slab finished at 1760F.

Effect of Reduction: Two test slabs were soaked for two hours at 2125F and rolled with lighter and heavier pass schedules than that described earlier. The slab which

Table 1

Chemistry (Wt. %)

<u>C</u>	<u>Mn</u>	<u>Si</u>	<u>Cr</u>	<u>Ni</u>	<u>Co</u>	<u>Fe</u>	<u>Mo</u>	<u>Ti</u>	<u>Al</u>	<u>B</u>	<u>Zr</u>	<u>S</u>	<u>P</u>	<u>Cu</u>
.06	<.10	<.10	19.4	Bal.	14.0	.14	4.15	3.10	1.35	.005	.07	.003	<.01	<.10

received the lighter reduction was rolled as follows: 2.00-inches → 1.90-inches (5.0%) → 1.80-inches (5.3%) → 1.75-inches (2.8%) → 1.69-inches (3.4%) → 1.64-inches (3.0%). This rolling sequence produced a total reduction of about 18%. The heavier reduction schedule consisted of the following: 2.10-inches → 1.74-inches (18.0%) → 1.53-inches (12.0%) → 1.35-inches (11.8%) → 1.18-inches (12.6%) → 1.06-inches (10.2%) which resulted in a total reduction of about 49%.

Mechanical Testing Technique

The transverse, mid-thickness test specimens were cut so that the gage length corresponded to the middle, 3-inch region of the 6-inch wide test slabs. The test specimen blanks were heat treated as follows: 1865F/4hrs/Oil Quench+1550F/4hrs/Air Cool+1400F/16hrs/Air Cool. Diameter of the test specimens was .250-inch. The strain rate during tensile testing was .005 in/in/min. up to the yield and .075 in/in/min. after yield. The slabs were tested in the transverse direction to learn the material's mechanical property behavior under severe conditions.

Microscopy Techniques

Kallings reagent was used for etching specimens examined on the light microscope. Specimens for replication electron microscopy were electropolished in a solution of 7 parts methanol, 1 part sulfuric acid and 0.6 parts hydrochloric acid with a stainless steel beaker as the cathode. Then the electropolished specimens were immersion etched in a dilute solution (1:4) of Marble's reagent. Chromium shadowed parlodian replicas were prepared.

Thin foils were prepared as follows. Roughly 1/8-inch thick wafers were cut from the slabs. The wafers were spark machined to about 10 mils and prethinned to about 5 mils by the open cell method using Disa A-3 electrolyte. Final thinning was done on a dual jet apparatus in which twin jets of Disa A-3 electrolyte were impinged on each side of the prethinned disc until perforation occurred.

Results and Discussion

No serious hot workability problems were encountered during the rolling. A few shallow edge cracks developed on the slab given the heavy reduction schedule. Although test slabs were rolled from preheat temperatures as high as 2250F with a total reduction of 33%, no edge cracking resulted from overheating. Gleeble testing has indicated that Waspaloy displays satisfactory hot ductility following preheats as high as 2250F⁽⁶⁾. However, the recommended maximum preheat temperature is 2200F which allows higher hot ductility than a 2250F preheat, which is near Waspaloy's zero-ductility temperature as determined by Gleeble testing⁽⁶⁾. More commonly Waspaloy is forged from temperatures in the 2050F to 2150F range, where hot ductility is quite good.

Effect of Preheat Temperature on Structure and Tensile Properties

The preheat or furnace temperature used during preliminary conversion of an ingot or billet is ordinarily fixed by the maximum temperature from which the material may be hot worked without excessive cracking. However, during fabrication of parts, the purported effect of preheat temperature on mechanical properties is the over-riding consideration.

With the exception of the slab rolled from 2050F, optical microstructural examination revealed only slight variations in the as-worked grain size. All specimens were characterized by dynamically recrystallized⁽⁷⁾ grains with some dynamically

unrecrystallized grains interspersed*. Excluding the slab rolled from 2050F, there were no striking trends in the optical microstructure as a function of preheat temperature. The slab rolled from 2050F (Figure 1) had the highest population of dynamically unrecrystallized grains but the finest, dynamically recrystallized grains, obviously indicating that the dynamically recrystallized regions deformed at the expense of the large, dynamically unrecrystallized regions. The presence of a high concentration of dynamically unrecrystallized grains in the slab rolled from 2050F is consistent with an earlier study in which it was learned that deformation temperatures below 2000F tend to foster the development of dynamically unrecrystallized grains^(8,9).

The slabs rolled from preheat temperatures of 2125F to 2250F possessed similar grain structures with minor, spasmodic variations in the amount of dynamically recrystallized grains and slight differences in the average grain size. The microstructures of the slabs rolled from 2225F (Figure 2) and 2250F (Figure 3) are typical of this group of slabs. Incidentally, all optical photomicrographs displayed in this paper represent the as-hot rolled condition since no change in grain structure was observed within 4 hours as long as the first stage of the heat treatment was 1875F or below.

Transverse room temperature tensile data on the slabs rolled from various preheat temperatures are presented in Table 2 and Figure 4. There is considerable scatter in the data suggesting that some other variable has influenced the results more powerfully than preheat temperature. Although the slab rolled from 2050F contained the finest, dynamically recrystallized grains and showed higher strength than most of the other slabs, it was not the strongest. The slab rolled from 2250F, whose dynamically recrystallized grain size was larger than that of the slab rolled from 2050F, was the strongest. In fact, the slabs rolled from 2250F (Figure 3) and 2225F (Figure 2) possess practically the same grain structure but the former's yield strength surpassed the latter's by approximately 15 ksi. Thus, grain size, within the limits studied, is not the most important structural feature affecting Waspaloy's tensile strength. Also, some hot working parameter other than preheat temperature has greater control over tensile strength.

Effect of Finish Temperature on Structure and Tensile Properties

Finish temperature (surface temperature at exit from the mill) is a variable distinctly different from the preheat (furnace) temperature but often the two variables are not clearly distinguished in the literature. Finish temperature is generally limited by (a) capabilities of the press or mill, (b) lowest temperature at which the material can be deformed without excessive cracking or (c) mechanical property or microstructural considerations.

To establish the effect of finish temperature on Waspaloy's structure and properties, two slabs were preheated at 2125F, rolled from 2.10-inches to 1.44-inches in five passes as described earlier and finished at 1940F and 1760F. The slab previously rolled from the 2125F preheat was finished at 1900F and was suitable for inclusion in evaluation of the effect of finish temperature.

* Dynamically recrystallized grains are those grains that have recrystallized under the combined influence of load and temperature, e.g., during hot working. Statically recrystallized grains are those grains that recrystallize in the absence of load under the influence of temperature. Dynamically unrecrystallized grains are those grains which have statically recrystallized at the preheat temperature but have not dynamically recrystallized during hot working.

Table 2

Effect of Preheat Temperature on Waspaloy's Transverse Tensile Properties

<u>Specification</u>	<u>Room Temp. Tensile</u>				<u>1000F Tensile</u>			
	<u>U.T.S.</u> <u>(Ksi)</u>	<u>Y.S.</u> <u>(Ksi)</u>	<u>Elong.</u> <u>(%)</u>	<u>R.A.</u> <u>(%)</u>	<u>U.T.S.</u> <u>(Ksi)</u>	<u>Y.S.</u> <u>(Ksi)</u>	<u>Elong.</u> <u>(%)</u>	<u>R.A.</u> <u>(%)</u>
PWA 1016E	180.0	125.0	15.0	18.0	160.0	110.0	15.0	18.0
PWA 1027C	190.0	137.5	10.0	13.0	170.0	125.0	11.0	12.0
<u>Preheat Temp./</u> <u>Reduction/Finish</u> <u>Temp.</u>								
<u>2050F/33%/</u> <u>1860F</u>	191.5 190.8	135.0 132.0	19.1 19.1	19.2 18.7	171.5	119.0	18.8	21.3
<u>2125F/33%/</u> <u>1900F</u>	188.0 188.9	126.2 127.0	17.7 18.9	16.5 17.2	167.0	113.3	20.4	20.9
<u>2150F/33%/</u> <u>1910F</u>	192.6 193.1	130.0 128.3	21.4 24.2	20.3 21.8	171.0	114.5	22.1	24.0
<u>2175F/33%/</u> <u>1940F</u>	188.6 187.2	125.9 125.3	19.1 19.0	17.6 18.0	168.0	112.5	20.3	23.6
<u>2200F/33%/</u> <u>1860F</u>	187.0 191.0	130.0 128.5	15.4 21.1	15.8 19.7	170.0	115.0	22.0	25.9
<u>2225F/33%/</u> <u>1940F</u>	188.0 190.0	128.5 130.0	18.0 18.5	16.8 18.6	168.5	113.0	18.8	23.0
<u>2250F/33%/</u> <u>1800F</u>	196.0 197.0	142.0 142.0	22.1 19.8	22.0 20.7	177.0	124.7	18.5	21.5

Metallographic examination revealed a slightly larger grain size in the slab finished at 1940F (Figure 5) as compared with the slab finished at 1760F (Figure 6). In general, the microstructures of these slabs were essentially the same.

Transverse tensile data on the slabs preheated at 2125F, reduced 33%, and finished at 1940F, 1900F and 1760F are posted in Table 3 and plotted in Figure 7. It is readily apparent that finish temperature has a strong influence on tensile strength. In addition, there appears to be a slight, favorable effect on room temperature tensile ductility. A dependence of strength on hot working temperature for Pyromet 860 was reported by Whitney and Krauss⁽²⁾. These investigators found that hot working below the γ' solvus temperature brought about an increase in tensile strength. Furthermore, from the work of Donachie and co-workers⁽¹⁾, it can be inferred that a low finish deformation temperature has a beneficial influence on Waspaloy's tensile ductility due to the manner in which carbide particles precipitate. That is, deleterious carbide layers form with high finish temperatures (>1925F) causing a decrease in tensile ductility. It is conceivable, however, that sufficiently heavy reductions at temperatures in the vicinity of 1750F would degrade tensile ductility because the detrimental influence of a work-hardening effect on tensile ductility

Table 3

Effect of Finish Temperature on Waspaloy's Transverse Tensile Properties

<u>Specification</u>	<u>Room Temp. Tensile</u>				<u>1000F Tensile</u>			
	<u>U.T.S.</u> <u>(Ksi)</u>	<u>Y.S.</u> <u>(Ksi)</u>	<u>Elong.</u> <u>(%)</u>	<u>R.A.</u> <u>(%)</u>	<u>U.T.S.</u> <u>(Ksi)</u>	<u>Y.S.</u> <u>(Ksi)</u>	<u>Elong.</u> <u>(%)</u>	<u>R.A.</u> <u>(%)</u>
PWA 1016E	180.0	125.0	15.0	18.0	160.0	110.0	15.0	18.0
PWA 1027C	190.0	137.5	10.0	13.0	170.0	125.0	11.0	12.0
<u>Finish Temp./</u> <u>Preheat Temp./</u> <u>Reduction</u>								
<u>1940F/2125F/</u> <u>33%</u>	184.0 182.0	122.0 125.0	19.0 17.1	18.7 18.6	164.0	111.0	19.1	21.1
<u>1900F/2125F/</u> <u>33%</u>	188.0 188.9	126.2 127.0	17.7 18.9	16.5 17.2	167.0	113.0	20.4	20.9
<u>1760F/2125F/</u> <u>33%</u>	194.0 193.6	143.0 144.6	24.1 20.2	23.6 20.2	173.5	131.5	18.4	20.7

could override the favorable effect of non-continuous grain boundary carbides. However, a loss of tensile ductility due to excessive reductions has not been observed to date.

The slab finished at 1760F had only a slightly finer grain size but considerably better strength and somewhat better ductility than the slab finished at 1940F. These results further substantiate the contention that grain size is not the most important structural feature influencing Waspaloy's tensile strength.

The finish temperature of the slabs rolled from various preheat temperatures vacillated rather widely. So, that mechanical property data were plotted versus finish temperature as shown in Figure 8. When the data are plotted in this way, it becomes evident that finish temperature was the critical factor dominating the room temperature tensile properties of the slabs rolled from various preheat temperatures.

The finish temperatures of the slabs preheated at 2175F and 2225F in the previous section and plotted in Figure 8 were measured as 1940F, the same finish temperature measured on the hot finished slab in this section. Why do these three slabs show different tensile strengths? The mill separating forces on the final pass for the slabs preheated at 2175F and 2225F, which were inadvertently finished at 1940F, were higher than that for the slab intentionally finished at 1940F. This information suggests that the slab intentionally finished at 1940F was either slightly hotter or received a lighter final pass reduction than the other slabs whose finish temperature was measured as 1940F. In fact, the correlation between tensile strength and the mill separating force on the last pass was monotonic - the higher the mill separating force, the higher the tensile strength.

Effect of Reduction on Structure and Tensile Properties

During hot working, the reduction per reheat is usually limited by the development of unacceptably deep, surface cracks. However, if the reduction is too small, grain

growth or other undesirable structural changes may occur causing mechanical properties to suffer.

Reduction is a hot working variable of utmost importance⁽¹⁾. To demonstrate its effect, two test slabs were preheated at 2125F and rolled to produce total reductions of 18% and 49%, and, thereby, bracket the 33% obtained in the section on preheat temperature.

The most striking microstructural feature of this portion of the study was the noticeably finer grain size exhibited by the slab which received the heavy reduction (Figure 10), especially when compared with the slab that experienced the light reduction (Figure 9). It was previously learned that to produce a uniform, dynamically recrystallized grain structure a heavy total reduction (>50%) within the 2000F to 2150F range was required^(8,9). Light reductions or deformation temperatures outside the 2000F to 2150F range promote the presence of dynamically unrecrystallized grains.

The salient characteristic of the transverse tensile data as a function of reduction, as recorded in Table 4 and depicted in Figure 11, is the beneficial influence of a heavy reduction on tensile ductility. This relationship was also observed by Donachie et al⁽¹⁾. The fine grain size displayed by the heavily deformed slab is apparently responsible for the superb tensile ductility since less MC would be able to form in the final grain boundaries. Tensile strength was also increased by the heavy reduction; however, within the variable limits studied, reduction was not as powerful as finish temperature in boosting tensile strength.

To distinctly demonstrate the damaging influence of no deformation⁽¹⁾, material was preheated two hours at 2125F but was not rolled. Following full heat treatment, the transverse room temperature tensile properties were as follows: U.T.S. - 132 to 136 ksi, Y.S. - 107 to 109 ksi, elongation - 4 to 7%, R.A. - 6 to 8%. These degraded properties clearly show that deformation is essential to the attainment of satisfactory tensile properties following heating at temperatures above the γ' solvus.

Table 4

Effect of Reduction on Waspaloy's Transverse Tensile Properties

<u>Specification</u>	<u>Room Temp. Tensile</u>				<u>1000F Tensile</u>			
	<u>U.T.S.</u> <u>(Ksi)</u>	<u>Y.S.</u> <u>(Ksi)</u>	<u>Elong.</u> <u>(%)</u>	<u>R.A.</u> <u>(%)</u>	<u>U.T.S.</u> <u>(Ksi)</u>	<u>Y.S.</u> <u>(Ksi)</u>	<u>Elong.</u> <u>(%)</u>	<u>R.A.</u> <u>(%)</u>
PWA 1016E	180.0	125.0	15.0	18.0	160.0	110.0	15.0	18.0
PWA 1027C	190.0	137.5	10.0	13.0	170.0	125.0	11.0	12.0
<u>Reduction/</u> <u>Preheat Temp./</u> <u>Finish Temp.</u>								
<u>18%/2125F/</u> <u>1900F</u>	179.0 183.0	127.0 128.0	16.0 16.1	17.3 17.1	162.0	116.0	17.6	23.4
<u>33%/2125F/</u> <u>1900F</u>	188.0 188.9	126.2 127.0	17.7 18.9	16.5 17.2	167.0	113.3	20.4	20.9
<u>49%/2125F/</u> <u>1890F</u>	198.0 199.0	138.0 138.0	27.7 25.4	29.8 27.8	180.0	124.0	23.5	27.4

Consequently, areas in a workpiece which have experienced little or no deformation following a preheat above the γ' solvus would possess poor tensile properties.

Replication and Thin-Foil Electron Microscopy

It has been clearly shown that finish temperature and reduction are the most crucial factors in determining Waspaloy's tensile properties. Why do finish temperatures below the γ' solvus temperature elevate Waspaloy's tensile strength? Why do heavy reductions improve Waspaloy's tensile ductility? To answer these questions replication and thin-foil electron microscopy were performed. Fully heat treated longitudinal sections were used for preparing replicas, but the longitudinal wafers used for thin-foil examination received only the first stage of the heat treatment (1865F/4hrs/Oil Quench) since the fine γ' that develops in the full heat treatment obscures the dislocation structure.

Distinct differences in γ' and dislocation structures were observed between the slabs finished at 1940F (Figures 12 and 13) and 1760F (Figure 14). In the former, there were relatively large regions with just fine γ' and no coarse γ' mixed with some areas of both fine and coarse γ' . This type of γ' structure has been seen by others⁽¹⁰⁾. Furthermore, those areas which contained no coarse γ' also contained practically no dislocations while the areas which contained coarse γ' contained short, diffuse dislocations. In contrast, the slab finished at 1760F consisted of coarse and fine γ' throughout but the pronounced, cellular dislocation pattern was the outstanding characteristic of this slab. The coarse γ' population in slabs rolled from various preheat temperatures correlated with the finish temperature, the coarse γ' population increased with lower finish temperatures.

As the Ti+Al content is increased the γ' solvus temperature is raised⁽¹⁰⁾; thereby, improving the chances that a wrought part will have been finish deformed below its γ' solvus temperature and contain both coarse and fine γ' throughout.

Since the alignment of the primary MC particles into distinct stringers degrades transverse tensile ductility, the current trend in Waspaloy is to lower the carbon level to mitigate the effects of MC stringers. Reducing the carbon level increases the effective Ti content by releasing Ti which would otherwise be tied up as MC. The higher effective Ti content increases the γ' concentration, raises the γ' solvus temperature and thereby increases the likelihood of retaining a cellular dislocation structure.

The coarse γ' develops during the first stage of the heat treatment because certain γ' particles grow after others have dissolved. The irregular coarse γ' structure is caused by finish temperatures that are too hot but is aggravated by retained, dendritic segregation which results in variations in the Ti+Al content from one micro-spot to another. Consequently, in a workpiece finished somewhat too hot the coarse γ' concentration fluctuates from region to region. Owing to retained, dendritic segregation, the regions enriched in Ti+Al will possess both coarse and fine γ' while the regions impoverished in Ti+Al will possess only fine γ' . If the finish deformation temperature was sufficiently high to exceed the γ' solvus temperature everywhere, the entire sample would contain only fine γ' without any coarse γ' or a significant dislocation concentration. On the other hand, if the finish deformation temperature was low enough to reside below the γ' solvus temperature in every region, then coarse and fine γ' plus a substantial dislocation population would exist throughout.

Thus, it appears that the finish deformation temperature and the resultant dislocation structure influences the solubility of γ' in γ . A high, finish deformation

temperature increases the solubility of γ' in γ in certain regions, consequently allowing no coarse γ' to develop or a significant dislocation population to remain. Not only do γ' particles stabilize the dislocation structure formed during hot working but the retained dislocation structure enables the γ' particles to resist complete dissolution during the first stage of the heat treatment.

The well-developed, cellular dislocation structure increased the room temperature and 1000F yield strengths of the slab finished at 1760F by about 20 ksi relative to the slab finished at 1940F. Similarly, preservation of a dislocation substructure developed during hot working has been found to appreciably strengthen Armco iron, silicon steel and aluminum at room temperature⁽¹¹⁾.

The slab intentionally finished at 1940F was the only one to exhibit a static recrystallization temperature noticeably different from other samples. Static recrystallization occurred in most slabs within 4 hours at a temperature between 1875F and 1900F. In contrast, the slab finished at 1940F statically recrystallized within 4 hours at a temperature between 1900F and 1925F. Apparently, the absence of a significant dislocation structure delayed static recrystallization. Presumably, well-developed dislocation centers constitute recrystallization nuclei. The premature complete dissolution of γ' in certain regions did not trigger static recrystallization in the slab intentionally finished at 1940F because the dislocation structure was inadequate. In a sample containing a pronounced dislocation structure, ordinarily static recrystallization immediately follows the complete dissolution of γ' since the dislocation complexes act as recrystallization nuclei.

There were no differences in the γ' structure of the slabs rolled with light (Figure 15) and heavy (Figure 16) reductions. However, as might be expected, the specimen which experienced the heavy reduction schedule contains a lower concentration of grain boundary carbides than the specimen which received a light reduction schedule. The former's grain size was much finer than the latter's, providing greater grain boundary surface and therefore a lower grain boundary phase density. These two slabs displayed virtually the same dislocation structure - short, diffuse dislocation in some areas plus long, discrete dislocations in tangles in other areas. The cleaner grain boundary structure of the heavily deformed slab is probably responsible for its superior tensile ductility.

Thin-foil microscopy has demonstrated that dislocation strengthening should be an essential ingredient in producing Waspaloy parts capable of meeting the greater demands being placed on Waspaloy's tensile strength. Replication electron microscopy has indicated that a reduced concentration of grain boundary carbides enhances Waspaloy's tensile ductility.

Summary

Although Waspaloy is regarded as a γ' precipitation strengthened superalloy, its properties are determined by thermal-deformation techniques as well. Regrettably, the importance of the hot working practice is often neglected not only in commercial operations but also in alloy development and alloy modification.

It has been demonstrated that a heavy reduction improves Waspaloy's tensile ductility markedly and tensile strength moderately. Enhancement of the ductility has been attributed to the lower, grain boundary phase concentration resulting from the fine grain size. While, the higher strength results from the fine grain size consistent with a Hall-Petch relationship.

Also, it was shown that a finish deformation temperature below the γ' solvus temperature is desirable in order to produce high tensile strength. A low finish deformation

temperature (in the 1725F to 1825F range) for the reductions studied is not detrimental to tensile ductility and, in fact, is slightly beneficial compared to a finish deformation temperature above 1925F.

Replication electron microscopy disclosed that the sample intentionally finish deformed at 1940F exhibited an irregular γ' structure - areas of fine γ' only mixed with areas of fine and coarse γ' . All other samples displayed a uniform γ' structure - coarse and fine γ' throughout. Thin-foil electron microscopy showed that, in the slab intentionally finish deformed at 1940F, the regions which contained no coarse γ' also contained virtually no dislocations while the regions which did possess some coarse γ' displayed short, diffuse dislocations. In contrast, a well-developed, cellular dislocation network was found in the slab finish deformed at 1760F. These observations clearly illustrate that the γ' solubility and the dislocation structure are dependent upon the finish deformation temperature. Furthermore, a suitable dislocation structure can certainly boost Waspaloy's room temperature and 1000F yield strengths at least 15 ksi and probably as much as 30 ksi above the primarily γ' strengthened matrix strengths, which are approximately 125 ksi and 115 ksi respectively when the grain size is in the ASTM 5 to 6 range.

Moreover, preheat temperatures in the 2050F to 2250F range did not have a dominant effect on tensile properties. However, preheat temperature is potentially important to tensile strength because it may influence the finish deformation temperature. That is, a workpiece preheated at 2150F, for example, and finish deformed 100F above the γ' solvus temperature would display noticeably lower tensile strength than a workpiece preheated at 2050F and finish deformed 100F below the γ' solvus temperature. In addition, preheat temperature is crucial if light reductions are taken⁽¹⁾. In the case of light (<40%) reductions, the preheat temperature should be lowered to a temperature slightly above or below the γ' solvus temperature. For heavy (>40%) reductions, the preheat temperature is relatively unimportant provided the total reduction is taken in sequences and the finish deformation temperature is 50F or more below the γ' solvus temperature. If a heavy reduction is to be taken, it is preferable to set the preheat temperature so that a considerable portion of the deformation lies somewhere in the 2150F to 2000F range so as to produce predominantly fine, dynamically recrystallized grains with a minimum of coarse, dynamically unrecrystallized grains.

Subsequent work on Waspaloy has verified that its transverse room temperature ultimate and yield strengths can be increased to the vicinity of 200 ksi and 155 ksi respectively while maintaining elongation and reduction in area in the neighborhood of 22% and 25%, respectively. These property levels were attained in samples rolled from blocks cut from billet. Following the final reheat operation, the four pass reductions were about 44% and the finish deformation temperature was around 1750F with a 16% pass reduction. A substantial portion but not all of the deformation was below the γ' solvus temperature.

Recommendations

In order to achieve optimum tensile properties in Waspaloy, it is advisable to take a heavy total reduction (40 to 70%) and finish deform (with 10 to 30% pass reductions) at temperatures below the γ' solvus temperature; e.g., in the 1725F to 1825F range. Processing of this type may be accomplished by (a) deforming in sequential operations following a single heating, (b) deforming in sequential operations following more than one operation whereby the preheat temperature is appropriately reduced with each successive operation, or (c) deforming at a properly adjusted strain rate so that the piece is continuously being worked as the temperature decreases.

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References

1. M. J. Donachie, A. A. Pinkowish, W. P. Danesi, J. F. Radavich, and W. H. Coutts, "Effect of Hot Work on the Properties of Waspaloy", Metallurgical Transactions, Volume 1, September 1970, pp. 2623-2630.
2. C. R. Whitney and G. Krauss, "Effects of Titanium and Aluminum Variations on an Iron-Nickel Superalloy", Metals Engineering Quarterly, November 1971, pp. 25-30.
3. D. R. Muzyka, "Effects of Solution Treating Temperature and Microstructure on the Properties of Hot Rolled 718 Alloy", ASM Westec Paper, 1969.
4. R. K. Hotzler, R. J. Maciag, G. J. Fischer, and E. Troc, "Thermomechanical Working of Astroloy", Metallurgical Transactions, Volume 1, April 1970, pp. 963-967.
5. J. M. Oblak and W. A. Owczarski, "Thermomechanical Precipitation-Hardened Nickel-Base Alloy", Metallurgical Transactions, Volume 3, March 1972, pp. 617-626.
6. R. E. Bailey, "Hot Working Data on Alloy 718 and Waspaloy Generated Through Use of the Gleeble", Allegheny Ludlum Research Report SP-68-4, August 19, 1968.
7. M. J. Luton and C. M. Sellars, "Dynamic Recrystallization in Nickel and Nickel-Iron Alloys During High Temperature Deformation", Acta Metallurgica, Volume 17, August 1969, pp. 1033-1043.
8. R. E. Bailey, "Microstructural Examination of Waspaloy and AL-718 Gleeble Hot Workability Test Specimens", Allegheny Ludlum Research Report SP-69-9, September 2, 1969.
9. R. E. Bailey, "Ductility of Waspaloy Under Simulated Hot Working Conditions", Paper Presented at 1970 AIME Meeting in Las Vegas.
10. W. P. Rehrer, D. R. Muzyka and G. B. Heydt, "Solution Treatment and Al+Ti Effects on the Structure and Tensile Properties of Waspaloy", Journal of Metals, February 1970, pp. 32-38.
11. O. Kosik, D. J. Abson and J. J. Jonas, "Strengthening Effect of Hot-Work Subgrains at Room Temperature", Journal of the Iron and Steel Institute, August 1971, pp. 624-629.

Figure 1

2050F preheat, 33% reduction, 1860F finish. Microstructure consists of fine, dynamically recrystallized grains with a fairly high population of coarse, dynamically unrecrystallized grains interspersed.

50X

Kallings

Figure 2

2225F preheat, 33% reduction, 1940F finish. Microstructure contains reasonably fine, dynamically recrystallized grains mixed with a few coarse, dynamically unrecrystallized grains.

50X

Kallings

Figure 3

2250F preheat, 33% reduction, 1800F finish. A few coarse, dynamically unrecrystallized grains are dispersed through fairly fine, dynamically recrystallized grains.

50X

Kallings

Figure 4. Effect of preheat temperature on Waspaloy's transverse room temperature tensile properties

Figure 5

1940F finish, 33% reduction, 2125F preheat. Microstructure contains a few coarse, dynamically unrecrystallized grains distributed among fairly fine dynamically recrystallized grains.

50X

Kallings

Figure 6

1760F finish, 33% reduction, 2125F preheat. Microstructure consists of a few coarse, dynamically unrecrystallized grains dispersed through rather fine, dynamically recrystallized grains.

50X

Kallings

Figure 7. Effect of finish temperature on Waspaloy's transverse room temperature tensile properties

Figure 8. Effect of finish temperature on Waspaloy's transverse room temperature tensile properties with various preheat temperatures

Figure 9

18% reduction, 2125F preheat, 1900F finish. Many large, dynamically unrecrystallized grains are mixed with fairly fine, dynamically recrystallized grains.

50X

Kallings

Figure 10

49% reduction, 2125F preheat, 1890F finish. A few coarse, dynamically unrecrystallized grains are interspersed among very fine, dynamically recrystallized grains.

50X

Kallings

Figure 11. Effect of reduction on Waspaloy's transverse room temperature tensile properties

Fully Heat Treated

7200X

1865F/4hrs/OQ

20,000X

Figure 12

1940F finish, 2125F preheat, 33% reduction. Regions which display fine γ' but no coarse γ' also exhibit practically no dislocations, indicating that all γ' dissolved at 1865F and dislocations either were not present following deformation or were annealed out at 1865F.

Fully Heat Treated

7200X

1865F/4hrs/OQ

20,000X

Figure 13

1940F finish, 2125F preheat, 33% reduction. Regions which display both coarse and fine γ' exhibit short, diffuse dislocations.

1865F/4hrs/OQ

20,000X

Fully Heat Treated

7200X

Figure 14

1760F finish, 2125F preheat, 33% reduction. Coarse and fine γ' exist throughout the fully heat treated sample. Dislocations are arranged in a cellular pattern. The dislocation density is higher than in any other specimen in the investigation.

Fully Heat Treated

7200X

Figure 15

18% reduction, 2125F preheat,
1900F finish. The phase density
in the grain boundaries is quite
high.

Fully Heat Treated

7200X

Figure 16

49% reduction, 2125F preheat,
1900F finish. The concentra-
tion of phases in the grain
boundaries is rather low.