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HAYNES 244 alloy – a new 760 °C capable low thermal expansion alloy

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Abstract. HAYNES® 244™ alloy is a new 760 °C capable, high strength low thermal expansion (CTE) alloy. Its nominal chemical composition in weight percent is Ni – 8 Cr – 22.5 Mo – 6 W. Recently, a first mill-scale heat of 244 alloy was melted by Haynes International, and processed to various product forms such as re-forge billet, plate, and sheet. This paper presents key attributes of this new alloy (CTE, strength, low-cycle fatigue performance, oxidation resistance, thermal stability) as they pertain to the intended use in rings and seals of advanced gas turbines.

1. Introduction

The demand for more fuel efficient gas turbines drives the need for higher operating temperatures, thus impacting material requirements for both rotating and static parts. In the latter category, current generation low thermal expansion alloys such as HAYNES 242® alloy or INCONEL® alloy 783 appear to be limited to service temperatures of approximately 650 °C.

Addressing the need for a higher temperature capable, yet low thermal expansion alloy, HAYNES 244 alloy has been developed [1]. This new alloy builds conceptually on the metallurgy of HAYNES 242 alloy (nominal composition in wt. % of Ni – 8 Cr – 25 Mo): imparting strength by the formation of ordered domains upon age hardening, and ensuring low thermal expansion by virtue of a high refractory element content [2]. On a lab scale it was found that tungsten, when replacing a portion of the molybdenum, resulted in higher temperature capable material. Hence, the new alloy's nominal composition (in weight percent) was selected to be Ni – 8 Cr – 22.5 Mo – 6 W, with nickel being the balance and carbon being kept as low as possible.

This paper presents the basic metallurgy and key performance attributes of this new alloy as they pertain to the intended use in seals and rings of advanced gas turbine engines.

2. Material and experimental procedure

2.1. Material

A mill-scale heat was melted to the aforementioned aim and cast into two electrodes, both of which were electro-slag re-melted into 406 mm diameter ingots.

After an ingot homogenization treatment, ingot 1 was press forged to 200 mm and 162 mm diameter billet stock, respectively. Slugs were obtained from the center of the billets, and up-set forged at 1121 °C to approximately 18 mm thick pancakes. The corresponding reduction ratio was 4.3 : 1. Blanks, which were extracted from these pancake forgings, provided sample stock for subsequent heat treating, testing, and characterization. Care was exercised that areas affected by the die lock in the course of pancake forging were excluded from testing and evaluation.

Ingot 2 was homogenized as well, forged to a slab, and subsequently hot rolled to 12.5 mm thick plate. A portion of this plate was processed further and cold rolled to 2.4 mm thick sheet. Transverse blanks obtained from plate and sheet provided the sample stock for comparative testing of different product forms.

2.2. Experimental procedure

Heat treating of those blanks comprised:

a) a solution anneal 1135 °C / 30 min / water quench
b) two-step age-hardening 760 °C / 16 h / furnace cool to 649 °C / 32 h / air cool.

The solution annealing parameters were optimized by balancing strength, ductility, and grain size. The age-hardening cycle maximizes tensile strength at acceptable economics.

Fully heat treated specimens were subjected to measurements of the coefficient of thermal expansion, room and elevated temperature tensile properties, creep-rupture properties, and low-cycle fatigue resistance in accordance with applicable ASTM standards.

Oxidation resistance was evaluated by exposing sheet samples at 760 °C to laboratory air for a total duration of 1008 hours, whereby the coupons were cycled weekly down to room temperature. Measures of attack were metal loss and internal penetration.

Thermal stability was evaluated by exposing pancake and plate samples to four different temperatures: 427 °C, 649 °C, 705 °C, and 760 °C. The respective durations

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Figure 1. Light microscopy micrograph of the typical grain structure in 244 alloy in the solution-annealed condition.

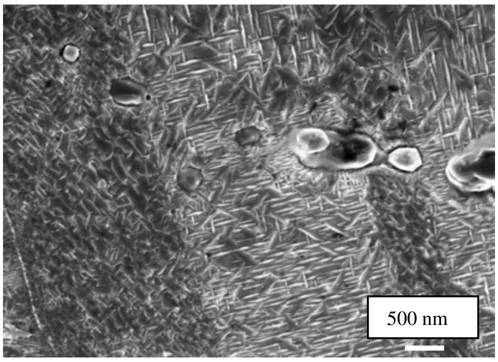

Figure 2. SEM in-lens image of the typical domain structure in 244 alloy in the annealed plus aged condition.

at each temperature were 1000, 4000, and 8000 hours. Retained room and elevated temperature tensile properties were determined, however, only the retained 760 °C tensile properties are included in this paper. The analysis was supported by metallographic examination in the light microscope and the SEM.

3. Results and discussion

3.1. Metallurgy

The typical microstructure in the solution-annealed condition is shown in Fig. 1. The grains are equi-axed and of average size ASTM no. 4. Light stringers of primary precipitates, a residual from the solidification process, are discernable to different degrees in the various product forms.

In the age-hardened condition, 244 alloy features distinct, sub-micron size precipitates (their long axis being on the order of 500 nm) as shown in Fig. 2. Their morphology is presumably lenticular. Several orientation variants are apparent. Notice that these features nucleated homogeneously in the bulk of the grain. No denuded zones along grain or twin boundaries are apparent. Due to their similar morphology compared to the features found in aged 242 alloy [2], these precipitates will be referred to as "domains". More in-depth TEM work revealed their Pt_2Mo type crystal structure, and a $Ni_2(Cr,Mo,W)$ type chemical composition [3].

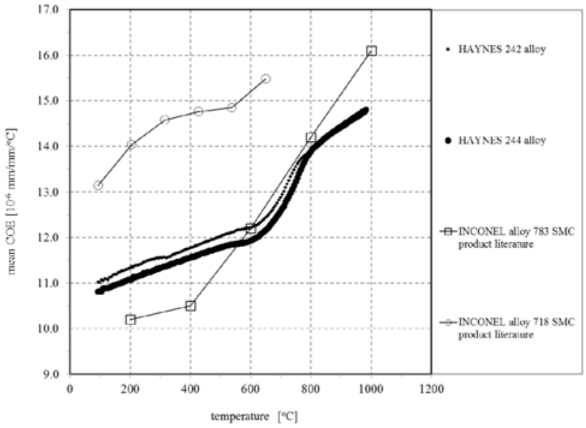

Figure 3. Mean coefficient of thermal expansion of new 244 alloy and several current generation low CTE alloys.

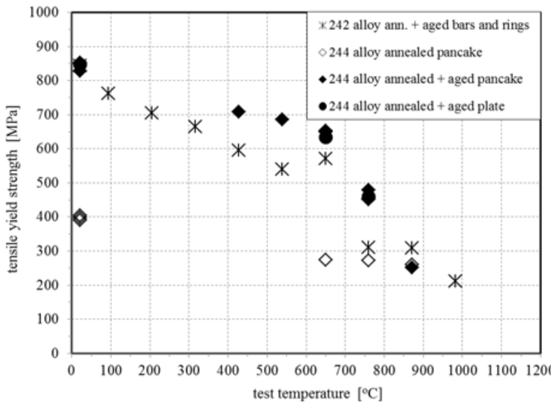

Figure 4. Plot of comparative yield strength data of 242 alloy (benchmark) and of the new 244 alloy as a function of test temperature.

3.2. Thermal expansion

Thermal expansion measurements were conducted on carefully machined and low-stress-ground pins. Figure 3 shows the mean coefficient of thermal expansion (CTE) between room temperature and the indicated test temperature for 244 alloy and several current-generation low CTE alloys.

Notably, 244 alloy exhibits the lowest mean CTE of any of these alloys above 550 °C. This is believed to be due to the large amount of refractory alloying elements, particularly tungsten.

Interestingly, its CTE exhibits an inflection point at approximately 790 °C, which coincides with the alloy's softening temperature. HAYNES 242 alloy displays a similar behavior, however, with an inflection point shifted to a lower temperature.

3.3. Mechanical properties

3.3.1. Tensile properties

Room and elevated temperature 0.2% offset yield strength of the various product forms is plotted in Fig. 4. Yield strength more than doubles upon age-hardening. Notice the distinct advantage in strength of 244 alloy over 242 alloy at 760 °C.

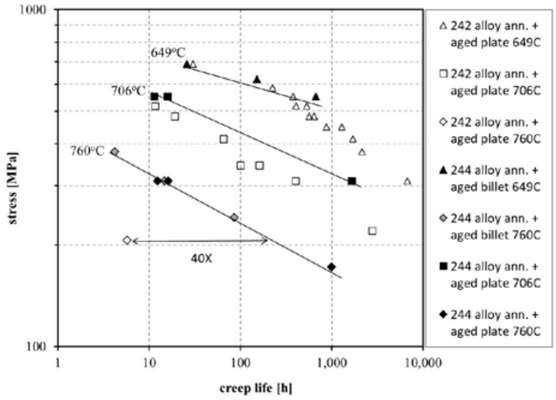

Figure 5. Log stress – log 1% creep life plot of creep data of 242 alloy and new 244 alloy.

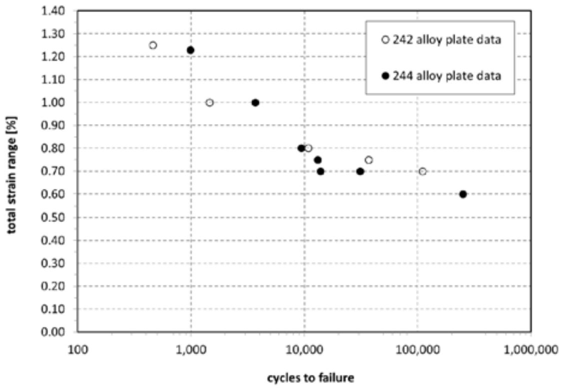

Figure 6. Low-cycle fatigue lives of 242 alloy and 244 alloy at 649 °C as a function of the total strain range.

Although not shown explicitly, ductility (tensile elongation) was greater than 20% for all test conditions. It is noted that there is a strain rate effect on ductility in the 600–700 °C temperature range [3], indicative of environmental effects. Similar effects were observed in the same temperature range in 242 alloy [4].

As for the age-hardening effect, it is noted that 244 alloy rapidly softens at higher temperatures; some hardness is still retained after exposures to 774 °C, however, a one hour exposure at 788 °C completely canceled the hardening effect.

3.3.2. Creep properties

A log stress – log 1% creep life plot of the creep data is shown in Fig. 5. The straight lines, test temperature being the parameter, were regressed using a power law.

The greater creep strength of 244 alloy over 242 alloy at 760 °C is evident. Notice also the consistency in the creep performance of the two studied product forms, i.e., billet and plate. At temperatures of 705 °C or less, it appears that the creep strengths of the two alloys are roughly comparable.

3.3.3. Low-cycle fatigue properties

Strain-controlled, fully reversed ($R = -1$) low cycle fatigue lives of 242 alloy and 244 alloy tested at 649 °C are plotted in Fig. 6. At this and lower test temperatures, fatigue lives were comparable.

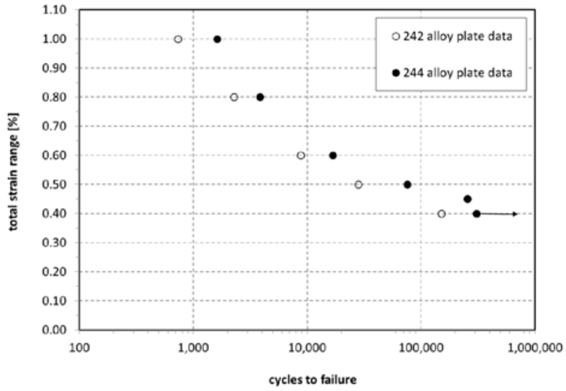

Figure 7. Low-cycle fatigue lives of 242 alloy and 244 alloy at 760 °C as a function of the total strain range. The arrow indicates a run-out.

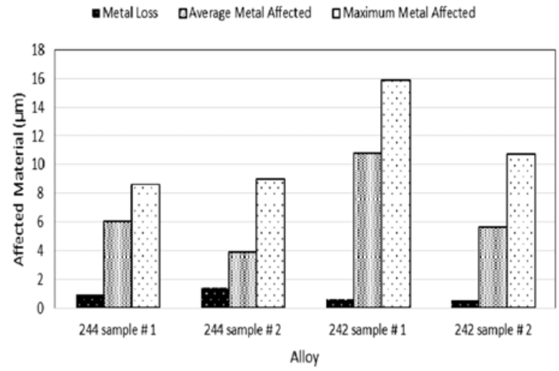

Figure 8. Measurements of environmental attack of fully heat treated 244 and 242 alloy sheet samples after a 1400 °F/1008 hours exposure to laboratory air. Duplicate tests.

The enhanced temperature capability of 244 alloy becomes evident when comparing the 760 °C fatigue lives in Fig. 7. It is surmised that the increased 760 °C tensile strength of 244 alloy resulted in a smaller plastic strains (at a given total strain) and, hence, improved fatigue performance.

Summarizing the mechanical properties section, it needs to be noted that the average grain size in the 244 alloy specimens and the benchmark 242 alloy specimens was comparable with less than one ASTM number difference. Hence, it appears that the enhanced 760 °C properties of 244 alloy are primarily due to an intrinsically higher thermal stability of the $Ni_2(Cr,Mo,W)$ domains over that of the $Ni_2(Cr,Mo)$ domains. This notion is supported by the measured aforementioned softening temperatures of 790 °C (244 alloy) versus 760 °C (242 alloy).

3.4. Oxidation resistance

The results of a static oxidation test after a 760 °C / 1008 hour exposure to laboratory air are plotted in Fig. 8.

It appears that the oxidation resistance of the new 244 alloy is, at least in this static environment, comparable to that of well-established 242 alloy. This in encouraging since the good oxidation resistance of 242 alloy has allowed for its use in gas turbine applications in the uncoated condition.

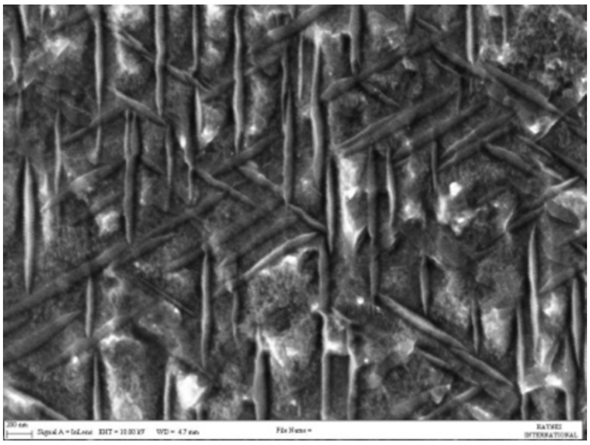

Figure 9. SEM in-lens image of the typical microstructure of 244 alloy after a 427 °C/8000 h thermal exposure. The scale bar indicates 500 nm.

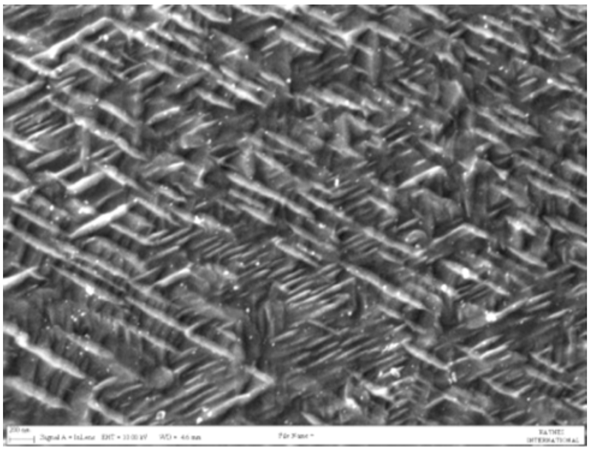

Figure 10. SEM in-lens image of the typical microstructure of 244 alloy after a 649 °C/8000 h thermal exposure. The scale bar indicates 500 nm.

3.5. Thermal stability

Sufficient thermal stability is one of the key performance criteria for any high-temperature alloy. In particular, it is the retention of application-relevant properties that determines the usefulness of a new alloy.

3.5.1. Microstructure evolution

High-resolution SEM in-lens images of the microstructures of the long-term exposed samples are shown in Figs. 9–11.

No changes in the microstructure after a one-year long exposure at this temperature compared to the initial condition are discernable. The typical domain structure is apparent.

At this temperature of 649 °C, a second population of domains formed, resulting in bi-modal size distribution. The grain boundaries remained comparatively clean.

The defining features of the (706–760) °C exposed conditions were (a) coarsened primary domains, and (b) inter- and intra-granular Mo- and W-rich bulky particles as verified by SEM / EDS (shown in Fig. 11). The latter were consistently associated with domain-denuded zones.

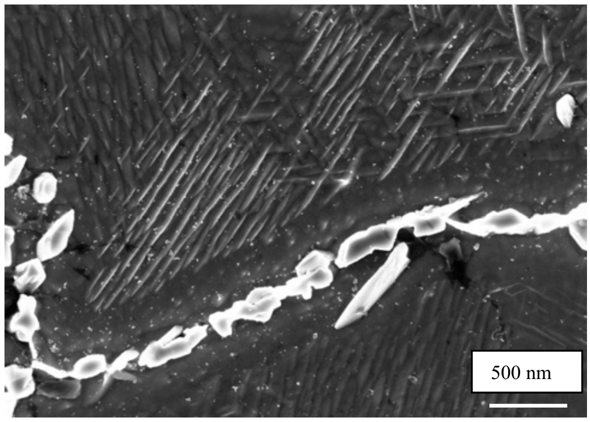

Figure 11. SEM in-lens image of the typical microstructure of 244 alloy after a 760 °C/8000 h thermal exposure. Magnification 45 kX.

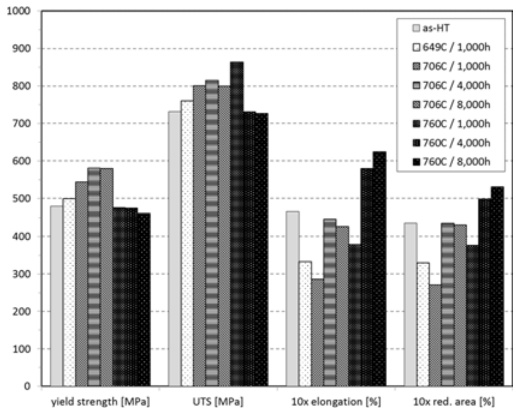

Figure 12. Retained 760 °C temperatures tensile properties of 244 alloy after various thermal exposures.

Hence, it appears that the domains gradually transformed into a more stable phase(s) under those conditions.

3.5.2. Retained tensile properties

Retained tensile properties at the targeted application temperature of 760 °C after the aforementioned thermal exposures are displayed in Fig. 12.

It is evident that the alloy continues to age-harden when exposed to temperatures of up to 706 °C. Exposure to higher temperatures, as shown in Fig. 11, result in the gradual transformation of the strengthening A_2B phase into TCP phases. The corresonding debit is most pronounced in retained room temperature ductility with values in the 10% ballpark. However, application-relevant elevated temperature strength and ductility characteristics are still comparable to those in the as-heat treated condition.

4. Summary and conclusions

1. HAYNES 244 alloy is a new 760 °C capable, low-thermal expansion alloy intended for use in static parts of advanced gas turbines. Its nominal composition in weight percent is Ni – 8 Cr – 22.5 Mo – 6 W. A first mill-scale heat was melted, and several product forms (billet, plate, sheet) were produced.

2. In the fully heat treated condition, the alloy offers attractive strength (tensile and creep) and low-cycle fatigue properties. Its mean coefficient of thermal expansion at temperatures exceeding 550 °C is lower than those of current generation low-thermal expansion alloys.
3. Long-term thermal exposures in the (706–760) °C range result in the very gradual transformation of the strengthening A_2B phase into less desirable phases. However, application-relevant 760 °C tensile properties are largely retained even after 8000 hours of exposure.
4. Its environmental resistance, as assessed by static oxidation tests at 760 °C, appears to be comparable to that of current generation low-thermal expansion alloy HAYNES 242.

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References

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