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(54) **Nickel base alloy**

(57)

1. A composition of matter comprising:

5wt% to 8wt% rhenium;
4wt% to 8wt% tantalum;
2wt% to 5wt% tungsten;
2wt% to 5.5wt% molybdenum;
2wt% to 5wt% chromium;
2wt% to 6wt% ruthenium;
2wt% to 8wt% cobalt;
5wt% to 7wt% aluminium;
0wt% to 2wt% titanium;
0wt% to 0.5wt% hafnium;

and the balance nickel and incidental impurities.

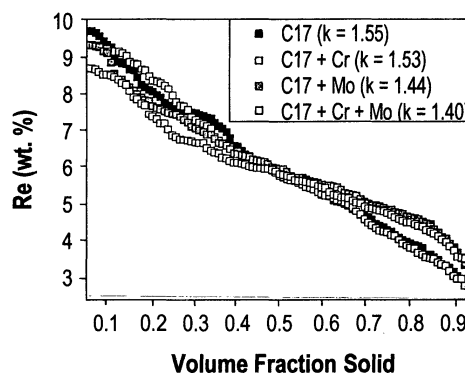
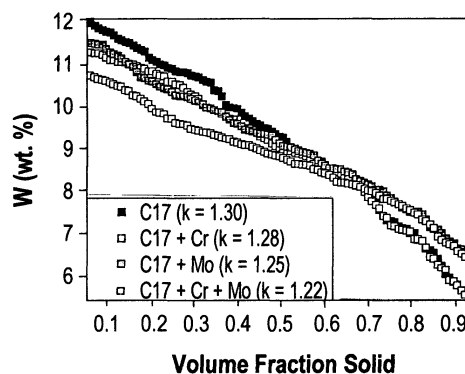


Fig. 1

The effect of Cr and Mo additions on the solidification paths of W and Re in C17.

Description

[0001] This invention relates to compositions of matter. More particularly, but not exclusively, this invention relates to nickel based alloys, such as nickel based superalloys. Embodiments of the invention relate to nickel-based single crystal superalloys.

[0002] To improve the performance and efficiency of gas turbine engines, single crystal Ni-base superalloy turbine blades have been increasingly alloyed with dense refractory elements to enhance high temperature creep properties. As single crystal compositions have become more heavily alloyed, the ease of manufacturing and processing has decreased, primarily due to formation of solidification related grain defects. Moreover, the recent trend of adding ruthenium to single crystal Ni-base superalloys has led to substantial increases in raw material costs, thus making manufacturing yield improvements through the reduction of casting defects of paramount importance. Hence, assessment of the solidification characteristics of these complex multi-component alloys and understanding the various elemental interactions is critical during the development of advanced single crystal Ni-base superalloys with improved high temperature properties and long term stability.

[0003] In multi-component alloys such as nickel-base superalloys, solidification involves solute redistribution of the alloying elements during dendrite growth. This causes microsegregation i.e. local variations in elemental concentrations from the dendrite cores to the dendrite peripherals and interdendritic region of the as-cast alloy. In single crystal Ni-base superalloys, solidification begins with the formation of primary γ - Ni dendrites and typically terminates at a $\gamma + \gamma'$ eutectic reaction. The composition of the solid phase forming from the bulk liquid during solidification varies from the initial bulk liquid composition and it continually changes as the temperature decreases.

[0004] The breakdown of single crystal solidification is often attributed to the presence of elevated levels of dense refractory elements that partition strongly to either the solid or liquid phase during solidification and ultimately result in the formation of freckle chains. Additions of Re and W partition strongly to the dendritic regions during solidification, thus depleting the liquid solute of these dense elements as solidification progresses. This gives rise to large density imbalances between the bulk liquid and the less dense solute contained within the dendritic mushy zone. The compositional differences lead to the formation of convective instabilities that create solute-rich plumes which solidify as channels of equiaxed grains, or freckles. Research into solid-liquid elemental partitioning during solidification has demonstrated the importance of Ta, W and Re segregation in promoting the formation of these grain defects.

[0005] According to a first aspect of this invention, there is provided a composition of matter comprising:

5wt% to 8wt% rhenium;
4wt% to 8wt% tantalum;
2wt% to 5wt% tungsten;
2wt% to 5.5wt% molybdenum;
2wt% to 5wt% chromium;
1wt% to 6wt% ruthenium;
2wt% to 8wt% cobalt;
5wt% to 7wt% aluminium;
0wt% to 2wt% titanium;
0wt% to 0.5wt% hafnium;
and the balance comprising nickel.

[0006] The composition of matter may comprise 5wt% to 7wt% rhenium. The composition of matter may comprise greater than 6wt% rhenium.

[0007] The composition of matter may comprise 3.5wt% to 5wt% tungsten. The composition of matter preferably comprises less than 4wt% tungsten.

[0008] The composition of matter may comprise 3.5wt% to 4.5wt% molybdenum. The composition of matter may comprise greater than 4.5wt% molybdenum. The composition of matter may comprise less than 2.9wt% molybdenum.

[0009] The composition of matter may comprise 3wt% to 4wt% chromium.

[0010] The composition of matter may comprise 2wt% to 6wt% ruthenium, preferably 3wt% to 5wt% ruthenium. The composition of matter may comprise greater than 4wt% ruthenium.

[0011] The composition of matter may comprise 3wt% to 8wt% cobalt.

[0012] The composition of matter may comprise 5wt% to 6.5wt% aluminium.

[0013] The composition of matter may comprise 0.05wt% to 0.5wt% hafnium.

[0014] The composition of matter may comprise 0.1wt% to 2wt% titanium.

[0015] In one embodiment the composition of matter may comprise:

5wt% to 7wt% rhenium;

4wt% to 8wt% tantalum;
 3.5wt% to 5wt% tungsten;
 3.5wt% to 4.5wt% molybdenum;
 3wt% to 4wt% chromium;
 3wt% to 8wt% cobalt;
 5wt% to 6.5wt% aluminium;
 0wt% to 0.5wt% hafnium;
 0wt% to 2wt% titanium;
 3wt% to 5wt% ruthenium;
 0.1wt% to 2wt% titanium;
 0.05wt% to 0.5wt% hafnium;
 and the balance comprising nickel.

[0016] One or more formulations of this embodiment may comprise less than 4wt% tungsten. One or more formulations of this embodiment may comprise greater than 4wt% tungsten.

[0017] One or more formulations of this embodiment may comprise greater than 4wt% ruthenium. One or more formulations of this embodiment may comprise less than 4wt% ruthenium.

[0018] The composition of matter is preferably a superalloy, desirably a nickel based superalloy.

[0019] According to a second aspect of this invention, there is provided a single crystal article formed from a composition of matter as described above.

[0020] Preferably the article is an aerofoil. The article may be an aerofoil blade, preferably a turbine blade.

[0021] Embodiments of the invention will now be described by way of example only with reference to the accompanying drawings, in which:

Figure 1 are graphs of the effect of Cr and Mo additions on the solidification paths of W and Re in C17;

Figure 2 is a photo of an as-cast turbine blade illustrating the four areas for documentation of solidification related defects arising during the casting trials;

Figure 3 are graphs illustrating the effects of Cr and Mo additions by comparing the solidification paths of W and Re an UCSX6 and UCSX7;

Figure 4 shows photos of the macroetched platform of the as-cast turbine blades of (a) UCSX6 (b) UCSX7 and (c) UCSX8 showing a decrease in the number of freckle defects from left to right;

Figure 5 shows optical micrographs of the as-cast microstructures of (a) C17 (b) C17 + Mo (c) C17 and (d) C17 + Cr + Mo showing decreasing levels of interdendritic eutectic as Mo and Cr are added;

Figure 6 is a graph of quantitative analysis showing a decreasing volume fraction of eutectic with increasing Mo and Cr contents in C17; and

Figure 7 is a graph of the effect of Ir additions on the partitioning behaviour of Ta in C17.

[0022] One feature of the preferred embodiment of the present invention is the specific combination of high Cr and Mo contents complemented by a low $(W+Re)/Ta$ ratio to reduce the susceptibility of the nickel-based superalloy to solidification related defects during single crystal solidification.

[0023] It is known from the prior art that some elements, such as W and Re, are detrimental to the ease of single crystal solidification. The beneficial effect of Cr and Mo additions in decreasing the severity of the solid-liquid partitioning of elements such as W and Re, was noted in the analysis of the as-cast structures of forty-seven Ni-base superalloy compositions to assess the influence of the constituent elements on their solidification characteristics. The compositions in wt% of selected alloys investigated are listed in Table 1.

[0024] A Cameca SX-100 electron microprobe with five wavelength dispersive spectrometers (WDS) was used to quantify the degree to which the constituent elements of all thirty-nine alloys segregate during solidification. A 15 by 15 point grid was used over a 1mm² area of the polished sample surface with a 10 second collection time per peak for each element in addition to a 5 second background measurement either side of the peak. This provided representative compositional information from the dendrite cores to the interdendritic regions of the non-equilibrium solidified alloys. The solid-liquid partition coefficients, or k values (where $k = X_S/X_L$), for each element were then quantified using a modified Scheil-analysis. The Scheil equation is:

$$X_s = kX_0 (1 - f_s)^{(k-1)}$$

Where X_s is the mole fraction of solute in the solid, f_s is the volume fraction solid, X_0 is the nominal composition, or in this instance the average composition of each element as determined by the electron microprobe. The degree of segregation is related to the magnitude of the partition coefficient. No segregation occurs when $k = 1$ while coefficients greater and less than unity indicate that the corresponding element is partitioned preferentially to the solid and liquid respectively during solidification. The compositional data for the elements in each alloy measured at each point in the electron probe microanalysis was arranged into ascending or descending order depending on whether the element partitioned preferentially to the dendrite core or to the interdendritic regions. This was then plotted as a function of the volume fraction solid. To determine the solid-liquid partition coefficients, k , for each of the constituent elements, the Scheil equation was fitted to the experimental data and then the value of k was adjusted until the best fit was achieved.

[0025] For the majority of the SRR300 series of alloys, levels of Co, Al and Hf were held constant while levels of Cr, Mo, W, Re and Ta were systematically varied to investigate the effects of these additions on the resulting solidification characteristics. For example, to identify the effect of increasing Re and W additions, SRR300A was doped with 1.2 wt% Re (SRR300B), 1.2wt% W (SRR300C) and 0.6wt% Re + 0.6wt% W (SRR300D). The influence of Co on the solid-liquid partition coefficients of the other major alloying elements was investigated with alloys SRR300J, SRR300D and SRR300K where Ni was substituted by increasing Co contents ranging from 2, to 8, to 12wt% respectively. Four of the alloys, RR3010, SRR300B, SRR300C and SRR300D were doped with 1 and 3 wt% (0.6 and 1.9 at %) ruthenium. Prior art has demonstrated Ru to be a potentially beneficial alloying element that is capable of stabilising the microstructure against the formation of topologically close-packed phases at elevated temperatures. It was therefore considered important to observe whether such additions would be detrimental to the solidification characteristics of the alloy. Included within these experimental alloys are nine high refractory Ru-containing single crystal alloys with the UCSX prefix. UCSX2 includes three variants of increasing Ru content ranging from 2 to 5wt% at the expense of Ni to negate dilution effects. UCSX6, UCSX7 and UCSX8 were designed for the purposes of casting trials and are detailed later in the document. A simplified Ni-base superalloy, C17, with constant levels of Co, W, Re, and Ta was used to isolate the effects of Al, Cr, Mo and Ir additions on the segregation behaviour of the constituent elements. While prior art has also demonstrated that Ir is a potent microstructural stabilising element, in this research Ir was added to investigate how the presence of another element, which also partitions preferentially to the growing solid during solidification, influences the relative severity of segregation of W and Re. Finally eight alloys, with the LDSX prefix, were investigated to explore the benefits of low W, with a combination of high Cr, Mo and Ru on castability.

[0026] The results from the electron probe microanalysis are summarised in Table 2. Statistical fluctuations associated with the modified-Scheil analysis are all within an average deviation of 0.05 pf the partition coefficients reported. Generally, the more strongly segregating the element, the greater the average deviation. Consistent with other investigations, the high-density refractory elements, Ta, W and Re were found to segregate most severely

Table 1: Compositions (in wt.%) of selected alloys analysed.

Alloy	Ni	Al	Cr	Co	Mo	Ti	Nb	Ta	W	Re	Ru	Ir	Hf
RR3010	Bal.	5.9	1.7	3.1	0.5	0.1	0.1	8.5	5.5	6.8	-	-	-
RR3010 + 1 Ru	Bal.	5.8	1.7	3.1	0.5	0.1	0.1	8.4	5.4	6.7	1.0	-	-
RR3010 + 3 Ru	Bal.	5.7	1.7	3.0	0.5	0.1	0.1	8.3	5.3	6.6	3.0	-	-
SRR300A	Bal.	5.8	4.0	8.0	2.2	-	-	7.5	4.6	4.1	-	-	0.1
SRR300B	Bal.	5.8	4.0	8.0	2.2	-	-	7.5	4.6	5.3	-	-	0.1
SRR300B + 1 Ru	Bal.	5.7	4.0	7.9	2.2	-	-	7.4	4.6	5.2	1.0	-	0.1
SRR300B + 3 Ru	Bal.	5.6	3.9	7.8	2.1	-	-	7.3	4.5	5.1	3.0	-	0.1
SRR300C	Bal.	5.8	4.0	8.0	2.2	-	-	7.5	5.8	4.1	-	-	0.1
SRR300C + 1 Ru	Bal.	5.7	4.0	7.9	2.2	-	-	7.4	5.7	4.1	1.0	-	0.1
SRR300C + 3 Ru	Bal.	5.6	3.9	7.8	2.1	-	-	7.3	5.6	4.0	3.0	-	0.1
SRR300D	Bal.	5.8	4.0	8.0	2.2	-	-	7.5	5.2	4.7	-	-	0.1

Table continued

Alloy	Ni	Al	Cr	Co	Mo	Ti	Nb	Ta	W	Re	Ru	Ir	Hf
SRR300D + 1 Ru	Bal.	5.7	4.0	7.9	2.2	-	-	7.4	5.1	4.7	1.0	-	0.1
SRR300D + 3 Ru	Bal.	5.6	3.9	7.8	2.1	-	-	7.3	5.0	4.6	3.0	-	0.1
SRR300E	Bal.	5.8	4.0	8.0	2.2	-	0.6	6.5	5.2	4.7	-	-	0.1
SRR300G	Bal.	5.8	4.0	8.0	3.5	-	0.6	6.5	4.0	4.0	-	-	0.1
SRR300H	Bal.	5.8	4.0	8.0	-	-	-	7.5	7.0	5.3	-	-	0.1
SRR300I	Bal.	5.8	5.5	8.0	2.0	-	-	7.5	4.0	5.3	-	-	0.1
SRR300J	Bal.	5.8	4.0	2.0	2.2	-	-	7.5	5.2	4.7	-	-	0.1
SRR300K	Bal.	5.8	4.0	12.0	2.2	-	-	7.5	5.2	4.7	-	-	0.1
SRR300L	Bal.	6.0	2.5	8.0	2.2	-	-	7.5	4.6	5.3	-	-	0.1
C17	Bal.	6.0	-	12.0	-	-	-	6.0	9.3	6.0	-	-	-
C17 + Al	Bal.	6.5	-	11.9	-	-	-	6.0	9.3	6.0	-	-	-
C17 + Cr	Bal.	5.7	4.5	11.5	-	-	-	5.7	8.9	5.7	-	-	-
C17 + Mo	Bal.	5.9	-	11.7	2.2	-	-	5.9	9.1	5.9	-	-	-
C17 + Cr + Mo	Bal.	5.6	4.5	11.7	2.2	-	-	5.6	8.7	5.6	-	-	-
C17 + 1 at.% Ir	Bal.	5.8	-	11.7	-	-	-	5.8	9.0	5.8	-	3.0	-
C17 + 3 at.% Ir	Bal.	5.5	-	11.0	-	-	-	5.5	8.6	5.5	-	8.6	-
UCSX2 + 2 Ru	Bal.	5.4	3.0	8.0	1.0	-	-	8.0	8.0	6.5	2.0	-	0.1
UCSX2 + 3 Ru	Bal.	5.4	3.0	8.0	1.0	-	-	8.0	8.0	6.5	3.0	-	0.1
UCSX2 + 5 Ru	Bal.	5.4	3.0	8.0	1.0	-	-	8.0	8.0	6.5	5.0	-	0.1
UCSX6	Bal.	6.3	-	4.0	-	-	-	6.0	8.0	6.8	3.0	-	-
UCSX7	Bal.	6.0	1.5	4.0	3.0	-	-	6.0	8.0	6.8	3.0	-	-
UCSX8	Bal.	5.7	1.5	6.0	3.0	-	-	8.0	6.0	6.0	3.0	-	-
LDSX1	Bal.	6.0	3.0	3.0	2.5	0.25	-	6.5	2.9	6.2	3.5	-	0.1
LDSX2	Bal.	6.0	3.0	8.0	5.0	0.25	-	6.5	2.9	6.2	3.5	-	0.1
LDSX3	Bal.	6.0	3.0	3.0	5.0	0.25	-	6.5	4.8	6.2	3.5	-	0.1
LDSX4	Bal.	6.0	3.0	8.0	2.5	0.25	-	6.5	4.8	6.2	3.5	-	0.1
LDSX5	Bal.	6.0	3.0	8.0	2.5	0.25	-	6.5	2.9	6.2	5.0	-	0.1
LDSX6	Bal.	6.0	3.0	3.0	2.5	0.25	-	6.5	4.8	6.2	5.0	-	0.1
LDSX7	Bal.	6.0	3.0	3.0	5.0	0.25	-	6.5	2.9	6.2	5.0	-	0.1
LDSX8	Bal.	6.0	3.0	8.0	5.0	0.25	-	6.5	4.8	6.2	5.0	-	0.1

during solidification i.e. their k values were furthest from unity. The degree to which each of these elements partitioned however, varied significantly with composition over the range of experimental alloys analysed. Relative changes in both the Mo and Cr alloying levels were found to have the most significant effect. The presence of Mo and Cr in the SRR300 series of alloys was found to decrease the extent of segregation for the dense refractory elements known to promote freckle defects. For example, alloy SRR300I, which has the highest overall content of Cr + Mo, exhibits a substantially lower degree of segregation when compared to alloys SRR300L and SRR300H, which have similar levels of refractory alloying additions by lower Cr + Mo levels. With an intermediate level of Cr + Mo, the measured segregation of Re, W and Ta in SRR300B is moderate when compared to SRR300I, SRR300L and SRR300H.

[0027] It is difficult to isolate the effects of Cr and Mo additions within the SRR300 series of alloys, since changes in their concentrations throughout the alloy compositions investigated are accompanied by significant changes in other im-

portant alloying elements. Hence, in an attempt to isolate their effects, additions of 4.5wt% Cr and 2.2wt% Mo were systematically made to the experimental Ni-based single crystal alloy containing no Cr and Mo additions, C17. The partition coefficients of the dense refractory elements in the base C17 alloy are far from unity and are comparable to RR3010 (Table 2), which is also a low Cr, low Mo content alloy. While the improvements in the solid-liquid partition coefficients of W and Re upon addition of Cr and Mo to C17 are not as dramatic as observed in the SRR300 alloy series, the trends are nonetheless consistent with the prior findings, emphasising the decrease in segregation associated with the overall Cr and Mo content present within a given alloy. These effects are illustrated more clearly in figure 1, where the segregation characteristics are clearly being influenced by the presence of Cr and Mo. In this particular set of alloys, Mo additions appear more potent than Cr in suppressing the segregation behaviour of W and Re. An addition of 2.2wt% (1.4 at %) Mo decreases the microsegregation of W and Re to a greater extent than an addition of 4.5wt% (5.2 at %) Cr. The largest decrease however, was achieved when both Cr and Mo were added to C17. No significant improvements to the partitioning of Ta were noted upon addition of Cr and Mo.

[0028] Ruthenium was found to be largely neutral in its influence on the solidification characteristics of the alloys. Slightly lower levels of Cr, Mo and Re segregation were measured in alloys containing 1wt% Ru, however little to no additional improvement accompanied an increase in Ru content to 3wt%. This is consistent with the results for the Ru-variants of UCSX2, where any changes in the partition coefficients of the constituent elements associated with increasing Ru contents are insignificant. Ru itself partitions only slightly to the dendrite core, having a k value close to unity.

[0029] No significant alteration to the solidification paths of the constituent elements was noted with large changes in Co contents from 2, to 8, to 12wt% in alloys SRR300J, SRR300D and SRR300K respectively. The same was true for an increase of 0.5wt% Al to the base C17 alloy. Excluding Cr and Mo additions, no other elemental additions were revealed to significantly influence the partitioning of W and Re. However, increasing the overall concentrations of W and Re leads to more severe partitioning of the elements to the initial fraction solid (compare SRR300A to SRR300B and SRR300C in Table 2). Comparison of the solid-liquid partition coefficients of W and Re in SRR300E to those in SRR300G in Table 2 shows the benefit of combining a high Mo concentration with lowered W and Re concentrations. The LDSX series of alloys support this finding. The severity of partitioning of the constituent elements is lessened through the combination of high Cr and Mo contents with a low W content despite maintaining the high Re and Ru contents necessary for enhanced creep properties and microstructural stability at elevated temperatures.

Table 2: Measured and calculated solid-liquid partition coefficients of selected alloys.

Alloy	Ni	Al	Cr	Co	Mo	Ta	W	Re	Ru	Ir
RR3010	0.97	0.88	1.15	1.08	-	0.77	1.26	1.57	-	-
RR3010 + 1 Ru	0.98	0.87	1.10	1.08	-	0.76	1.26	1.53	1.04	-
RR3010 + 3 Ru	0.98	0.87	1.10	1.08	-	0.76	1.27	1.54	1.04	-
SRR300A	0.98	0.94	1.04	1.04	1.06	0.80	1.20	1.36	-	-
SRR300B	0.97	0.92	1.11	1.06	1.09	0.78	1.21	1.39	-	-
SRR300B + 1 Ru	0.98	0.91	1.06	1.05	1.08	0.76	1.22	1.35	1.04	-
SRR300B + 3 Ru	0.98	0.91	1.05	1.05	1.07	0.76	1.21	1.36	1.04	-
SRR300C	0.97	0.92	1.11	1.06	1.10	0.78	1.23	1.36	-	-
SRR300C + 1 Ru	0.98	0.91	1.05	1.06	1.08	0.76	1.23	1.32	1.03	-
SRR300C + 3 Ru	0.98	0.91	1.04	1.05	1.07	0.77	1.23	1.32	1.03	-
SRR300D	0.97	0.91	1.11	1.07	1.09	0.76	1.24	1.43	-	-
SRR300D + 1 Ru	0.98	0.91	1.06	1.05	1.07	0.76	1.24	1.40	1.04	-
SRR300D + 3 Ru	0.98	0.91	1.05	1.05	1.07	0.77	1.23	1.39	1.04	-
SRR300E	0.98	0.90	1.08	1.06	1.09	0.77	1.23	1.42	-	-
SRR300G	0.98	0.95	1.06	1.04	1.08	0.83	1.19	1.27	-	-
SRR300H	0.97	0.89	1.06	1.07	-	0.75	1.27	1.47	-	-
SRR300I	0.98	0.95	1.08	1.04	1.08	0.87	1.12	1.23	-	-
SRR300J	0.98	0.91	1.07	1.07	1.08	0.77	1.25	1.43	-	-
SRR300K	0.97	0.91	1.06	1.06	1.07	0.76	1.24	1.43	-	-

Table continued

Alloy	Ni	Al	Cr	Co	Mo	Ta	W	Re	Ru	Ir
SRR300L	0.97	0.90	1.07	1.06	1.08	0.74	1.27	1.48	-	-
C17	0.95	0.85	-	1.05	-	0.65	1.30	1.55	-	-
C17 + Al	0.95	0.85	-	1.06	-	0.66	1.31	1.55	-	-
C17 + Cr	0.96	0.85	1.03	1.05	-	0.64	1.28	1.53	-	-
C17 + Mo	0.96	0.87	-	1.05	1.10	0.67	1.25	1.44	-	-
C17 + Cr + Mo	0.97	0.87	1.03	1.05	1.10	0.67	1.22	1.40	-	-
C17 + 1 at.% Ir	0.95	0.85	-	1.05	-	0.68	1.29	1.55	-	1.12
C17 + 3 at.% Ir	0.95	0.85	-	1.04	-	0.76	1.28	1.53	-	1.13
UCSX2 + 2 Ru	0.96	0.86	1.07	1.06	1.08	0.72	1.26	1.48	1.05	-
UCSX2 + 3 Ru	0.96	0.86	1.07	1.06	1.08	0.72	1.26	1.47	1.05	-
UCSX2 + 5 Ru	0.96	0.86	1.07	1.06	1.07	0.72	1.25	1.47	1.06	-
UCSX6	0.95	0.84	-	1.08	-	0.72	1.31	1.63	1.06	-
UCSX7	0.96	0.86	1.09	1.08	1.09	0.73	1.25	1.47	1.06	-
UCSX8	0.97	0.88	1.07	1.07	1.06	0.74	1.23	1.42	1.05	-
LDSX1	0.98	0.91	1.09	1.06	1.09	0.81	1.23	1.42	1.05	-
LDSX2	0.98	0.93	1.06	1.05	1.06	0.80	1.27	1.28	1.07	-
LDSX3	0.98	0.91	1.09	1.07	1.06	0.79	1.21	1.32	1.06	-
LDSX4	0.97	0.90	1.07	1.05	1.09	0.76	1.28	1.40	1.06	-
LDSX5	0.98	0.91	1.06	1.05	1.08	0.79	1.29	1.38	1.06	-
LDSX6	0.97	0.89	1.09	1.07	1.08	0.78	1.23	1.42	1.05	-
LDSX7	0.98	0.92	1.08	1.06	1.06	0.82	1.22	1.31	1.06	-
LDSX8	0.97	0.91	1.06	1.05	1.05	0.77	1.27	1.29	1.07	-

[0030] Having determined the partition coefficients for each composition, multiple linear regression analysis was performed on the experimental data in Table 2 to obtain formulae for the prediction of the solid-liquid partition coefficients of the major constituent elements. The magnitude of the coefficient associated with each of the elements in the linear regression analysis provides an indication of the relative influences of the other elements on the partitioning of the element in question. The regression equations corresponding to the elements known to be most important in the promotion of grain defects, namely W and Re, show the potential benefits of Cr and Mo additions in decreasing the intrinsic susceptibility of an alloy to single crystal breakdown during solidification (note that any coefficients of order 10^{-4} and less have been omitted):

$$K_W = 0.281 + 0.0988 [\text{wt}\% \text{Al}] - 0.00316 [\text{wt}\% \text{Cr}] + 0.0101 [\text{wt}\% \text{Co}] - 0.0063 [\text{wt}\% \text{Mo}] + 0.0289 [\text{wt}\% \text{Ta}] - 0.00325 [\text{wt}\% \text{W}] + 0.0258 [\text{wt}\% \text{Re}] + 0.00418 [\text{wt}\% \text{Ru}]$$

$$k_{R_e} = 1.37 + 0.0205 [\text{wt}\% \text{Al}] - 0.0168 [\text{wt}\% \text{Cr}] - 0.00586 [\text{wt}\% \text{Co}] - 0.0416 [\text{wt}\% \text{Mo}] - 0.0035 [\text{wt}\% \text{Ta}] + 0.0055 [\text{wt}\% \text{W}] + 0.0192 [\text{wt}\% \text{Re}] - 0.00461 [\text{wt}\% \text{Ru}]$$

[0031] The coefficients for Cr and Mo in the determination of k_W and k_{R_e} exert the largest influence in the minimisation of both towards unity. The coefficient for Mo is greater than that of Cr in both instances demonstrating the greater potency

of Mo additions in minimising the severity of W and Re segregation.

[0032] Casting trials were performed on three alloy compositions UCSX6, UCSX7 and UCSX8 (Table 1) specially devised to validate the importance of Cr and Mo additions and a low $(W+Re)/Ta$ ratio in minimising the formation of solidification related defects.

[0033] The elemental concentrations in each alloy are typical of advanced single crystal superalloy compositions and were intentionally designed to investigate whether such alloys could be made more amenable to single crystal solidification whilst maintaining the high refractory contents necessary to enhance creep resistance. UCSX6, a Cr- and Mo-free alloy with an undesirable $(W+Re)/Ta$ ratio was designed to be the most prone to solidification defects while UCSX8, with reduced amounts of Re and W, which partition preferentially to the growing solid during solidification, and complementing this with increased Ta contents, which further decreases the density inversion by partitioning preferentially to the bulk liquid, was designated to be the least prone. UCSX7 was designed to experimentally verify the potential benefits of Cr and Mo additions on the severity of the solid-liquid partitioning of Re and W. The sole difference between UCSX6 and UCSX7 is the addition of 1.5wt% Cr and 3.0wt% Mo and the amount of A1 was adjusted to ensure the same γ' volume fraction as predicted by the *JMatPro* software for UCSX6.

[0034] A production scale Bridgman furnace was used to simultaneously solidify five solid turbine blades in a ceramic cluster mould at constant processing conditions using a withdrawal rate of 230mm per hour. The as-cast crystals were subsequently macroetched to reveal the presence, location and number of macroscopic grain defects, such as freckle chains and misoriented grains, on the surface of the castings. To document the location of any defects, the blade was separated into four areas: the tip, blade, platform and root (Figure 2). For every blade of each composition the number of defects in each area were counted and averaged over the five blades for subsequent comparison.

[0035] The results were listed in Table 2 and Table 3 experimentally verify both the beneficial effect of Cr and Mo additions and the importance of maintaining a low $(W + Re)/Ta$ ratio.

Table 3: Number, location and total number of solidification related defects in each alloy tested in the casting trials.

Location	UCSX6	UCSX7	UCSX8
Tip	7.5 ± 1.0	0	0
Blade	1.5 ± 0.5	0	0
Platform	16.3 ± 1.5	10.8 ± 1.7	3.0 ± 1.4
Root	18.8 ± 1.3	9.3 ± 1.9	0.8 ± 0.5
Total No. of Defects	44.0 ± 1.4	20.0 ± 1.2	3.8 ± 1.3

[0036] The Cr- and Mo-free UCSX6 alloy with the most severe solid-liquid partitioning of the constituent elements was found to be the most prone to freckle formation. The total number of freckle defects in UCSX6 was more than halved in UCSX7 solely due to the addition of 1.5wt.% (1.9 at.%) Cr and 3.0wt.% (2.0 at.%) Mo. The change in the solidification paths of W and Re as a result of these additions is illustrated in Figure 3. Manipulation of the $(W + Re)/Ta$ ratio in UCSX8 resulted in further reductions in the solid-liquid partitioning coefficients and consequently substantially fewer defects.

[0037] In all three alloys, freckle defects were concentrated in the platform and root of the casting while only in UCSX6, designed to be the most susceptible of the three alloys to single crystal breakdown, were any freckle defects observed in the tip and blade. The macroetched platforms of the as-cast blades of UCSX6, UCSX7 and UCSX8 in Figure 4 show a decrease in the number of freckle defects from UCSX6 to UCSX8.

[0038] Freckle formation occurs when the driving force for fluid flow, as described by the destabilising buoyancy forces corresponding to the solute-induced density inversion term $\Delta\rho/\rho_0$ exceeds the surrounding frictional forces. Hence, by reducing the amount by which W and Re are depleted from the interdendritic solute during solidification, Cr and Mo additions decrease the potential for density inversion and, in so doing, lessen the susceptibility of the alloy to the formation of localised convective instabilities.

[0039] To explain the effect of Cr and Mo on the solid-liquid partitioning of Re and W the principal factors which control the solidification characteristics of an alloy need to be considered, namely the phases present in the as-cast microstructure, the freezing range and the overall thermodynamics of the system. During directional solidification under steady state conditions, the mushy zone is comprised of single phase γ dendrites and liquid solute. Since the alloying additions in Ni-base superalloys tend to partition preferentially into either the γ or γ' phases, limited solubility of γ' forming elements exists within the single phase dendrites during solidification. Hence, elements such as Ta, A1 and Hf become enriched into the liquid solute. The other alloying additions, Re, W, Cr, Co, Mo and Ru, are soluble in the γ phase and tend to partition preferentially to different degrees into the γ dendrites during solidification. A reduction in the degree of micro-segregation could occur if the respective alloying additions shifted the overall composition of the alloy closer to that of

the γ/γ' eutectic. An initial composition further from the eutectic composition would enable segregation over a greater freezing range prior to attainment of the eutectic composition, at which point the remaining liquid would solidify as eutectic and no further solid-liquid partitioning could take place. However, both Cr and Mo additions were shown to decrease the degree of segregation (Figure 3) and the volume fraction of eutectic in the as-cast condition (Figure 5 and Figure 6). Figure 5 reveals the dendritic as-cast structures for the C17 alloy series. Pools of γ/γ' eutectic dispersed in the interdendritic regions are clearly distinguishable within the dendritic structure. Qualitative examination of the as-cast microstructures of each alloy set indicated that the γ/γ' eutectic content decreased with increasing Cr and Mo contents (Figure 5(a)-(d)). In the base alloy a continuous distribution of eutectic around the dendrites is evident whereas the eutectic pools become more isolated and dispersed as the overall content of alloying additions increases. This trend was confirmed quantitatively (Figure 6), where the volume fraction eutectic decreased at a rate comparable to the overall amount of alloying addition. For example, an addition of 4.5wt% Cr decreased the eutectic content to a greater extent than an addition of 2.2wt% Mo, while the least amount of eutectic was present in the alloy containing 6.7wt% (4.5wt% Cr + 2.2wt% Mo) of alloying additions. The decrease in eutectic volume fraction in the C17 alloys was not unexpected since doping of the alloys with Cr and Mo effectively diluted the system, thus drawing the composition of the alloy further from that of the eutectic. In addition, Cr and Mo are primarily γ rather than γ' formers so it would be unlikely that they would promote eutectic formation.

[0040] The effect of Cr and Mo on the temperature range over which segregation could occur was also investigated by measuring the solidus and liquidus temperatures of the C17 base alloy and the Cr- and Mo-containing counterparts using Differential Scanning Calorimetry (DSC). Since the magnitude of the freezing range ($T_S - T_L$) governs the extent of the mushy zone during directional solidification, minor changes could also influence the segregation characteristics of the alloy. Alloys that solidify over a relatively small freezing range may exhibit minimal levels of W and Re segregation since the thermal fields are likely to have a larger influence than the solute fields during solidification. The results however, show that the freezing range is narrowest for the undoped C17 base alloy (Table 4). Increases of $\sim 7^\circ\text{C}$ were observed with 2.2wt% Mo additions while Cr additions to C17 increased the freezing range by $\sim 20^\circ\text{C}$. The alloy containing both elemental additions exhibited the largest freezing range. Coupled with the microstructural observations regarding the volume fraction of eutectic, results from this study indicate that the solidification characteristics are strongly dependent upon alloy composition.

Table 4: DSC results showing the effect of Cr and Mo additions on the freezing range of C17.

Alloy	Solidus ($^\circ\text{C}$)	Liquidus ($^\circ\text{C}$)	Freezing Range ($^\circ\text{C}$)
C17	1399	1420	21
C17 + Mo	1392	1420	28
C17 + Cr	1381	1422	41
C17 + Cr + Mo	1374	1420	46

[0041] As Ni-base superalloys become more heavily alloyed, supersaturation of the γ phase with Re, W, Co, Cr, Mo and Ru during solidification could occur as the solubility limits are exceeded. Elements that tend to increase the liquidus temperature of Ni (Re and W), also tend to segregate most strongly to the single phase γ dendrites during solidification. Ru is an unusual alloying addition as it slightly increases the liquidus temperature, but segregates only mildly to the γ phase. Other γ forming elements, Co, Cr and Mo, tend to slightly lower the solidus temperature and segregate only moderately to the γ phase during solidification. Based on the observed changes in microstructure and associated changes in freezing range, compositional changes associated with the Cr and Mo additions appeared to be altering the solid-solution solubility limits that govern segregation during solidification. In general, higher levels of refractory element segregation were measured in alloys containing low overall levels of the potent γ forming elements. Based on atomic percentages, the lowest combined levels of Re, W, Cr and Mo from the initial study were found in RR3010 and C17, 6.6% and 5.25% respectively. These alloys also exhibited the largest degree of segregation, with K_{R_e} of 1.57 and 1.55 and k_w of 1.26 and 1.30 for RR3010 and C17 respectively. Alloys, such as SRR300G and SRR300I, which contain significantly higher levels (9.6 and 10.9 at % respectively) of these potent γ forming elements tend to result in less segregation during solidification (K_{R_e} is 1.28 and 1.23 and k_w is 1.19 and 1.12 for SRR300G and SRR300I respectively). This was investigated further using 1 and 3 at % (3 and 9.6 wt%) iridium additions to C17. Despite Ir partitioning to the solid more strongly than either Cr or Mo in the same alloy system (Table 2) and the doping concentrations being greater than the amount to which Mo was added to C17, no significant changes in the solidification paths of either W or Re was noted. Interestingly however, Ir greatly reduced the solid-liquid partitioning of Ta (Figure 7). The Ir-Ta binary phase diagram indicates extensive interactions between the two elements, including the formation of σ phase over a wide composition range, the same intermetallic phase observed in the binary phase diagrams of Cr-Re, Mo-Re and W-Re. No such interactions

are observed for the elements (Co, Al and Ru) which exhibited a negligible influence on the solidification paths of W and Re. While it is an over simplification to compare binary with multi-component systems, the fact that Cr, Mo, W and Re all combine to form thermodynamically stable intermetallic topologically close-packed (TCP) phases in multi-component alloys at elevated temperatures suggest that these strong interactions extend to multi-component systems.

[0042] The electron configurations of Cr, Mo, W and Re are listed in Table 5.

Element	Atomic Number	Electron Configuration
Cr	24	$1s^2 2s^2 2p^6 3s^2 3p^6 \mathbf{3d^5} 4s^1$
Mo	42	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 \mathbf{4d^5} 5s^1$
W	74	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 4f^{14} 5s^2 5p^6 \mathbf{5d^4} 6s^2$
Re	75	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6 4d^{10} 4f^{14} 5s^2 5p^6 \mathbf{5d^5} 6s^2$

[0043] While not wishing to be limited to a particular theory, it is thought to be the electron vacancies in the d-shell orbitals (highlighted in bold) which provide the high potential for the formation of strong TCP phase bonds between these atoms. The d electrons are loosely bound and become delocalised together with s electrons resulting in stronger attractions due to the involvement of more electrons. The inherent stability of TCPs indicates there may be extensive covalent bonding interactions via the d electrons and orbitals of the atoms of the TCP forming elements supplementing their metallic bonding. While no long range ordering exists in the liquid state, a limited degree of short range ordering may exist between these elements. Hence, it is thought that the affinity these elements have for one another in the solid state persists in the melt and consequently the solidification paths of W and Re are altered through their interactions with Cr and Mo atoms. The greater potency of Mo as compared to Cr additions in reducing the partitioning of W and Re can also be explained through these d shell interactions. The 4d orbitals of Mo atoms are much more extended than the 3d orbitals of Cr relative to the filled s and p orbitals of the same shell. This is because the nuclear charge is increased from Cr to Mo, meaning the s and p filled subshells, which feel the increased nuclear charge more strongly due to their orbits running much closer to the nucleus, cannot expand as much as the 4d orbital thus allowing for greater overlap of the 4d orbitals with the d orbitals of neighbouring atoms resulting in greater interaction. This is exemplified by the wider composition range over which σ phase is stable in the Mo-Re binary phase diagrams compared to that of Cr-Re. The exact mechanisms by which these interactions decrease the extent of microsegregation of W and Re during solidification is unclear. The effect may be both thermodynamic and kinetic in nature. It is possible that these interactions cause Cr and Mo atoms to form metastable clusters with W and Re within the melt which increase the thermodynamic stability of the liquid with respect to the solid, particularly in the vicinity of the crystallisation temperature where volume differences between the solid and liquid are small and the atomic arrangements in the liquid are consequently more or less similar to their arrangements in the corresponding solid bodies. Kinetically, these same clusters could effectively lower the liquid diffusivities of W and Re, thus reducing the rate at which W and Re atoms can diffuse towards the solid-liquid interact. The result is a compromise of the solid-liquid partition coefficients of each participant element in the cluster; that is the coefficients of W and Re are reduced and those of Cr and Mo are increased. This is best illustrated by comparison of the solidification characteristics of UCSX6 to UCSX7 and SRR300A to SRR300B in Table 2. The addition of Cr and Mo to UCSX6 results in the reduction of the k values of W and RE closer to those of Cr and Mo whereas the increase in partitioning of Re in SRR300B, associated with a higher Re content, results in a corresponding increase in the partitioning of Cr and Mo to the growing solid K_{Cr} is 1.04 and 1.11 and K_{Mo} is 1.06 and 1.09 in SRR300A and SRR300B respectively). This compromise is beneficial to the overall castability of the alloy due to the higher density of W and Re compared to Cr and Mo.

[0044] Despite quantification of the mechanisms by which Cr and Mo influence the solid-liquid partitioning of W and Re, the observed effects of Mo and Cr are interesting particularly considering the recent trends towards developing low chromium, low molybdenum content superalloys, where for example in RR3010 the Mo and Cr contents are now at 0.5 and 1.7wt% respectively. This trend is primarily associated with the destabilising effect that Cr and Mo have on the γ - γ' microstructure after prolonged exposures at elevated temperatures. Minimisation of these elements have enabled advanced Ni-based single crystals to be alloyed with increasing levels of potent solid solution strengtheners, such as W and Re, to enhance the high temperature creep properties. Cr is typically maintained at sufficient concentrations to provide a certain level of hot corrosion and oxidation resistance. These changes however, appear to be detrimental to the manufacture and production of advanced single crystal components because of the increased likelihood for grain defect formation during directional solidification. As the overall content of Re has increased the price of bar stock, improvements in yield are of greater importance. The results from this investigation demonstrate that the intrinsic tendency of high refractory Ni-based single crystal alloys to form grain defects during solidification is decreased by increasing the overall level of Cr and Mo in the alloy. Both of these elements reduce the extent of microsegregation of the dense

refractory elements W and Re during solidification known to cause single crystal breakdown. In fact, this beneficial effect appears as though it is due to the very fact that both Cr and Mo are TCP forming elements. As a result, increasing the levels of both Cr and Mo to improve the solidification characteristics of single crystal Ni-base superalloys will further destabilise the microstructure. However, the resulting microstructural instabilities could potentially be controlled through the addition of ruthenium. Preliminary studies suggest that Ru can be added in the concentration necessary to improve microstructural stability without significant detriment to the solidification characteristics of the alloy. Moreover, the decreased level of microsegregation accompanying increases in Mo and Cr contents would reduce the extent of local Re supersaturation in the as-cast crystals and enable homogenisation to occur more rapidly during solution-heat treatment.

[0045] Any practical single crystal alloy has to have a combination of useful properties. These properties include alloy density, creep-rupture properties, high temperature strength and fatigue resistance, microstructural stability and oxidation and hot corrosion resistance, together with acceptable raw material and processing costs. Increasing the mechanical strength nearly always involves additions which are both costly and dense, so in order to maintain an acceptable component cost, the processing costs must be kept as low as possible.

[0046] This invention is linked to one important aspect of processing cost, the yield of acceptable castings, commonly called castability. The novel aspect of this invention is the identification of relatively high chromium and molybdenum contents as beneficial, in combination with the well-known damaging effects of rhenium and tungsten, and beneficial effect of tantalum. These considerations lead to the claimed composition ranges in the following way.

[0047] The chromium content, preferably 3 to 4 weight percent, should not be less than about 2 weight percent nor more than about 5 weight percent (all compositional percentages herein are by weight). The chromium content is desirably high due to its benefit on both hot corrosion and oxidation resistance and castability by minimising the formation of solidification related grain defects. However it desirably does not exceed 5% because chromium contributes to microstructural instability with respect to the formation of deleterious topologically close-packed (TCP) phases following prolonged exposure at elevated temperatures. Below 2% chromium the hot corrosion and oxidation resistance become unacceptable in the preferred embodiment.

[0048] The molybdenum content ranges from 2 to 5.5%, and preferably 3.5 to 4.5%. Molybdenum is preferably present in concentrations greater than 2% because it improves the castability of the alloy. It is also an effective strengthening element in the gamma phase and has a lower density than the alternative strengtheners tungsten and rhenium. An upper limit of 5.5% is desirable in the preferred embodiment because molybdenum destabilises the microstructure leading to precipitation of damaging TCP precipitates.

[0049] Ruthenium is present in the preferred embodiment in an amount of at least 1%, conveniently, from about 1 to about 6%, desirably 2 to about 6%, and preferably from about 3 to about 5%. Ruthenium provides strength and stabilises the microstructure with respect to the formation of TCP phases, so counteracting the effect of the necessary elevated chromium and molybdenum contents for improved castability. In this work ruthenium was found to be largely neutral in its effect on castability; high levels of ruthenium can therefore be added for strength and stability without compromising casting yield. A preferred upper limit is about 6%, due to the expense of ruthenium additions.

[0050] Tungsten contents range in the preferred embodiment, from about 2 to about 5%, preferably 3.5 to 5%. Tungsten partitions to both the gamma and gamma prime phases and is also an effective strengthener. Concentrations greater than 2% are desirable to provide sufficient strength to the superalloy but its density undesirably increases the density of the alloy and greatly hinders the ease of single crystal solidification. Its content must therefore be maintained below about 5% to ensure a good casting yield by minimising the $(W+Re)/Ta$ ratio. These lower levels of tungsten will also improve the microstructural stability and oxidation and hot corrosion resistance of the alloy.

[0051] Rhenium is present in an amount of from about 5 to about 8%, preferably from about 5 to about 7%. Concentrations of rhenium above 5% are desirable to achieve the high temperature strength, particularly when coupled with a relatively low tungsten content, since it is a potent solid-solution strengthening element of the gamma phase. Rhenium should not be added in amounts greater than about 8% to the preferred embodiments because it is a dense and expensive element, is detrimental to castability and promotes the formation of TCP phases.

[0052] Tantalum is present in an amount of from about 4 to 8%, preferably 5.5 to 7%. Tantalum is desirable in concentrations greater than 4% because it strengthens the gamma prime phase, provides resistance to hot corrosion but, most notably in this invention, reduces the formation of solidification related grain defects by minimising the $(W+Re)/Ta$ ratio. If the tantalum content is above 8% however, then density of the alloy is undesirably increased. The novel benefits of chromium and molybdenum, coupled with low tungsten mean that tantalum can be reduced to achieve a reduced alloy density.

[0053] The preferred embodiments of the present invention provide a nickel-based single crystal superalloy which have the advantage of exhibiting improved castability, i.e. less susceptibility to the formation of solidification related grain defects during single crystal solidification, by increasing the Cr and Mo contents and minimising the $(W+Re)/Ta$ ratio by decreasing the W content relative to typical nickel-based single crystal superalloy compositions.

[0054] The preferred embodiment comprises a nickel-based single crystal superalloy where the composition consists of 2-8 of Co, 2-5 of Cr, 2-5.5 of Mo, 2-5 of W, 5-7 of Al, 4-8 of Ta, 5-8 of Re, 2-6 of Ru, 0-2 of Ti and 0-0.5 of Hf in terms

of % by weight and residual part substantially consists of Ni wherein said alloy may contain unavoidable impurities.

Claims

1. A composition of matter comprising:

5wt% to 8wt% rhenium;
4wt% to 8wt% tantalum;
2wt% to 5wt% tungsten;
2wt% to 5.5wt% molybdenum;
2wt% to 5wt% chromium;
2wt% to 6wt% ruthenium;
2wt% to 8wt% cobalt;
5wt% to 7wt% aluminium;
0wt% to 2wt% titanium;
0wt% to 0.5wt% hafnium;
and the balance nickel and incidental impurities.

2. A composition of matter according to claim 1 comprising 5wt% to 7wt% rhenium.

3. A composition of matter according to any preceding claim comprising greater than 6wt% rhenium.

4. A composition of matter according to any preceding claim comprising 3.5wt% to 5wt% tungsten.

5. A composition of matter according to any preceding claim comprising less than 4wt% tungsten.

6. A composition of matter according to any preceding claim comprising 3.5wt% to 4.5wt% molybdenum.

7. A composition of matter according to any preceding claim comprising less than 2.9wt% molybdenum.

8. A composition of matter according to any of claims 1 to 5 comprising greater than 4.5wt% molybdenum.

9. A composition of matter according to any preceding claim comprising 3wt% to 4wt% chromium.

10. A composition of matter according to any preceding claim comprising 3wt% to 5wt% ruthenium.

11. A composition of matter according to any preceding claim comprising greater than 4wt% ruthenium.

12. A composition of matter according to any preceding claim comprising 3wt% to 8wt% cobalt.

13. A composition of matter according to any preceding claim comprising 5wt% to 6.5wt% aluminium.

14. A composition of matter according to any preceding claim comprising 0.05wt% to 0.5wt% hafnium.

15. A composition of matter according to any preceding claim comprising 0.1wt% to 2wt% titanium.

16. A single crystal article formed from a composition of matter according to any preceding claim.

17. A single crystal according to claim 16 in the form of aerofoil.

18. A single crystal article according to claim 16 or 17 in the form of aerofoil blade.

19. A single crystal article according to claim 17, 18 or 19 in the form of a turbine blade.

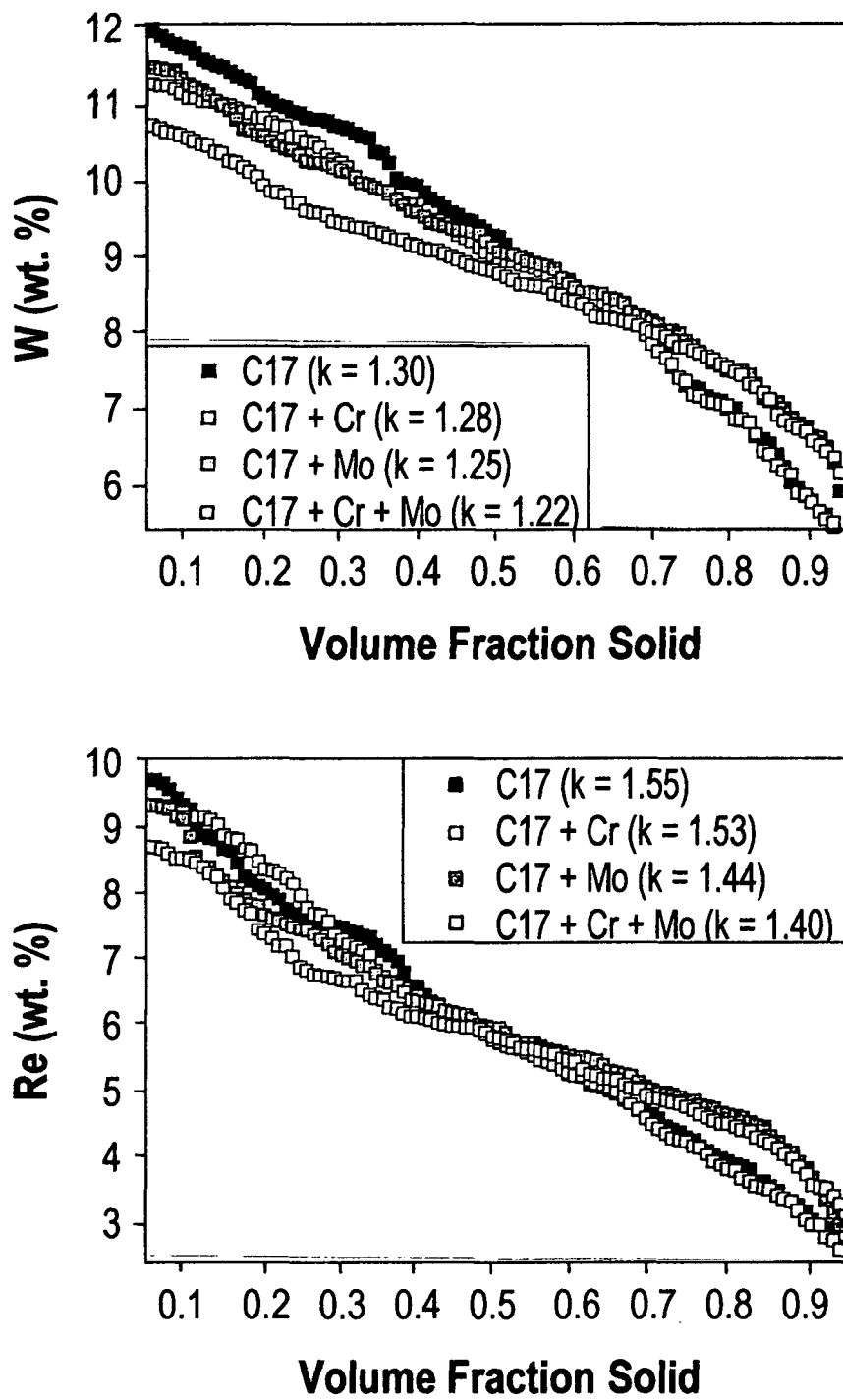


Fig. 1

The effect of Cr and Mo additions on the solidification paths of W and Re in C17.

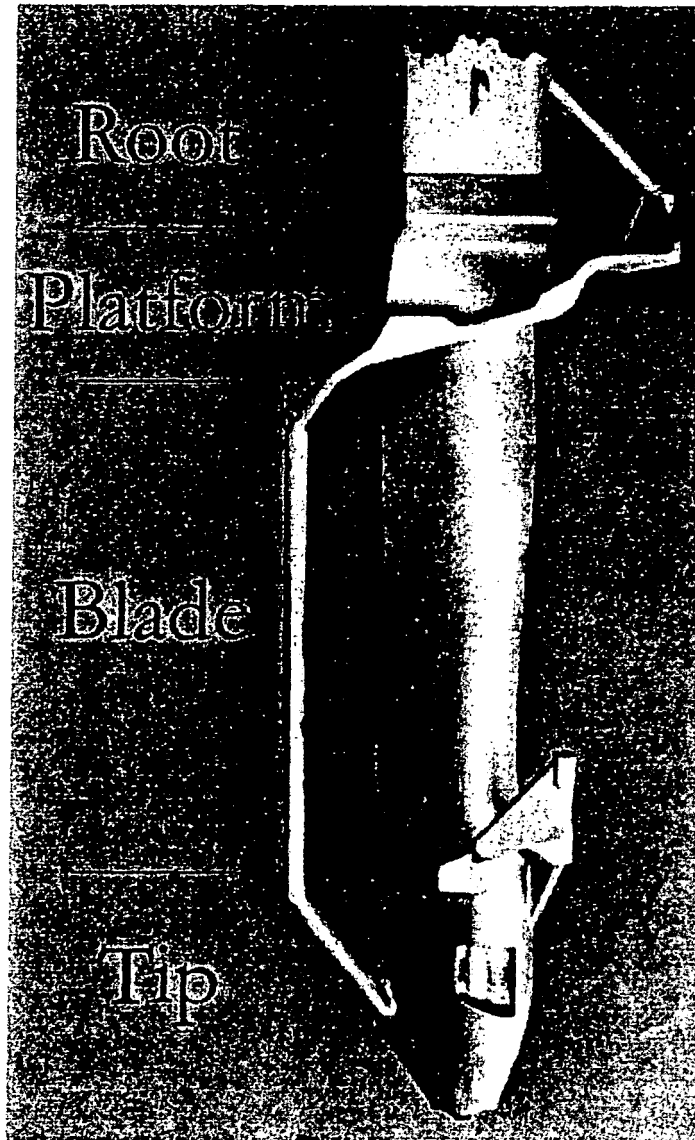


Fig. 2

As-cast turbine blade illustrating the four areas for defect documentation.

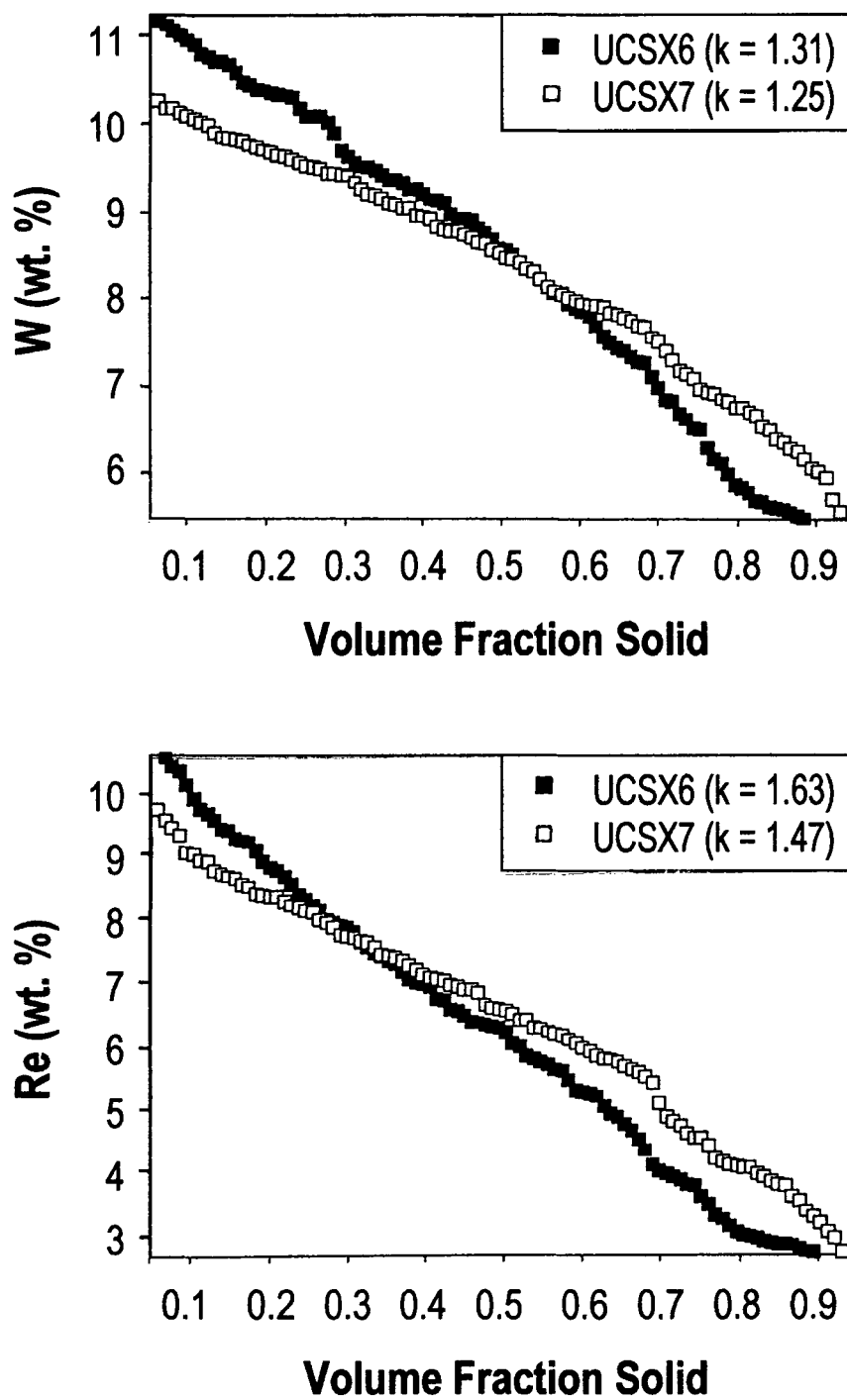


Fig. 3

Comparison of the solidification paths of W and Re in UCSX6 and UCSX7 illustrating the effects of Cr and Mo additions.

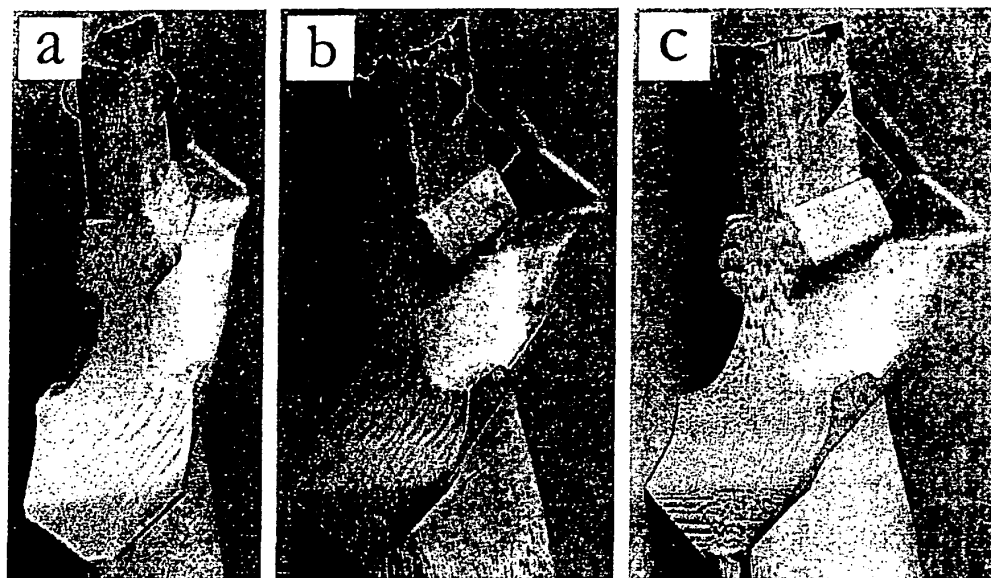


Fig. 4

Photos of the macroetched platform of the as-cast turbine blades of (a) UCSX6 (b) UCSX7 and (c) UCSX8 showing a decrease in the number of freckle defects from left to right.

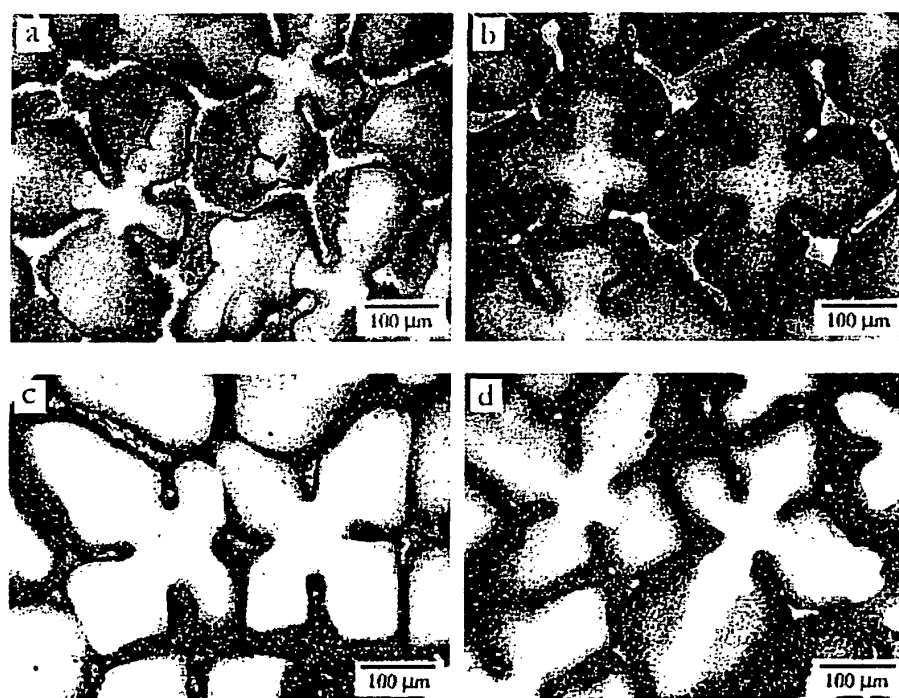
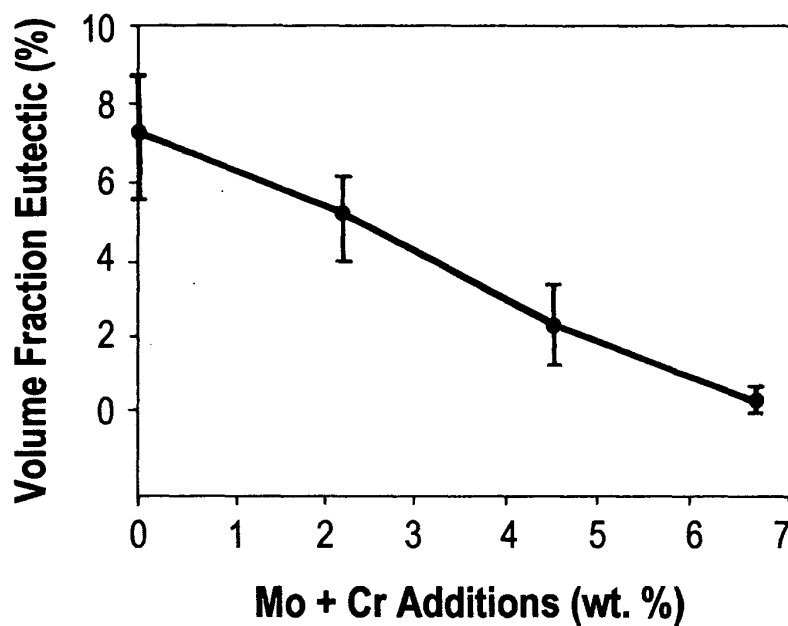
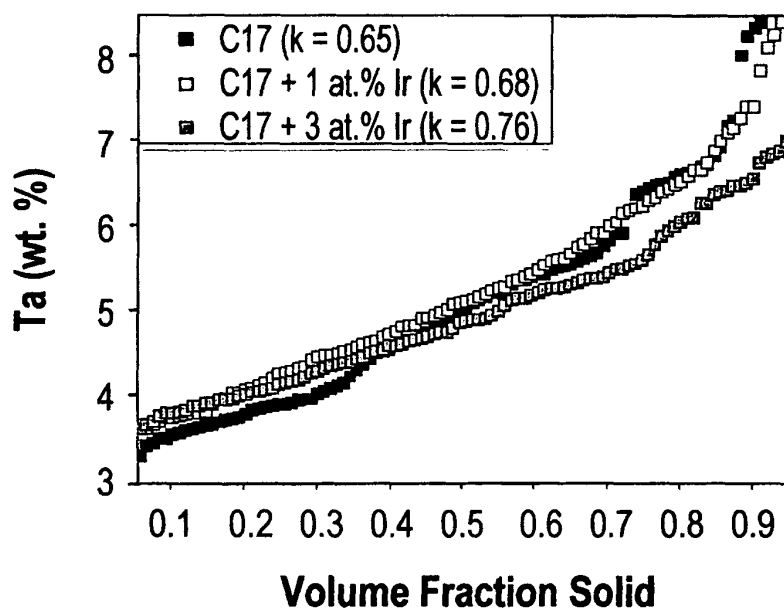


Fig. 5

Optical micrographs of the as-cast microstructures of (a) C17 (b) C17 + Mo (c) C17 + Cr and (d) C17 + Cr + Mo showing decreasing levels of interdendritic eutectic as Mo and Cr are added.

***Fig. 6***

Quantitative analysis showing decreasing volume fraction eutectic with increasing Mo and Cr contents in C17.

***Fig. 7***

The effect of Ir additions on the partitioning behaviour of Ta in C17.