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(54) **A NICKEL-BASED ALLOY**

NICKELBASISLEGIERUNG

ALLIAGE A BASE DE NICKEL

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EP 3 329 025 B1

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Description

[0001] The present invention relates to a nickel-based single crystal superalloy composition designed for high performance jet propulsion applications. The alloy - a fourth generation single crystal nickel-based superalloy - exhibits a combination of creep resistance and oxidation resistance which is comparable or better than equivalent grades of alloy. The density, cost, processing and long term stability of the alloy have also been considered in the design of the new alloy.

[0002] Examples of typical compositions of fourth generation nickel-based single crystal superalloys are listed in Table 1. These alloys may be used for the manufacture of rotating/stationary turbine blades used in gas turbine engines.

Table 1: Nominal composition in wt. % of commercially used fourth generation single crystal turbine blade alloys.

Alloy	Al	Cr	Co	Mo	Re	Ru	W	Ti	Ta	Hf
PW1497	5.6	2.0	16.5	2.0	6.0	3.0	6.0	0.0	8.3	0.2
TMS-162	5.8	2.9	5.8	3.9	4.9	6.0	5.8	0.0	5.6	0.1
TMS-138A	5.7	3.2	5.8	2.8	5.8	3.6	5.6	0.0	5.6	0.0

[0003] It is an aim of the invention is to provide an alloy which has similar or improved high temperature behaviour in comparison to the fourth generation alloys listed in Table 1.

[0004] The present invention provides a nickel-based alloy composition consisting, in weight percent, of: between 3.5 and 6.5% chromium, between 0.0 and 12.0% cobalt, between 4.5 and 11.5% tungsten, between 0.0 and 0.5% molybdenum, between 3.5 and 7.0% rhenium, between 1.0 and 3.7% ruthenium, between 3.7 and 6.8% aluminium, between 5.0 and 9.0% tantalum, between 0.0 and 0.5% hafnium, between 0.0 and 0.5% niobium, between 0.0 and 0.5% titanium, between 0.0 and 0.5% vanadium, between 0.0 and 0.1% silicon, between 0.0 and 0.1% yttrium, between 0.0 and 0.1% lanthanum, between 0.0 and 0.1% cerium, between 0.0 and 0.003% sulphur, between 0.0 and 0.05% manganese, between 0.0 and 0.05% zirconium, between 0.0 and 0.005% boron, between 0.0 and 0.01% carbon, the balance being nickel and incidental impurities. This composition provides a good balance between cost, density and creep and oxidation resistance.

[0005] In an embodiment, the nickel-based alloy composition consists, in weight percent, of between 4.0 and 5.0% chromium. Such an alloy is particularly resistant to TCP formation whilst still having good oxidation resistance.

[0006] In an embodiment, the nickel-based alloy composition contains at least 0.1 wt% cobalt to increase creep resistance and lower the γ' solvus temperature thereby to increase the solutioning window.

[0007] In an embodiment, the nickel-based alloy composition consists, in weight percent, of between 7.0 and 11.0% cobalt. Such an alloy has improved resistance to creep deformation with a limited level of creep anisotropy (orientation dependence) being observed and has increased ease of processing due to a reduced γ' solvus temperature. A maximum amount of cobalt of 10.9% further limits creep anisotropy.

[0008] In an embodiment, the nickel-based alloy composition consists, in weight percent, of between 7.0 and 9.5% tungsten. This composition strikes a compromise between reduced cost, low weight and creep resistance.

[0009] In an embodiment, the nickel-based alloy composition consists, in wt%, of at least 7.1% tungsten in order to achieve high creep resistance.

[0010] In an embodiment, the nickel-based alloy composition consists, in weight percent, of between 3.7 and 6.6% aluminium, preferably between 5.1 and 6.6% aluminium, or more preferably 5.5 and 6.6% aluminium. This composition achieves high creep resistance and reduced density alongside increased oxidation resistance.

[0011] In an embodiment, the nickel-based alloy composition consists, in weight percent, of between 5.0 and 9.0% tantalum. This provides a balance between creep resistance, ease of manufacture (based upon solutioning window) and density and/or prevents the possibility of formation of the Eta (ϵ) phase Ni_3Ta . Preferably the alloy consists of between 5.0 and 7.3% tantalum. This reduces the cost and density of the alloy further, increases the solutioning window as well as the propensity for ϵ phase formation.

[0012] In an embodiment, the nickel-based alloy composition consists, in weight percent, of 0.1% or more molybdenum. This is advantageous for improved creep resistance.

[0013] In an embodiment, the nickel-based alloy composition consists, in weight percent of, between 4.5 and 6.0% rhenium, or more preferably 5.3 and 6.0% rhenium. This composition provides a good balance of creep resistance, density, resistance to TCP formation and cost.

[0014] In an embodiment, the nickel-based alloy composition consists, in weight percent of, between 2.0 and 3.0% ruthenium. This composition provides a good balance of creep resistance and cost. An even better compromise is provided in the range of 2.1 and 2.9% ruthenium.

[0015] In an embodiment, the nickel-based alloy composition consists, in weight percent, of between 0.0 and 0.2% hafnium. This is optimum for tying up incidental impurities in the alloy, for example, carbon.

[0016] In an embodiment, the nickel-based alloy composition is such that the following equation is satisfied in which W_{Ta} and W_{Al} are the weight percent of tantalum and aluminium in the alloy respectively $33 \leq W_{Ta} + 5.1 W_{Al} \leq 39$. This is advantageous as it allows a suitable volume fraction γ' to be present.

[0017] In an embodiment, the nickel-based alloy composition is such that the following equation is satisfied in which W_{Ta} and W_{Al} are the weight percent of tantalum and aluminium in the alloy respectively $2.2 \leq 5.15 W_{Al} - 0.5 W_{Al}^2 - W_{Ta}$; preferably $2.9 \leq 5.15 W_{Al} - 0.5 W_{Al}^2 - W_{Ta}$. This is advantageous as it allows a suitable solutioning window for the alloy to allow for heat-treatment processes.

[0018] In an embodiment, the nickel-based alloy composition is such that the following equation is satisfied in which W_{Ru} and W_{Re} are the weight percent of ruthenium and rhenium in the alloy respectively $4.5 \geq W_{Ru} + 0.225 W_{Re}$; preferably $3.9 \geq W_{Ru} + 0.225 W_{Re}$. This is advantageous as it results in an alloy with a relatively low cost.

[0019] In an embodiment, the nickel-based alloy composition is such that the following equation is satisfied in which W_{Re} and W_W are the weight percent of rhenium and tungsten in the alloy respectively $15.8 \geq 1.13 W_{Re} + W_W$; preferably $14.4 \geq 1.13 W_{Re} + W_W$. This is advantageous as it results in an alloy with a relatively low density.

[0020] In an embodiment, the nickel-based alloy composition is such that the following equation is satisfied in which W_{Re} , W_{Mo} and W_W are the weight percent of rhenium, molybdenum and tungsten in the alloy respectively $21.9 \leq 2.92 W_{Re} + (W_W + W_{Mo})$; preferably $24.6 \leq 2.92 W_{Re} + (W_W + W_{Mo})$. This is advantageous as it results in an alloy with a high creep resistance.

[0021] In an embodiment, in the nickel-based alloy composition, the sum of the elements niobium, titanium and vanadium, in weight percent, is less than 1%, preferably 0.5% or less. This means that those elements do not have too much of a deleterious effect on environmental resistance of the alloy.

[0022] In an embodiment, in the nickel-based alloy composition, the sum of the elements niobium, titanium, vanadium and tantalum is between 5.0 - 9.0 wt.%, preferably 5.0 - 7.3 wt.%. This results in a preferred volume fraction of γ' and APB energy.

[0023] In an embodiment, the nickel-based alloy composition has between 60 and 70% volume fraction γ' .

[0024] In an embodiment, a single crystal article is provided, formed of the nickel-based alloy composition of any of the previous embodiments.

[0025] In an embodiment, a turbine blade for a gas turbine engine is provided, formed of an alloy according to any of the previous embodiments.

[0026] In an embodiment, a gas turbine engine comprising the turbine blade of the previous embodiment is provided.

[0027] The term "consisting of" is used herein to indicate that 100% of the composition is being referred to and the presence of additional components is excluded so that percentages add up to 100%.

[0028] The invention will be more fully described, by way of example only, with reference to the accompanying drawings in which:

Figure 1 shows the partitioning coefficient for the main components in the alloy design space;

Figure 2 is a contour plot showing the effect of γ' forming elements aluminium and tantalum on volume fraction of γ' for alloys within the alloy design space, determined from phase equilibrium calculations conducted at 900°C.;

Figure 3 is a contour plot showing the effect of elements aluminium and tantalum on anti-phase boundary energy, for alloys with a volume fraction of γ' between 60-70% at 900°C;

Figure 4 is a contour plot showing the effect of elements aluminium and tantalum on the solutioning window for alloys with a volume fraction of γ' between 60-70% at 900°C;

Figure 5 is a contour plot showing the effect of rhenium and ruthenium content on raw elemental cost, for alloys with a volume fraction of γ' between 60-70% at 900°C with tantalum between 5 - 9 wt.%;

Figure 6 is a contour plot showing the effect rhenium and tungsten on density, for alloys with a volume fraction of γ' between 60-70% at 900°C with tantalum between 5 - 9 wt.%;

Figure 7 is a contour plot showing the effect of elements rhenium and tungsten on the creep resistance, for alloys with a volume fraction of γ' between 60-70% at 900°C with tantalum between 5-9 wt.%, which contain 0 wt.% ruthenium;

Figure 8 is a contour plot showing the effect of elements rhenium and tungsten on the creep resistance, for alloys with a volume fraction of γ' between 60-70% at 900°C with tantalum between 5-9 wt.%, which contain 1 wt.% ruthenium;

Figure 9 is a contour plot showing the effect of elements rhenium and tungsten on the creep resistance, for alloys with a volume fraction of γ' between 60-70% at 900°C with tantalum between 5-9 wt.%, which contain 2 wt.% ruthenium;

Figure 10 is a contour plot showing the effect of elements rhenium and tungsten on the creep resistance, for alloys with a volume fraction of γ' between 60-70% at 900°C with tantalum between 5-9 wt.%, which contain 3 wt.% ruthenium; Figure 11 is a contour plot showing the effect of elements chromium and tungsten on microstructural stability, for alloys with a volume fraction of γ' between 60-70% at 900°C with tantalum between 5-9 wt.% and between 1-3 wt.% ruthenium, which contain 4 wt.% rhenium;

Figure 12 is a contour plot showing the effect of elements chromium and tungsten on microstructural stability, for alloys with a volume fraction of γ' between 60-70% at 900°C with tantalum between 5-9 wt.% and between 1-3 wt.% ruthenium, which contain 5 wt.% rhenium;

Figure 13 is a contour plot showing the effect of elements chromium and tungsten on microstructural stability, for alloys with a volume fraction of γ' between 60-70% at 900°C with tantalum between 5-9 wt.% and between 1-3 wt.% ruthenium, which contain 6 wt.% rhenium;

Figure 14 is a contour plot showing the effect of elements chromium and tungsten on microstructural stability, for alloys with a volume fraction of γ' between 60-70% at 900°C with tantalum between 5-9 wt.% and between 1-3 wt.% ruthenium, which contain 7 wt.% rhenium;

Figure 15 is a contour plot showing the effect of cobalt on the γ' solvus temperature for alloys with different ratios of aluminium to tantalum, where the alloys have a volume fraction of γ' between 60-70% at 900°C with tantalum between 5 - 9 wt.%;

Figure 16 shows the time to 1% creep strain for alloy ABD-2 of the present invention (circles) compared with the fourth generation single crystal turbine blade alloy TMS-138A (triangles);

Figure 17 shows the time to rupture for alloy ABD-2 of the present invention (circles) compared with the fourth generation single crystal turbine blade alloy TMS-138A (triangles); and

Figure 18 is a plot of measured weight change for the fourth generation single crystal turbine blade alloy TMS-138A (triangles) and alloy ABD-2 of the present invention (circles) when oxidised in air at 1000°C.

[0029] Traditionally, nickel-based superalloys have been designed through empiricism. Thus their chemical compositions have been isolated using time consuming and expensive experimental development, involving small-scale processing of limited quantities of material and subsequent characterisation of their behaviour. The alloy composition adopted is then the one found to display the best, or most desirable, combination of properties. The large number of possible alloying elements indicates that these alloys are not entirely optimised and that improved alloys are likely to exist.

[0030] In superalloys, generally additions of chromium (Cr) and aluminium (Al) are added to impart resistance to oxidation, cobalt (Co) is added to improve resistance to sulphidisation. For creep resistance, molybdenum (Mo), tungsten (W), Co, rhenium (Re) and sometimes ruthenium (Ru) are introduced, because these retard the thermally-activated processes - such as, dislocation climb - which determine the rate of creep deformation. To promote static and cyclic strength, aluminium (Al), tantalum (Ta) and titanium (Ti) are introduced as these promote the formation of the precipitate hardening phase gamma-prime (γ'). This precipitate phase is coherent with the face-centered cubic (FCC) matrix phase which is referred to as gamma (γ).

[0031] A modelling-based approach used for the isolation of new grades of nickel-based superalloys is described here, termed the "Alloys-By-Design" (ABD) method. This approach utilises a framework of computational materials models to estimate design relevant properties across a very broad compositional space. In principle, this alloy design tool allows the so called inverse problem to be solved; identifying optimum alloy compositions that best satisfy a specified set of design constraints.

[0032] The first step in the design process is the definition of an elemental list along with the associated upper and lower compositional limits. The compositional limits for each of the elemental additions considered in this invention - referred to as the "alloy design space" - are detailed in Table 2.

Table 2: Alloys design space in wt. % searched using the "Alloys-by-Design" method.

	Cr	Co	Re	W	Al	Ta	Ru
Min	2.0	0.0	3.0	4.0	3.0	3.0	0.0
Max	10.0	16.0	10.0	12.0	9.0	16.0	4.0

[0033] The second step relies upon thermodynamic calculations used to calculate the phase diagram and thermodynamic properties for a specific alloy composition. Often this is referred to as the CALPHAD method (CALculate PHase Diagram). These calculations are conducted at the service temperature for the new alloy (900°C), providing information about the phase equilibrium (microstructure).

[0034] A third stage involves isolating alloy compositions which have the desired microstructural architecture. In the case of single crystal superalloys which require superior resistance to creep deformation, the creep rupture life is maximised when the volume fraction of the precipitate hardening phase γ' lies between 60%-70%. It is also necessary that the γ/γ' lattice misfit should conform to a small value, either positive or negative, since coherency is otherwise lost; thus limits are placed on its magnitude. The lattice misfit δ is defined as the mismatch between γ and γ' phases, and is determined according to

$$\delta = \frac{2(a_{\gamma'} - a_{\gamma})}{a_{\gamma'} + a_{\gamma}} \quad (1)$$

where a_{γ} and $a_{\gamma'}$ are the lattice parameters of the γ and γ' phases.

[0035] Rejection of alloy on the basis of unsuitable microstructural architecture is also made from estimates of susceptibility to topologically close-packed (TCP) phases. The present calculations predict the formation of the deleterious TCP phases sigma (σ), P and mu (μ) using CALPHAD modelling.

[0036] Thus the model isolates all compositions in the design space which are calculated to result in a volume fraction of γ' of between 60 and 70%, which have a lattice misfit γ' of less than a predetermined magnitude and have a total volume fraction of TCP phases below a predetermined magnitude.

[0037] In the fourth stage, merit indices are estimated for the remaining isolated alloy compositions in the dataset. Examples of these include: creep-merit index (which describes an alloy's creep resistance based solely on mean composition), anti-phase boundary (APB) energy, density, cost and solutioning window.

[0038] In the fifth stage, the calculated merit indices are compared with limits for required behaviour, these design constraints are considered to be the boundary conditions to the problem. All compositions which do not fulfil the boundary conditions are excluded. At this stage, the trial dataset will be reduced in size quite markedly.

[0039] The final, sixth stage involves analysing the dataset of remaining compositions. This can be done in various ways. One can sort through the database for alloys which exhibit maximal values of the merit indices - the lightest, the most creep resistant, the most oxidation resistant, and the cheapest for example. Or alternatively, one can use the database to determine the relative trade-offs in performance which arise from different combination of properties.

[0040] The example five merit indices are now described.

[0041] The first merit index is the creep-merit index. The overarching observation is that time-dependent deformation (i.e. creep) of a single crystal superalloy occurs by dislocation creep with the initial activity being restricted to the γ phase. Thus, because the fraction of the γ' phase is large, dislocation segments rapidly become pinned at the γ/γ' interfaces. The rate-controlling step is then the escape of trapped configurations of dislocations from γ/γ' interfaces, and it is the dependence of this on local chemistry which gives rise to a significant influence of alloy composition on creep properties.

[0042] A physically-based microstructure model can be invoked for the rate of accumulation of creep strain $\dot{\epsilon}$ when loading is uniaxial and along the $\langle 001 \rangle$ crystallographic direction. The equation set is

$$\dot{\epsilon}_{\langle 001 \rangle} = \frac{16}{\sqrt{6}} \rho_m \phi_p D_{\text{eff}} (1 - \phi_p) (1 / \phi_p^{1/3} - 1) \sinh \left\{ \frac{\sigma b^2 \omega}{\sqrt{6} K_{\text{CF}} kT} \right\} \quad (2)$$

$$\dot{\rho}_m = C \dot{\epsilon}_{\langle 001 \rangle} \quad (3)$$

where ρ_m is the mobile dislocation density, ϕ_p is the volume fraction of the γ' phase, and ω is width of the matrix channels.

The terms σ and T are the applied stress and temperature, respectively. The terms b and k are the Burgers vector and Boltzmann constant, respectively. The term $K_{CF} = 1 + 2\phi_p^{1/3} / 3\sqrt{3\pi}(1 - \phi_p^{1/3})$ is a constraint factor, which accounts for the close proximity of the cuboidal particles in these alloys. Equation 3 describes the dislocation multiplication process which needs an estimate of the multiplication parameter C and the initial dislocation density. The term D_{eff} is the effective diffusivity controlling the climb processes at the particle/matrix interfaces.

[0043] Note that in the above, the composition dependence arises from the two terms ϕ_p and D_{eff} . Thus, provided that the microstructural architecture is assumed constant (microstructural architecture is mostly controlled by heat treatment) so that ϕ_p is fixed, any dependence upon chemical composition arises through D_{eff} . For the purposes of the alloy design modelling described here, it turns out to be unnecessary to implement a full integration of Equations 2 and 3 for each prototype alloy composition. Instead, a first order merit index M_{creep} is employed which needs to be maximised, which is given by

$$M_{creep} = \sum_i x_i / \tilde{D}_i \quad (4)$$

where X_i is the atomic fraction of solute i in the alloy and $\tilde{D}_i$ is the appropriate interdiffusion coefficient.

[0044] The second merit index is for anti-phase boundary (APB) energy. Fault energies in the γ' phase - for example, the APB energy - have a significant influence on the deformation behaviour of nickel-based superalloys. Increasing the APB energy has been found to improve mechanical properties including, tensile strength and resistance to creep deformation. The APB energy was studied for a number of Ni-Al-X systems using density functional theory. From this work the effect of ternary elements on the APB energy of the γ' phase was calculated, linear superposition of the effect for each ternary addition was assumed when considering complex multicomponent systems, resulting in the following equation,

$$\gamma_{APB} = 195 - 1.7x_{Cr} - 1.7x_{Mo} + 4.6x_W + 27.1x_{Ta} + 21.4x_{Nb} + 15x_{Ti} \quad (5)$$

where, x_{Cr} , x_{Mo} , x_W , x_{Ta} , x_{Nb} and x_{Ti} represent the concentrations, in atomic percent, of Cr, Mo, W, Ta, Nb and Ti in the γ' phase, respectively. The composition of the γ' phase is determined from phase equilibrium calculations.

[0045] The third merit index is density. The density, ρ , was calculated using a simple rule of mixtures and a correctional factor, where, ρ_i is the density for a given element and x_i is the atomic fraction of the alloy element.

$$\rho = 1.05[\sum_i x_i \rho_i] \quad (6)$$

[0046] The fourth merit index was cost. In order to estimate the cost of each alloy a simple rule of mixtures was applied, where the weight fraction of the alloy element, x_i , was multiplied by the current (2015) raw material cost for the alloying element, c_i .

$$Cost = \sum_i x_i c_i \quad (7)$$

[0047] The estimates assume that processing costs are identical for all alloys, i.e. that the product yield is not affected by composition.

[0048] A fifth merit index is the solutioning window. By conducting thermodynamic modelling (CALPHAD) calculations across a range of temperatures the solutioning window for each alloy can be calculated. This value - measured in degrees Celsius - can be used to determine if a given alloy is amenable to conventional manufacturing processes used for the production of single crystal turbine blades. Typically the solutioning window must be greater than 50°C to allow for a solution heat treatment. The solution heat treatment is conducted in the single phase region, at this point the alloy will reside solely within the γ phase field. This solution heat treatment is necessary to homogenise the composition of the as cast alloy which may be highly segregated. In order determine the solution heat treatment window the phase equilibrium - or more specifically phase transformations - must be determined over a temperature range. The temperature at which completed dissolution of the γ' phase (known as the γ' solvus temperature) occurs must be known, as must the solidus temperature. The difference between the solidus temperature and the γ' solvus temperature will give the solutioning window. So the solutioning window index calculates as the difference between the solidus temperature and the γ' solvus

temperature.

[0049] The ABD method described above was used to isolate the inventive alloy composition. The design intent for this alloy was to isolate the composition of a fourth generation single crystal nickel-based superalloy that exhibits a combination of creep resistance and oxidation resistance which is comparable or better than equivalent grades of alloy.

The density, cost, processing and long term stability of the alloy have also been considered in the design of the new alloy.

[0050] The material properties - determined using the ABD method - for the commercially used fourth generation single crystal turbine blade alloys are listed in Table 3. The design of the new alloy was considered in relation to the predicted properties listed for these alloys. The calculated material properties for an alloy ABD-2 with a nominal composition according to Table 4 and in accordance with the present invention are also given.

Table 3: Calculated phase fractions and merit indices made with the "Alloys-by-Design" software. Results for fourth generation single crystal turbine blades listed in Table 1 and the nominal composition of the new alloy ABD-2 listed in Table 4.

Alloy	γ^*	Phase Fractions		Creep Merit Index ($m^{-2}s \times 10^{-15}$)		Density (g/cm^3)	Cost (\$/lb)	$\gamma_{APB(111)}$ (mJ/m^2)	γ/γ^* Misfit (%)	Solutioning Window ($^{\circ}C$)
PW1497	0.61	0.000	0.054	0.054	14.6	9.2	296	322	-0.02	43
TMS-162	0.64	0.000	0.060	0.060	13.8	9.0	467	274	-0.44	94
TMS-138A	0.60	0.016	0.032	0.048	12.3	9.0	328	278	-0.19	116
ABD-2	0.66	0.000	0.037	0.037	12.3	8.9	260	274	-0.14	62

[0051] Optimisation of the alloy's microstructure - primarily comprised of an austenitic face centre cubic (FCC) gamma phase (γ) and the ordered L_{12} precipitate phase (γ') - was required to maximise creep resistance. A volume fraction of the γ' phase between 60-70% is generally regarded as optimum as this microstructure is known to provide the maximum level of creep resistance in single crystal blade alloys. A volume fraction γ' of between 60 and 70% was the target for the present alloy but the inventive alloy may deviate from this target.

[0052] The partitioning coefficient for each element included in the alloy design space was determined from phase equilibrium calculations conducted at 900°C, Figure 1. A partitioning coefficient of unity describes an element with equal preference to partition to the γ or γ' phase. A partitioning coefficient less than unity describes an element which has a preference for the γ' phase, the closer the value to zero the stronger the preference. The greater the value above unity the more an element prefers to reside within the γ phase. The partitioning coefficients for aluminium and tantalum show that these are strong γ' forming elements. The elements chromium, cobalt, rhenium, ruthenium and tungsten partition preferably to the γ phase. For the elements considered within the alloy design space, aluminium and tantalum partition most strongly to the γ' phase. Hence, aluminium and tantalum levels were controlled to produce the desired γ' volume fraction.

[0053] Figure 2 shows the effect the elements which are added to form the γ' phase - predominantly aluminium and tantalum - have on the fraction of γ' phase in the alloy at the operation temperature, 900°C in this instance. For the design of this alloy compositions which result in a volume fraction of γ' between 60-70% were considered. Hence between 3.7 and 6.8 weight percent (wt.%) of aluminium was required.

[0054] The change in γ' volume fraction was related to the change in aluminium and tantalum content according to the formula

$$f(\gamma') = W_{Ta} + 5.1W_{Al}$$

where, $f(\gamma')$ is a numerical value which ranges between 33 and 39 for an alloy with the desired γ' fraction, between 0.6 and 0.7 in this case, and W_{Ta} and W_{Al} are the weight percent of tantalum and aluminium in the alloy, respectively.

[0055] Optimisation of aluminium and tantalum levels was also required to increase the anti-phase boundary (APB) energy of the γ' phase. The APB energy is strongly dependent upon the chemistry of the γ' phase. Figure 3 shows the influence of aluminium and tantalum on the APB energy. Compositions where the APB energy was equivalent to or greater than current fourth generation single crystal alloys ($\sim 270 \text{ mJ/m}^2$) were determined. Modelling calculation showed that tantalum levels in the alloy greater than 5.0 wt.% (at Al = 3.7-6.8 wt.%, meaning 60-70% volume γ') produce an alloy with an acceptably high APB energy and so high creep resistance and at the same time producing a high enough volume fraction of γ' .

[0056] With the minimum tantalum concentration, aluminium additions being limited to a maximum of 6.6 wt.% is desirable so that the desirable γ' volume fraction of 60-70% is achieved, Figure 2. Therefore, Al concentration of between 3.7 and 6.6 wt.% is desirable to achieve both the desired γ' volume fraction and a high APB energy. The maximum tantalum content will be explained below with reference to Figure 4 and results in a tantalum range of 5.0 - 9.0 wt.% and a preferred range of 5.0 to 7.3 wt.% this results from the preferred combination of APB energy and solutioning window (dealt with below). That is, the preferred minimum levels of tantalum ensure a higher APB energy for any given amount of aluminium and a level of at least 270 mJ/m^2 in the range of aluminium for the alloy. From Figure 2 it is seen that in particular for higher lower levels of tantalum, concentrations of aluminium of 5.1 wt.% or more, preferably 5.5 wt.% or more produce the desired volume fraction of γ' . Therefore, it is preferable to have the ratio of aluminium to tantalum, in weight percent, ranging between 0.41 (Al=3.7 wt.%, Ta=9.0 wt.%) and 1.36 (Al=6.8 wt.%, Ta=5.0 wt.%), or more preferably ranging between 0.70 (Al=5.1 wt.%, Ta=7.3 wt.%) and 1.32 (Al=6.6 wt.%, Ta=5.0 wt.%), or even more preferably between 0.75 (Al=5.5 wt.%, Ta=7.3 wt.%) and 1.32 (Al=6.6 wt.%, Ta=5.0 wt.%).

[0057] Niobium, titanium, vanadium elements behave in a similar way to that of tantalum i.e. they are gamma prime forming elements which increase anti-phase boundary energy. These elements can optionally be added to the alloy. The benefits of this may include lower cost and density in comparison to tantalum. However, additions of these elements must be limited as they can have a negative impact on the environmental resistance of the alloy. Therefore, those elements can each be present in an amount of up to 0.5 wt.%. Preferably those elements are substituted for tantalum meaning that the sum of the elements consisting of niobium, titanium, vanadium and tantalum is preferably limited to 5.0-9.0 wt.%, more preferably 5.0-7.3 wt.% which are the preferred ranges for tantalum. Independently, in an embodiment, the sum of the elements consisting of niobium, titanium and vanadium is preferably limited to below 1.0 wt.% and preferably below 0.5 wt.% so as to avoid reduction in environmental resistance of the alloy.

[0058] The balance of aluminium and tantalum can be adjusted such that there is a balance between desired target volume fraction of γ' as well as a sufficiently high APB energy. However, consideration must also be given to the processing of the alloy. One such consideration is the solutioning window; there should exist a sufficient temperature range window,

below the melting temperature of the alloy, across which only the γ phase is stable. As the solutioning window depends upon the dissolution of the γ' phase it is strongly influenced by γ' chemistry, hence, aluminium and tantalum content. This solutioning heat treatment is used to remove any residual microsegregation and eutectic mixtures rich in γ' which might occur during the casting processes used to produce the single crystal alloy. It is preferred that the solutioning window is greater than 50°C to allow for conventional processing methods. Figure 4 shows the solutioning window magnitude (in °C) for varying wt% Al and Ta with a volume fraction γ' of 60-70%. From this Figure it can be seen that limiting the tantalum content to 9.0 wt.% ensures that the alloy has a suitable solutioning window. Preferably the tantalum content is limited to 7.3 wt.% as this produces an alloy with a solutioning window greater than 60°C further improving the processing of the alloy.

[0059] The change in solutioning window was related to the change in aluminium and tantalum content according to the formula

$$f(T_{sol.}) = 5.15W_{Al} - 0.57W_{Al}^2 - W_{Ta}$$

where, $f(T_{sol.})$ is a numerical value which is greater than 2.2 to produce an alloy with a solutioning window greater than or equal to 50°C. $f(T_{sol.})$ is preferably greater than 2.9 to produce an alloy with a solutioning window greater than 60°C.

[0060] For the alloys which satisfied the previously described requirements (volume fraction of γ' between 60-70%, APB energy greater than 270mJ/m², solutioning window greater than 50°C) the levels of refractory elements were determined for creep resistance and oxidation performance. For fourth generation single crystal turbine blades additions of the elements ruthenium, rhenium and tungsten are made to impart substantial creep performance, this is described later with reference to Figures 7-10. However, the elements rhenium and ruthenium strongly effect cost, Figure 5. The elements tungsten and rhenium significantly increase alloy density, Figure 6. Moreover, elements such as rhenium, tungsten and chromium (chromium is added for oxidation resistance) must be suitably balanced such that a balance between creep resistance and oxidation is achieved without resulting in a microstructurally unstable alloy which is prone to the formation of deleterious TCP phases, Figures 11-14. Thus, a complex balance between trade-offs in cost, density, creep resistance, oxidation resistance and microstructural stability must be managed, the process for optimising these trade-offs is described below with reference to Figures 5-14.

[0061] The current (2015) raw material cost for the elements ruthenium and rhenium is substantial. Therefore, to optimise the design of the alloy levels of ruthenium and rhenium are selected which best manage the trade-off between the cost and creep resistance in the present invention. In Figure 5 a contour plot shows the effect which levels of ruthenium and rhenium have on alloy cost for an alloy of 60-70% γ' volume fraction at 900°C. It is seen that ruthenium has the strongest influence on alloy cost. Thus, the ruthenium content in the alloy is limited to 3.7 wt.% ensuring that the cost of the present invention is equivalent to or less than current grades of fourth generation alloy. It is preferred that the ruthenium content is limited to 3.0 wt.% or less to ensure an optimal balance between cost and creep resistance.

[0062] In order to limit the cost of the alloy, additions of ruthenium and rhenium preferably adhere to the following Equation,

$$f(Cost) = W_{Ru} + 0.225W_{Re}$$

where, $f(Cost)$ is a numerical value which is less than or equal to 4.5 to produce an alloy with a cost of 300\$/lb or less and W_{Ru} and W_{Re} is the weight percent of ruthenium and rhenium in the alloy respectively. Preferably the numerical value for $f(Cost)$ is less than or equal to 3.9 as this produces an alloy with a lower cost of 260\$/lb or less.

[0063] The additions of the elements tungsten, rhenium and ruthenium are optimised in order to design an alloy which is highly resistant to creep deformation. The creep resistance was determined by using the creep merit index model. It is desirable to maximise the creep merit index as this is associated with an improved creep resistance. The influence which tungsten, rhenium and ruthenium have on creep resistance is presented in Figures 7-10. It is seen that increasing the levels of tungsten, rhenium and ruthenium improve creep resistance. However, the quantities of tungsten and rhenium required mean that they have a strong influence on alloy density, Figure 6. The calculations to produce the graphs of Figures 6-10 are done such that the γ' volume fraction at 900°C is between 60 and 70%. Therefore the trade-off between creep resistance and alloy density must be balanced.

[0064] In order to limit the density of the alloy additions of tungsten and rhenium preferably adhere to the following Equation,

$$f(Density) = 1.13W_{Re} + W_W$$

where, $f(\text{Density})$ is a numerical value which is less than or equal to 15.8 to produce an alloy with a density of 9.0 g/cm³ or less and W_W is the weight percent of tungsten in the alloy. Preferably the numerical value for $f(\text{Density})$ is less than or equal to 14.4 as this produces an alloy with a density of 8.9 g/cm³ or less.

[0065] Current fourth generation single crystal alloys have a creep merit index of $12 \times 10^{-15} \text{ m}^{-2} \text{ s}$ or greater (see Table 3). This level of creep resistance is desirably attained in combination with a low density of less than 9.0 g/cm³ or preferably 8.9 g/cm³. In Figures 7-10 the contours from Figure 6 (dashed lines) which show the effect which rhenium and tungsten have on density are superimposed on the effect which rhenium, tungsten and ruthenium have on creep merit index.

[0066] In order to attain a minimum creep merit index of $12 \times 10^{-15} \text{ m}^{-2} \text{ s}$, the alloy contains at least 1.0 wt.% of ruthenium. Preferably the ruthenium content is 2.0 wt.% or greater more preferably 2.1 wt.% or greater as this produces even higher creep resistance. Ruthenium is preferably limited to 3.0 wt.% as this gives the preferred balance between cost and creep resistance. A more preferred maximum level of ruthenium is 2.9 wt.% yet further to reduce cost, whilst still benefiting from a high creep merit index. If the tungsten content is limited to 11.5 wt.% or less, the alloy density can be decreased to 9.0 g/cm³ or less. Preferably the tungsten content is limited to 9.5 wt.% as this produces an alloy with an even lower density (Figures 6 and 10). Lower levels of tungsten also ensure microstructural stability (Figures 11-14).

[0067] From Figures 7-10 a minimum content of rhenium of 3.5 wt.% or more is shown to produce a high creep merit index. Preferably the rhenium content is greater than 4.5 wt.% as this produces an alloy with a better balance between density (Figure 6) and creep resistance (Figure 10). Even more preferable is an alloy containing at least 5.3 wt.% of rhenium as this composition produces an alloy with an even better balance of creep resistance, density. In such an alloy cost can also be reduced as lower levels of ruthenium may be required (Figure 9).

[0068] Molybdenum behaves in a similar way to tungsten i.e. this slow diffusing element can improve creep resistance. Therefore, it is preferred that molybdenum is present in an amount of at least 0.1 wt%. However, additions of molybdenum must be controlled as it strongly increases the alloys propensity to form deleterious TCP phases. Therefore, molybdenum is limited to 0.5 wt.% or less.

[0069] From Figures 7-10 and a knowledge that molybdenum can substitute tungsten, it can be determined that a good level of creep resistance is achieved when additions of tungsten, rhenium, molybdenum adhere to the following Equation,

$$f(\text{Creep}) = 2.92W_{Re} + (W_W + W_{Mo})$$

where, $f(\text{Creep})$ is a numerical value which is greater than or equal to 21.9 and W_{Mo} is the weight percent of molybdenum in the alloy. This produces an alloy with a creep merit index as calculated of $12 \times 10^{-15} \text{ m}^{-2} \text{ s}$ or more. Preferably the numerical value for $f(\text{Creep})$ is greater than 24.6 as this produces an alloy with increased creep resistance. Additionally this allows lower levels of ruthenium to attain equivalent creep resistance thus reducing cost.

[0070] Additions of cobalt are optional. However, modelling calculations show that cobalt increases the creep merit index. Additions of cobalt are also known to lower the stacking fault energy in the gamma matrix which also improves creep resistance. Furthermore, additions of cobalt can improve the ease of processing as it can lower the γ' solvus temperature, helping to increase the solutioning window. Thus, at least 0.1 wt% cobalt is desirably present. Figure 15 shows that cobalt additions lower the γ' solvus temperature when the aluminium to tantalum ratio is in the most preferred range 0.75 - 1.36. A preferred lower limit of cobalt is 7.0 wt.% as this produces an alloy with improved creep resistance and a lower γ' solvus temperature which is beneficial for heat treatment processes. However, cobalt additions must be limited as high cobalt levels will increase the alloy's creep anisotropy, particularly in primary creep. This makes the creep rate strongly dependent upon orientation of the single crystal. An upper limit of 12.0 wt.% cobalt controls the amount of creep anisotropy to an acceptable level. A preferred upper limit is 11.0 wt.% as creep anisotropy is even less prevalent. A more desirable upper limit is 10.9 wt.% even further to decrease the chance of creep anisotropy.

[0071] In order to remain resistant to creep over a significant time period the addition of slow diffusing elements rhenium, tungsten and ruthenium is required. Additions of chromium are also required to promote resistance to oxidation/corrosion damage. However, the addition of high levels of tungsten, rhenium and chromium were found to increase the propensity to form unwanted TCP phases, primarily σ , P and μ phases. Figures 11-14 shows the effect of chromium, tungsten and rhenium additions on the overall fraction of TCP phases ($\sigma + \mu + P$). Preferably the additions of these elements were controlled to ensure that the levels of the TCP phases were equivalent to or lower than current fourth generation superalloys (Table 3).

[0072] The minimum chromium content for the present invention is greater than or equal to 3.5 wt.% and preferably greater than or equal to 4.0 wt.% in order to attain oxidation resistance which is improved in comparison to current fourth generation single crystal alloys which have Cr contents ranging between 2.0-3.2 wt.%. That is, a higher weight percent of chromium is provided than in the current fourth generation alloys on the basis that this will improve oxidation resistance compared to those alloys. The chromium content is limited to 6.5 wt.% to reduce the propensity for the alloy to form the

deleterious TCP phases (Figures 11-14). Preferably the chromium content in the alloy is limited to 5.0 wt.% as this produces an alloy with the best balance between oxidation resistance and microstructural stability. In the present invention the rhenium content in the alloy is limited to 7.0 wt.% or less (to ensure acceptable microstructural stability, Figure 14) and more preferably 6.0 wt.% or less as rhenium at a level of between 4.5 wt.% and 6.0 wt.% provides a good balance between density, creep resistance and microstructural stability. Based upon the rhenium levels allowable for a balance between microstructural stability, density and creep resistance the minimum tungsten level required for the present invention is 4.5 wt.% or more, as this provides a balance between creep resistance (Figures 7-10), cost and microstructural stability (Figures 11-14). In order to achieve high creep resistance (Figures 7-10) a preferred minimum level of tungsten is 7.0 wt.%, desirably at least 7.1 wt%.

[0073] It is beneficial that when the alloy is produced, it is substantially free from incidental impurities. These impurities may include the elements carbon (C), boron (B), sulphur (S), zirconium (Zr) and manganese (Mn). If concentrations of carbon remain at 100 PPM or below (in terms of mass) the formation of unwanted carbide phases will not occur. Boron content is desirably limited to 50 PPM or less (in terms of mass) so that formation of unwanted boride phases will not occur. Carbide and boride phases tie up elements such as tungsten or tantalum which are added to provide strength to the γ and γ' phases. Hence, mechanical properties including creep resistance are reduced if carbon and boron are present in greater amounts. The elements Sulphur (S) and Zirconium (Zr) preferably remain below 30 and 500 PPM (in terms of mass), respectively. Manganese (Mn) is an incidental impurity which is preferably limited to 0.05wt% (500PPM in terms of mass). The presence of Sulphur above 0.003 wt.% can lead to embrittlement of the alloy and sulphur also segregates to alloy/oxide interfaces formed during oxidation. This segregation may lead to increased spallation of protective oxide scales. The levels of zirconium and manganese must be controlled as these may create casting defects during the casting process, for example freckling. If the concentrations of these incidental impurities exceed the specified levels, issues surround product yield and deterioration of the material properties of the alloy is expected.

[0074] Additions of hafnium (Hf) of up to 0.5wt.%, or more preferably up to 0.2wt.% are beneficial for tying up incidental impurities in the alloy, in particular carbon. Hafnium is a strong carbide former, so addition of this element is beneficial as it will tie up any residual carbon impurities which may be in the alloy. It can also provide additional grain boundary strengthening, which is beneficial when low angle boundaries are introduced in the alloy.

[0075] Additions of the so called 'reactive-elements', Silicon (Si), Yttrium (Y), Lanthanum (La) and Cerium (Ce) may be beneficial up to levels of 0.1 wt.% to improve the adhesion of protective oxide layers, such as Al_2O_3 . These reactive elements can 'mop-up' tramp elements, for example sulphur, which segregates to the alloy oxide interface weakening the bond between oxide and substrate leading to oxide spallation. In particular, it has been shown that additions of silicon to nickel based superalloys at levels up to 0.1 wt.% are beneficial for oxidation properties. In particular silicon segregates to the alloy/oxide interface and improves cohesion of the oxide to the substrate. This reduces spallation of the oxide, hence, improving oxidation resistance.

[0076] Based upon the description of the invention presented in this section, broad and preferred ranges for each elemental addition were defined, these ranges are listed in Table 4. An example composition - alloy ABD-2 - was selected from the preferred compositional range, the composition of this alloy is defined in Table 4. Alloy ABD-2 was found to be amenable to standard methods used for the production of single crystal turbine blade components. This production method involves: preparation of an alloy with the composition of ABD-2, preparation of a mould for casting the alloy using investment casting methods, casting the alloy using directional solidification techniques where a 'grain selector' is used to produce a single crystal alloy, subsequent multi-step heat treatment of the single crystal casting.

Table 4: Compositional range in wt. % for the newly design alloy.

	Broad		Preferred		Nominal
	Min	Max	Min	Max	ABD-2
Cr	3.5	6.5	4.0	5.0	4.0
Co	0.0	12.0	7.0	11.0	9.0
W	4.5	11.5	7.0	9.5	7.4
Al	3.7	6.8	5.1	6.6	6.4
Ta	5.0	9.0	5.0	7.3	5.6
Mo	0.0	0.5	0.1	0.5	0.0
Re	3.5	7.0	4.5	6.0	5.6
Ru	1.0	3.7	2.0	3.0	2.6
Hf	0.0	0.5	0.0	0.2	0.0
Nb	0.0	0.5	0.0	0.5	0.0
Ti	0.0	0.5	0.0	0.5	0.0

(continued)

	Broad		Preferred		Nominal
	Min	Max	Min	Max	ABD-2
V	0.0	0.5	0.0	0.5	0.0
Si	0.0	0.1	0.0	0.1	0.0
Ce	0.0	0.1	0.0	0.1	0.0
Y	0.0	0.1	0.0	0.1	0.0
La	0.0	0.1	0.0	0.1	0.0

[0077] Experiment testing of alloy ABD-2 was used to validate the key material properties aimed at with the alloy of the invention, mainly sufficient creep resistance and improved oxidation behaviour in comparison to that of a current single crystal alloys used for IGT applications. The behaviour of alloy ABD-2 was compared with alloy TMS-138-A, which was tested under the same experimental conditions.

[0078] Single crystal castings of alloy ABD-2 of nominal composition according to Table 4 were manufactured using conventional methods for producing single crystal components. The castings were in the form of cylindrical bars of 10 mm diameter and 160 mm in length. The cast bars were confirmed to be single crystals with an orientation within 10° from the <001> direction.

[0079] The as cast material was given a series of subsequent heat treatments in order to produce the required y/y' microstructure. A solution heat treatment was conducted at 1325°C for 6 hours, this was found to remove residual microsegregation and eutectic mixtures. The heat treatment window for the alloy was found to be sufficient to avoid incipient melting during the solution heat treatment. Following the solution heat treatment the alloy was given a two stage ageing heat treatment, the first stage conducted at 1120°C for 2 hours and the second stage conducted at 870°C for 16 hours.

[0080] Creep specimens of 20 mm gauge length and 4 mm diameter were machined from fully heat-treated single crystal bars. The orientation of the test specimens were within 10° from the <001> direction. Test temperatures ranging from 800 to 1100°C were used to evaluate the creep performance of the ABD-2 alloy. Cyclic oxidation tests were performed on the fully heat treated material. Cyclic oxidation tests were carried out at 1000°C using 2 hours cycles over a time period of 50 hours.

[0081] A Larson-Miller diagram was used to compare the creep resistance of alloy ABD-2 with alloy TMS-138A. In Figure 16 a comparison of time to 1% creep strain is presented for both alloys. The time to 1% strain is critical as most gas turbine components are manufactured to tight tolerances to achieve maximum engine performance. After low levels of strain - in the order of a few percent - components will often be replaced. It is seen that alloy ABD-2 is comparable to TMS-138A in time to 1% creep strain. Figure 17 shows a comparison of time to creep rupture for both alloys, it is seen that alloy ABD-2 has a rupture life comparable to that of TMS-138A.

[0082] The oxidation behaviour of alloys ABD-2 and TMS-138A was also compared. As turbine temperatures continue to rise - improving thermal efficiency of the engine - component failure due to corrosion damage such as oxidation is becoming more prevalent. Hence, significant gains in component life may be attained by improving oxidation/corrosion resistance. The alloy ABD-2 was designed such that it would have improved oxidation behaviour relative to current second generation alloys. Cyclic oxidation results for ABD-2 and TMS-138A are presented in Figure 18. A reduction in mass gain with respect to time is evidence of improved oxidation behaviour as the formation of a protective oxide scale has occurred limiting the ingress of oxygen into the substrate material. The ABD-2 alloy shows significantly reduced weight gain with respect to time when compared to TMS-138A, indicative of improved oxidation performance.

[0083] Overall the alloy ABD-2 shows equivalent creep behaviour in comparison to TMS-138A. This has been achieved using an alloy with a significantly improved oxidation behaviour. Thus, design goals have been met whilst still achieving a low cost and density alloy which is amenable to conventional manufacturing techniques.

Claims

1. A nickel-based alloy composition consisting, in weight percent, of: between 3.5 and 6.5% chromium, between 0.0 and 12.0% cobalt, between 4.5 and 11.5% tungsten, between 0.0 and 0.5% molybdenum, between 3.5 and 7.0% rhenium, between 1.0 and 3.7% ruthenium, between 3.7 and 6.8% aluminium, between 5.0 and 9.0% tantalum, between 0.0 and 0.5% hafnium, between 0.0 and 0.5% niobium, between 0.0 and 0.5% titanium, between 0.0 and 0.5% vanadium, between 0.0 and 0.1% silicon, between 0.0 and 0.1% yttrium, between 0.0 and 0.1% lanthanum, between 0.0 and 0.1% cerium, between 0.0 and 0.003% sulphur, between 0.0 and 0.05% manganese, between 0.0 and 0.05% zirconium, between 0.0 and 0.005% boron, between 0.0 and 0.01% carbon, the balance being nickel

and incidental impurities.

2. The nickel-based alloy composition according to claim 1, consisting, in weight percent, of between 4.0 and 5.0% chromium.

3. The nickel-based alloy composition according to claim 1 or 2, consisting, in weight percent, of between 0.1 to 12.0 wt% cobalt, more preferably 0.1 to 11.0% cobalt, or 0.1 to 10.9% cobalt, most preferably 7.0 and 11.0% cobalt or even between 7.0 and 10.9% cobalt.

4. The nickel-based alloy composition according to claim 1, 2 or 3, consisting, in weight percent, of between 7.0 and 9.5% tungsten, or of between 7.1 and 11.5 wt% tungsten, preferably between 7.1 and 9.5% tungsten.

5. The nickel-based alloy composition according to any of claims 1-4, consisting, in weight percent of, between 3.7 and 6.6%, preferably between 5.1 and 6.6% aluminium, more preferably between 5.5 and 6.6% aluminium.

6. The nickel-based alloy composition according to any of claims 1-5, consisting, in weight percent, of between 5.0 and 7.3% tantalum.

7. The nickel-based alloy according to any of claims 1-6, consisting, in weight percent, of at least 0.1% molybdenum.

8. The nickel-based alloy according to any of claims 1-7, consisting, in weight percent, of between 4.5 and 6.0% rhenium, more preferably between 5.3 and 6.0% rhenium, and/or consisting, in weight percent, of between 2.0 and 3.0% ruthenium, preferably between 2.1 and 2.9% ruthenium.

9. The nickel-based alloy composition according to any of claims 1-8, wherein the following equation is satisfied in which W_{Ta} and W_{Al} are the weight percent of tantalum and aluminium in the alloy respectively

$$33 \leq W_{Ta} + 5.1 W_{Al} \leq 39.$$

10. The nickel-based alloy composition according to any of claims 1-9, wherein the following equation is satisfied in which W_{Ta} and W_{Al} are the weight percent of tantalum and aluminium in the alloy respectively

$$2.2 \leq 5.15 W_{Al} - 0.5 W_{Al}^2 - W_{Ta},$$

$$\text{preferably } 2.9 \leq 5.15 W_{Al} - 0.5 W_{Al}^2 - W_{Ta}.$$

11. The nickel-based alloy composition according to any of claims 1-10, wherein the following equation is satisfied in which W_{Ru} and W_{Re} are the weight percent of ruthenium and rhenium in the alloy respectively

$$4.5 \geq W_{Ru} + 0.225 W_{Re},$$

$$\text{preferably } 3.9 \geq W_{Ru} + 0.225 W_{Re}.$$

12. The nickel-based alloy composition according to any of claims 1-11, wherein the following equation is satisfied in which W_{Re} and W_W are the weight percent of rhenium and tungsten in the alloy respectively

$$15.8 \geq 1.13 W_{Re} + W_W$$

$$\text{preferably } 14.4 \geq 1.13 W_{Re} + W_W.$$

13. The nickel-based alloy composition according to any of claims 1-12, wherein the following equation is satisfied in which W_{Re} , W_{Mo} and W_W are the weight percent of rhenium, molybdenum and tungsten in the alloy respectively

$$21.9 \leq 2.92 W_{Re} + (W_W + W_{Mo}),$$

$$\text{preferably } 24.6 \leq 2.92 W_{Re} + (W_W + W_{Mo}).$$

14. The nickel-based alloy composition according to any of claims 1-13, wherein the sum of the elements niobium, titanium and vanadium, in weight percent, is less than 1%, preferably less than 0.5 wt%, and/or consisting, in weight percent, of between 0.0 and 0.2% hafnium, and/or wherein the sum of the elements niobium, titanium, vanadium and tantalum, in weight percent, is between 5.0 and 9.0%, preferably between 5.0 - 7.3%.

15. The nickel-based alloy composition according to any of claims 1-14, having between 60% and 70% volume fraction γ' .

Patentansprüche

1. Legierungszusammensetzung auf Nickelbasis, bestehend in Gewichtsprozent aus: zwischen 3,5 und 6,5 % Chrom, zwischen 0,0 und 12,0 % Kobalt, zwischen 4,5 und 11,5 % Wolfram, zwischen 0,0 und 0,5 % Molybdän, zwischen 3,5 und 7,0 % Rhenium, zwischen 1,0 und 3,7 % Ruthenium, zwischen 3,7 und 6,8 % Aluminium, zwischen 5,0 und 9,0 % Tantal, zwischen 0,0 und 0,5 % Hafnium, zwischen 0,0 und 0,5 % Niob, zwischen 0,0 und 0,5 % Titan, zwischen 0,0 und 0,5 % Vanadium, zwischen 0,0 und 0,1 % Silizium, zwischen 0,0 und 0,1 % Yttrium, zwischen 0,0 und 0,1 % Lanthan, zwischen 0,0 und 0,1 % Cerium, zwischen 0,0 und 0,003 % Schwefel, zwischen 0,0 und 0,05 % Mangan, zwischen 0,0 und 0,05 % Zirkonium, zwischen 0,0 und 0,005 % Bor, zwischen 0,0 und 0,01 % Kohlenstoff, wobei der Rest Nickel und zufällige Verunreinigungen sind.
2. Legierungszusammensetzung auf Nickelbasis nach Anspruch 1, bestehend, in Gewichtsprozent, aus zwischen 4,0 bis 5,0 % Chrom.
3. Legierungszusammensetzung auf Nickelbasis nach Anspruch 1 oder 2, bestehend, in Gewichtsprozent, aus zwischen 0,1 bis 12,0 Gewichts% Kobalt, besonders bevorzugt 0,1 bis 11,0 % Kobalt, oder 0,1 bis 10,9 % Kobalt, ganz besonders bevorzugt 7,0 und 11,0 % Kobalt oder sogar zwischen 7,0 und 10,9 % Kobalt.
4. Legierungszusammensetzung auf Nickelbasis nach Anspruch 1, 2 oder 3, bestehend, in Gewichtsprozent, aus zwischen 7,0 und 9,5 % Wolfram, oder aus zwischen 7,1 und 11,5 Gewichts% Wolfram, bevorzugt zwischen 7,1 und 9,5 % Wolfram.
5. Legierungszusammensetzung auf Nickelbasis nach einem der Ansprüche 1 - 4, bestehend, in Gewichtsprozent, aus zwischen 3,7 und 6,6 %, bevorzugt zwischen 5,1 und 6,6 % Aluminium, besonders bevorzugt zwischen 5,5 und 6,6 % Aluminium.
6. Legierungszusammensetzung auf Nickelbasis nach einem der Ansprüche 1 - 5, bestehend, in Gewichtsprozent, aus zwischen 5,0 und 7,3% Tantal.
7. Legierungszusammensetzung auf Nickelbasis nach einem der Ansprüche 1 - 6, bestehend, in Gewichtsprozent, aus mindestens 0,1 % Molybdän.
8. Legierungszusammensetzung auf Nickelbasis nach einem der Ansprüche 1 - 7, bestehend, in Gewichtsprozent, aus zwischen 4,5 und 6,0 % Rhenium, besonders bevorzugt zwischen 5,3 und 6,0 % Rhenium, und/oder bestehend, in Gewichtsprozent, aus zwischen 2,0 und 3,0 % Ruthenium, bevorzugt zwischen 2,1 und 2,9 % Ruthenium.
9. Legierungszusammensetzung auf Nickelbasis nach einem der Ansprüche 1 - 8, wobei die folgende Gleichung erfüllt ist, in der W_{Ta} und W_{Al} jeweils das Gewichtsprozent von Tantal und Aluminium in der Legierung sind

$$3,3 \leq W_{Ta} + 5,1 W_{Al} \leq 39.$$

10. Legierungszusammensetzung auf Nickelbasis nach einem der Ansprüche 1 - 9, wobei die folgende Gleichung erfüllt ist, in der W_{Ta} und W_{Al} jeweils das Gewichtsprozent von Tantal und Aluminium in der Legierung sind

$$2,2 \leq 5,15 W_{Al} - 0,5 W_{Al}^2 - W_{Ta},$$

$$\text{bevorzugt } 2,9 \leq 5,15 W_{Al} - 0,5 W_{Al}^2 - W_{Ta}.$$

11. Legierungszusammensetzung auf Nickelbasis nach einem der Ansprüche 1 -10, wobei die folgende Gleichung erfüllt ist, in der W_{Ru} und W_{Re} jeweils das Gewichtsprozent von Ruthenium und Rhenium in der Legierung sind

$$4,5 \geq W_{Ru} + 0,225 W_{Re},$$

$$\text{bevorzugt } 3,9 \geq W_{Ru} + 0,225 W_{Re}.$$

12. Legierungszusammensetzung auf Nickelbasis nach einem der Ansprüche 1 - 11, wobei die folgende Gleichung erfüllt ist, in der W_{Re} und W_W jeweils das Gewichtsprozent von Rhenium und Wolfram in der Legierung sind

$$15,8 \geq 1,13 W_{Re} + W_W$$

$$\text{bevorzugt } 14,4 \geq 1,13 W_{Re} + W_W.$$

13. Legierungszusammensetzung auf Nickelbasis nach einem der Ansprüche 1 - 12, wobei die folgende Gleichung erfüllt ist, in der W_{Re} , W_{Mo} und W_W jeweils das Gewichtsprozent von Rhenium, Molybdän und Wolfram in der Legierung sind

$$21,9 \leq 2,92 W_{Re} + (W_W + W_{Mo}),$$

$$\text{bevorzugt } 24,6 \leq 2,92 W_{Re} + (W_W + W_{Mo}).$$

14. Legierungszusammensetzung auf Nickelbasis nach einem der Ansprüche 1 - 13, wobei die Summe der Elemente Niob, Titan, und Vanadium, in Gewichtsprozent, weniger als 1 % ist, bevorzugt weniger als 0,5 Gewichts%, und/oder bestehend, in Gewichtsprozent, aus zwischen 0,0 und 0,2 % Hafnium, und/oder wobei die Summe der Elemente Niob, Titan, Vanadium und Tantal, in Gewichtsprozent, zwischen 5,0 und 9,0 % ist, bevorzugt zwischen 5,0 - 7,3 % ist.

15. Legierungszusammensetzung auf Nickelbasis nach einem der Ansprüche 1 - 14, mit einem Volumenanteil γ' zwischen 60 % und 70 %.

Revendications

1. Composition d'alliages à base de nickel consistant en pourcentage en poids : entre 3,5 et 6,5% de chrome, entre 0,0 et 12,0% de cobalt, entre 4,5 et 11,5% de tungstène, entre 0,0 et 0,5% de molybdène et entre 3,5 et 7,0% de rhénium, entre 1,0 et 3,7% de ruthénium, entre 3,7 et 6,8% d'aluminium, entre 5,0 et 9,0% de tantale, entre 0,0 et 0,5% d'hafnium, entre 0,0 et 0,5% de niobium, entre 0,0 et 0,5% de titane, entre 0,0 et 0,5% de vanadium, entre 0,0 et 0,1% de silicium, entre 0,0 et 0,1% d'yttrium, entre 0,0 et 0,1% de lanthane, entre 0,0 et 0,1% de cérium,

EP 3 329 025 B1

entre 0,0 et 0,003% de soufre, entre 0,0 et 0,05% de manganèse, entre 0,0 et 0,05% de zirconium, entre 0,0 et 0,005% de bore, entre 0,0 et 0,01% de carbone, le reste étant constitué de nickel et d'impuretés fortuites.

2. Composition d'alliage à base de nickel selon la revendication 1, consistant en pourcentage en poids entre 4,0 et 5,0% de chrome.

3. Composition d'alliage à base de nickel selon la revendication 1 ou 2, consistant en pourcentage en poids entre 0,1 et 12,0% de cobalt, de manière davantage préférée de 0,1 à 11,0% de cobalt ou de 0,1 à 10,9% de cobalt, de manière davantage préférée entre 7,0 et 11,0% de cobalt ou même entre 7,0 et 10,9% de cobalt.

4. Composition d'alliage à base de nickel selon la revendication 1, 2 ou 3, consistant en pourcentage en poids entre 7,0 et 9,5% de tungstène ou entre 7,1 et 11,5% de tungstène, de manière préférée entre 7,1 et 9,5% de tungstène.

5. Composition d'alliage à base de nickel selon l'une quelconque des revendications 1 à 4, consistant en pourcentage en poids compris entre 3,7 et 6,6%, de préférence entre 5,1 et 6,6% d'aluminium, de manière davantage préférée entre 5,5 et 6,6% d'aluminium.

6. Composition d'alliage à base de nickel selon l'une quelconque des revendications 1 à 5, consistant en pourcentage en poids entre 5,0 et 7,3% de tantale.

7. Alliage à base de nickel selon l'une quelconque des revendications 1 à 6, constitué en pourcentage en poids d'au moins 0,1% de molybdène.

8. Alliage à base de nickel selon l'une quelconque des revendications 1 à 7, consistant en, en pourcentage en poids, entre 4,5 et 6,0% de rhénium, plus préférablement entre 5,3 et 6,0% de rhénium, et / ou consistant, en pourcentage en poids, entre 2,0 et 3,0% de ruthénium, de préférence entre 2,1 et 2,9% de ruthénium.

9. Composition d'alliage à base de nickel selon l'une quelconque des revendications 1 à 8, dans laquelle l'équation suivante est satisfaite dans laquelle W_{Ta} et W_{Al} représentent respectivement le pourcentage en poids de tantale et d'aluminium dans l'alliage.

$$33 \leq W_{Ta} + 5.1 W_{Al} \leq 39.$$

10. Composition d'alliage à base de nickel selon l'une quelconque des revendications 1 à 9, dans laquelle l'équation suivante est satisfaite dans laquelle W_{Ta} et W_{Al} représentent respectivement le pourcentage en poids de tantale et d'aluminium dans l'alliage,

$$2.2 \leq 5.15 W_{Al} - 0.5 W_{Al}^2 - W_{Ta},$$

$$\text{de préférence } 2.9 \leq 5.15 W_{Al} - 0.5 W_{Al}^2 - W_{Ta}.$$

11. Composition d'alliage à base de nickel selon l'une quelconque des revendications 1 à 10, dans laquelle l'équation suivante est satisfaite dans laquelle W_{Ru} et W_{Re} représentent respectivement le pourcentage en poids de ruthénium et de rhénium dans l'alliage.

$$4.5 \geq W_{Ru} + 0.225 W_{Re},$$

$$\text{de préférence } 3.9 \geq W_{Ru} + 0.225 W_{Re}$$

12. Composition d'alliage à base de nickel selon l'une quelconque des revendications 1 à 11, dans laquelle l'équation suivante est satisfaite dans laquelle W_{Re} et W_W représentent respectivement le pourcentage en poids de rhénium et de tungstène dans l'alliage.

$$15.8 \geq 1.13 W_{\text{Re}} + W_{\text{W}}$$

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de préférence $14.4 \geq 1.13 W_{\text{Re}} + W_{\text{W}}$.

- 13.** Composition d'alliage à base de nickel selon l'une quelconque des revendications 1 à 12, dans laquelle l'équation suivante est satisfaite dans laquelle W_{Re} , W_{MO} et W_{W} représentent respectivement le pourcentage en poids de rhénium, de molybdène et de tungstène dans l'alliage.

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$$21.9 \leq 2.92 W_{\text{Re}} + (W_{\text{W}} + W_{\text{MO}}),$$

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de préférence $24.6 \leq 2.92 W_{\text{Re}} + (W_{\text{W}} + W_{\text{MO}})$.

- 14.** Composition d'alliage à base de nickel selon l'une quelconque des revendications 1 à 13, dans laquelle la somme des éléments niobium, titane et vanadium, en pourcentage en poids, est inférieure à 1%, de préférence inférieure à 0,5% en poids, et / ou consistant en, en pourcentage en poids, entre 0,0 et 0,2% d'hafnium, et / ou dans laquelle la somme des éléments niobium, titane, vanadium et tantale, en pourcentage en poids, est comprise entre 5,0 et 9,0%, de préférence entre 5,0 et 7,3%.

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- 15.** Composition d'alliage à base de nickel selon l'une quelconque des revendications 1 à 14, ayant entre 60% et 70% de fraction volumique γ' .

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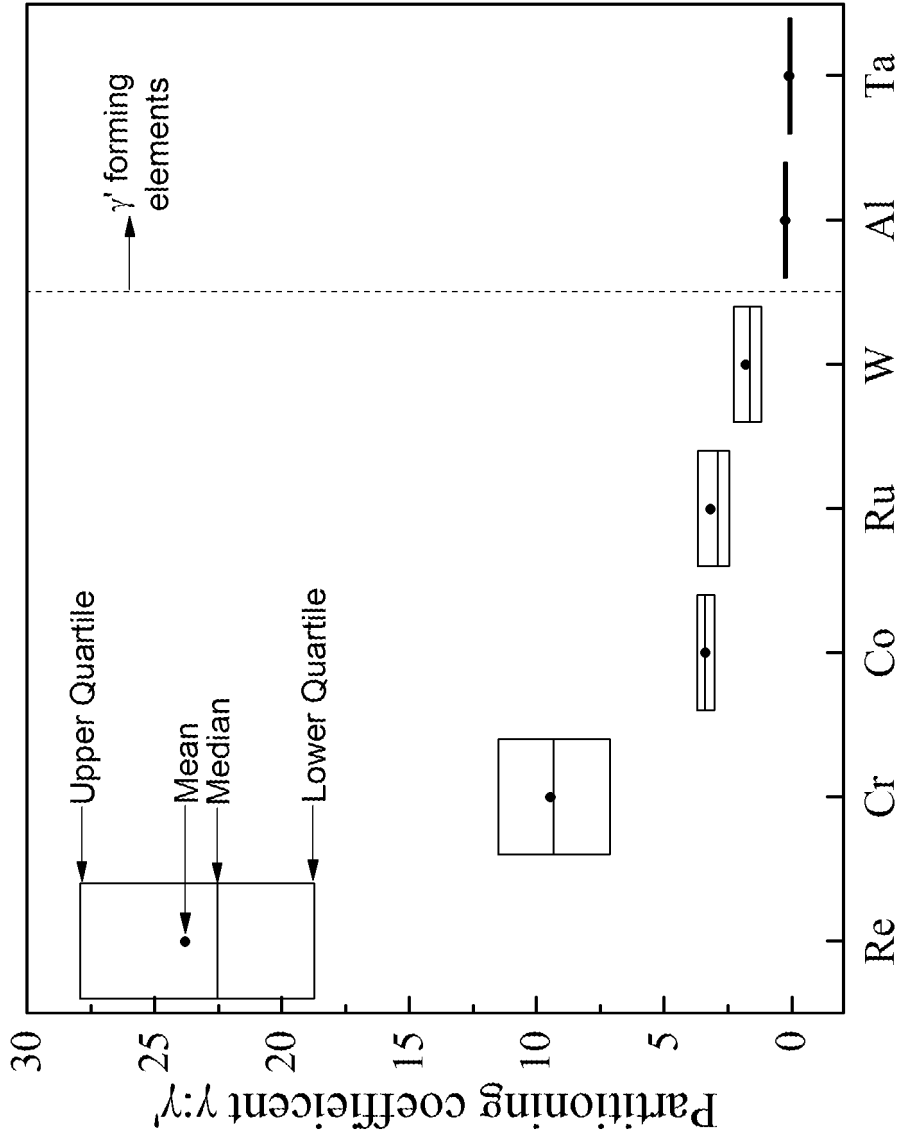


Figure 1

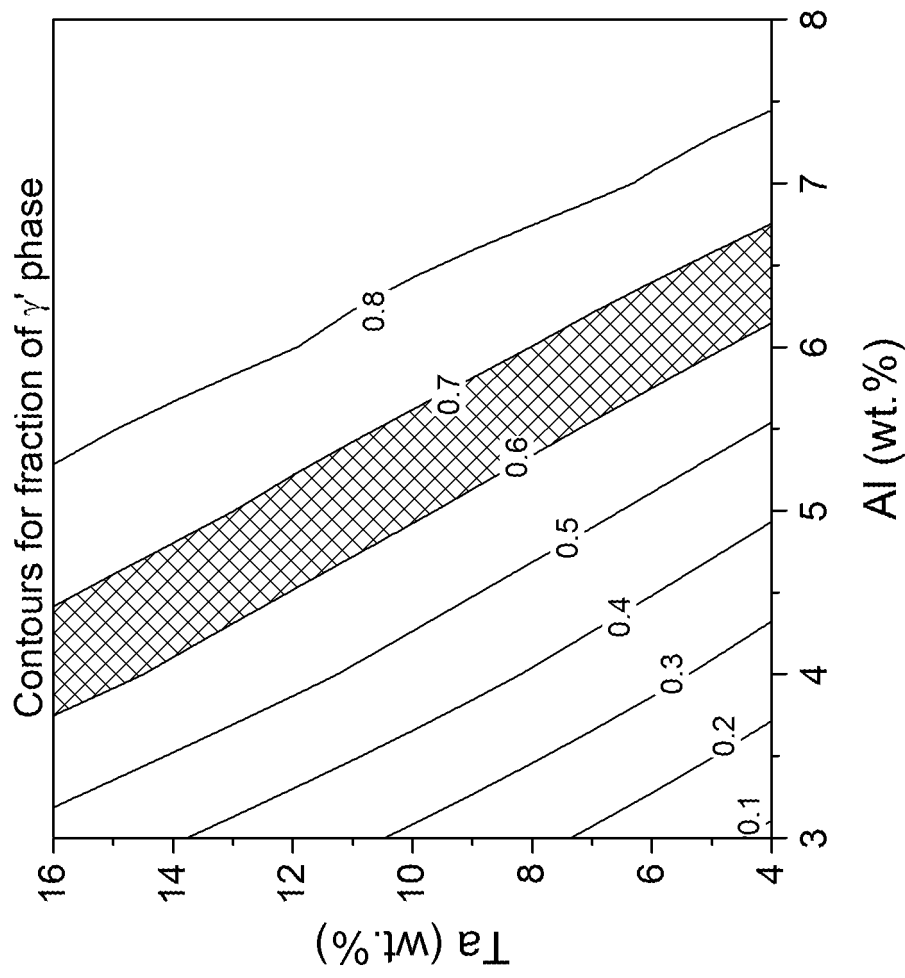
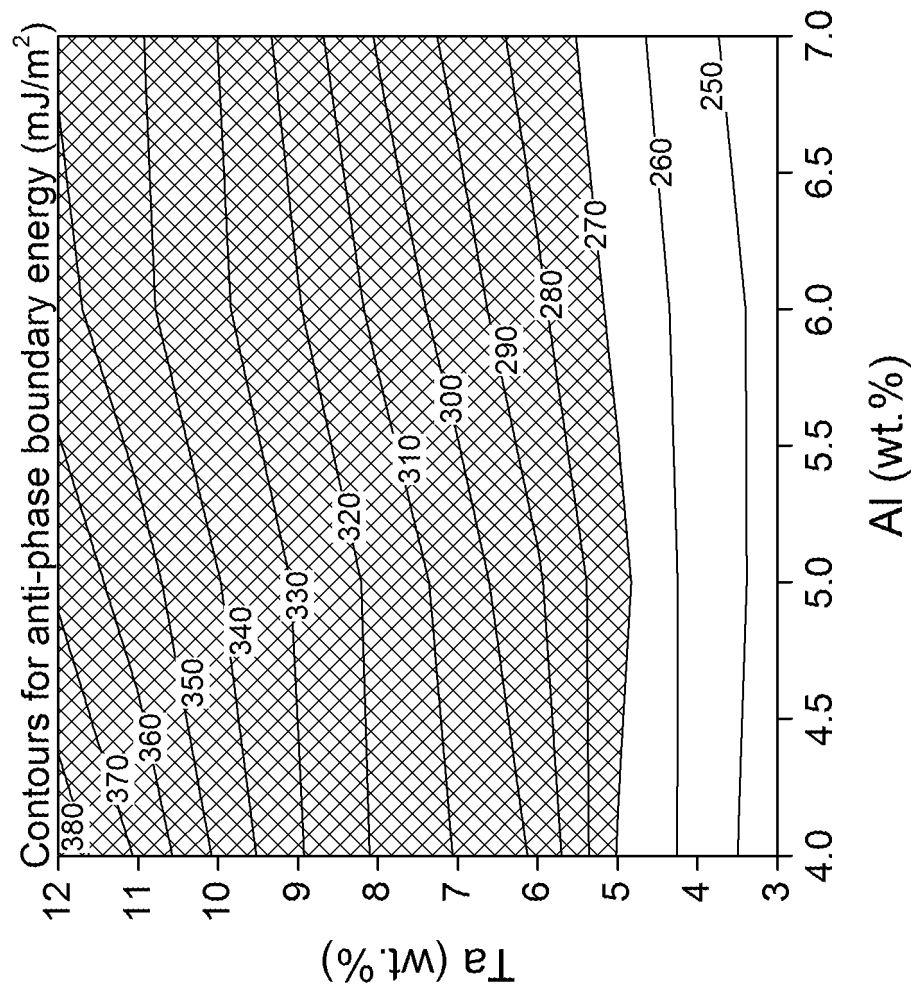


Figure 2

*Figure 3*

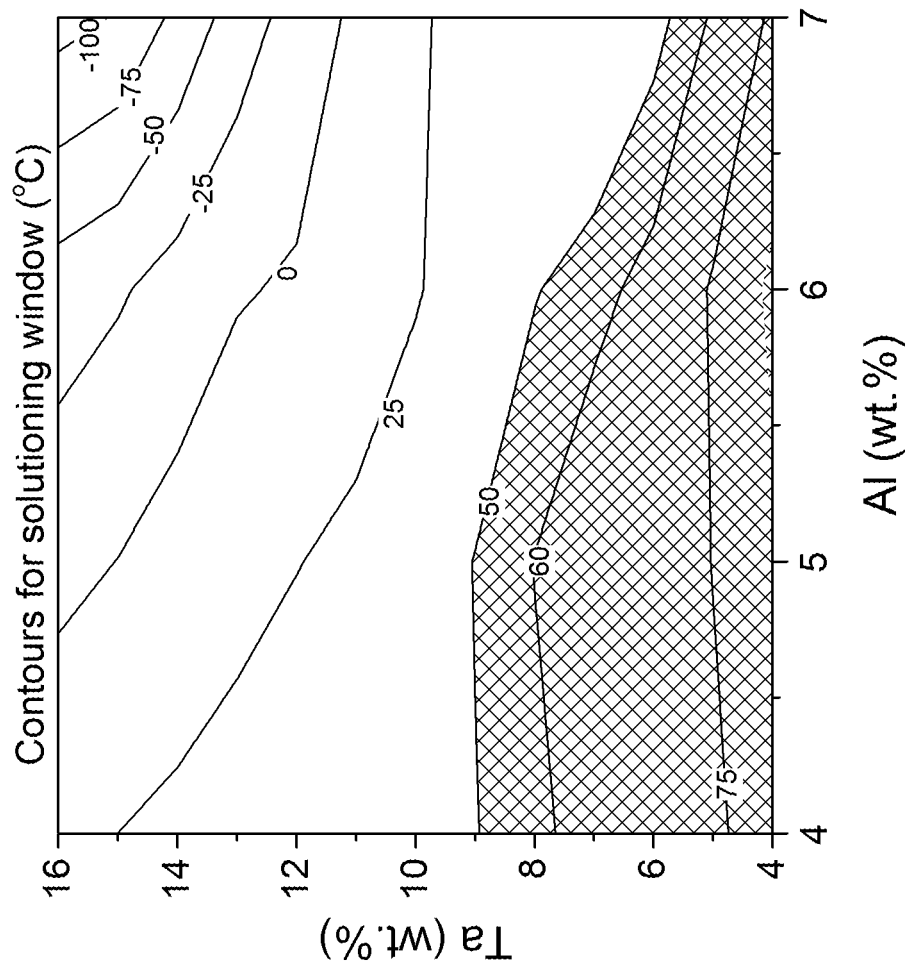


Figure 4

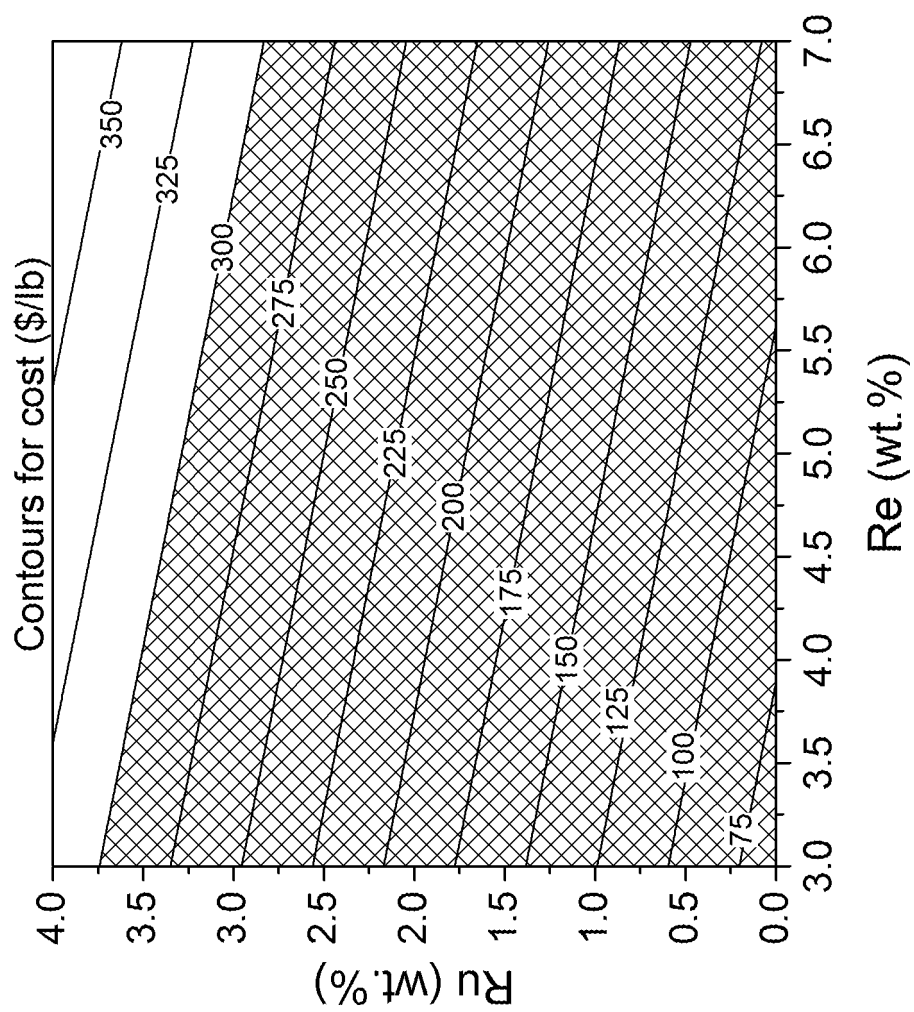


Figure 5

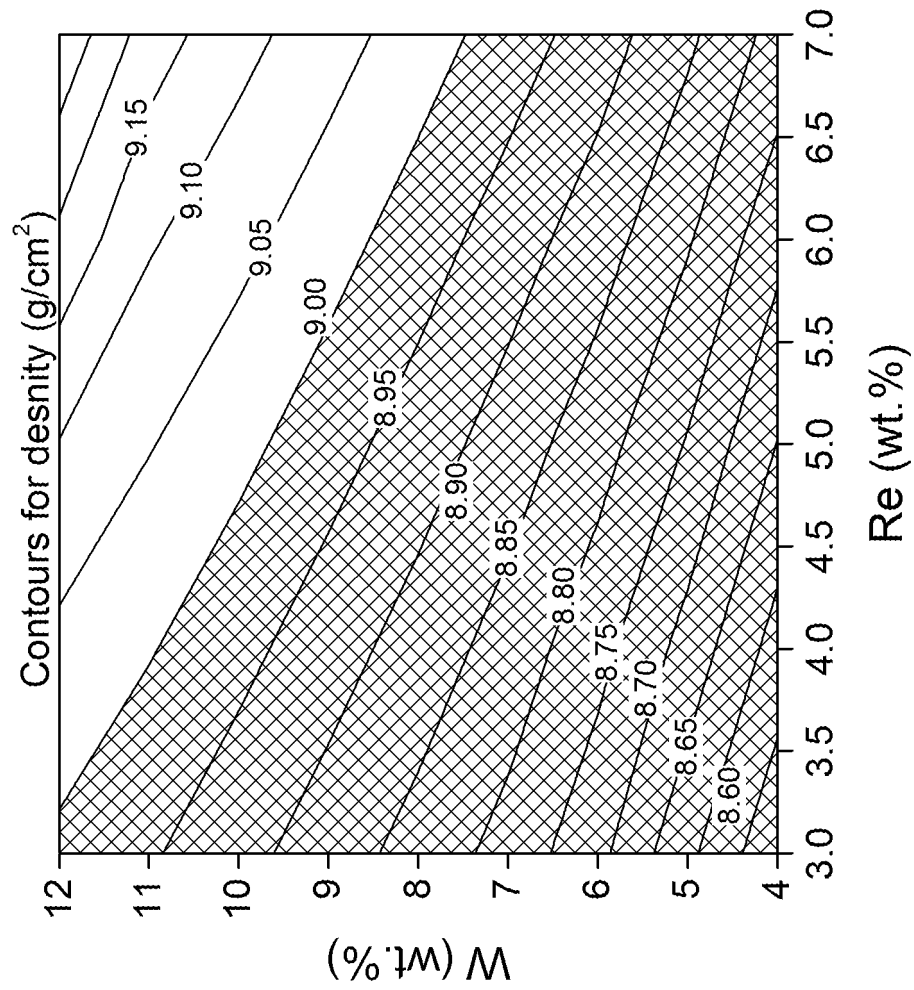


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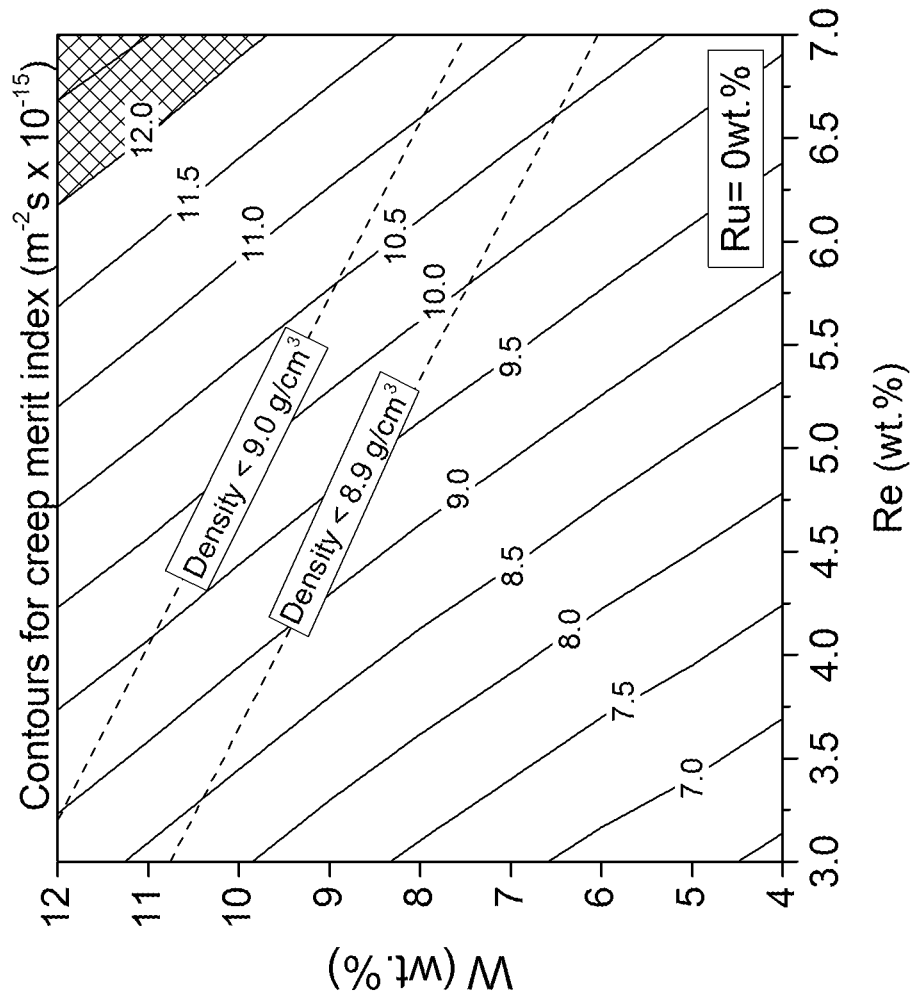


Figure 7

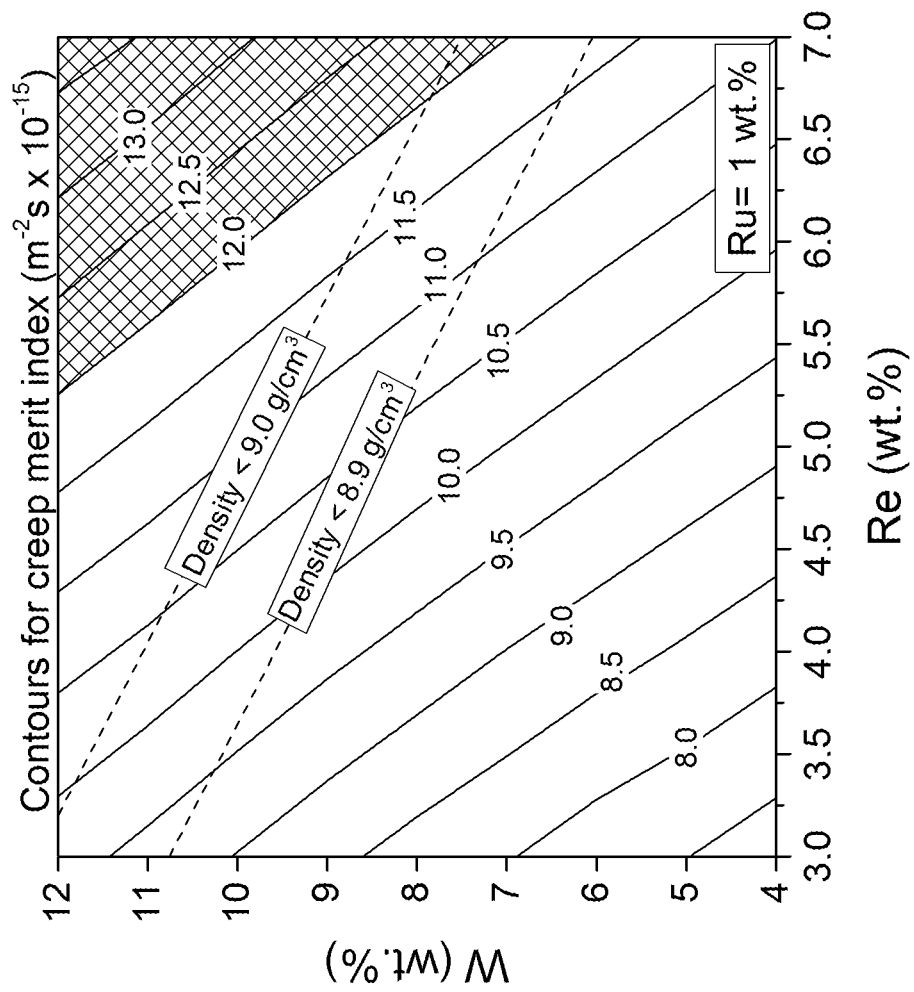


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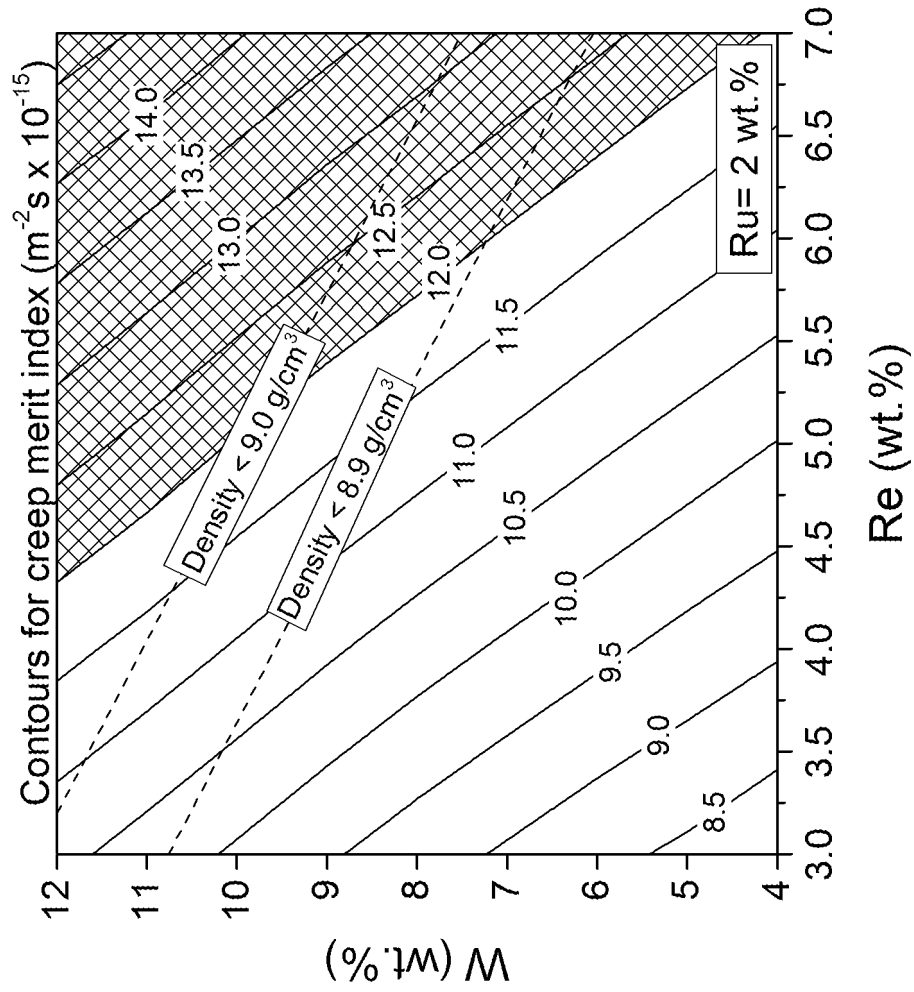


Figure 9

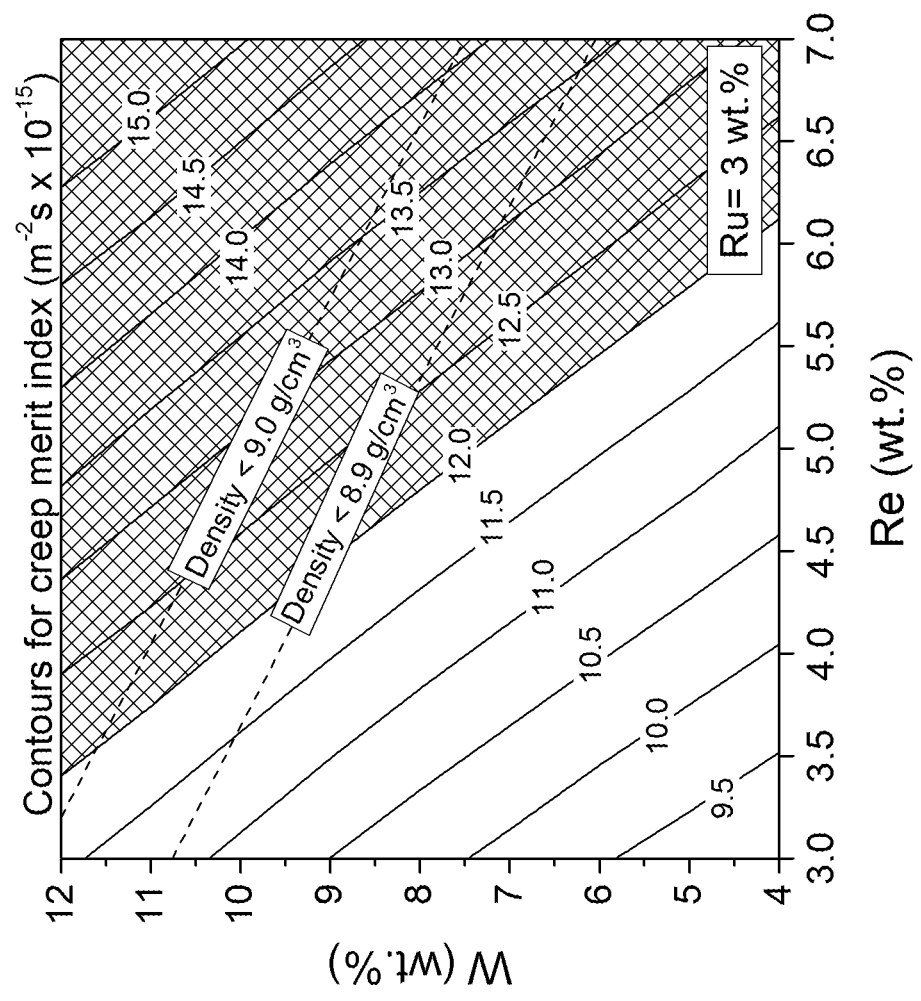


Figure 10

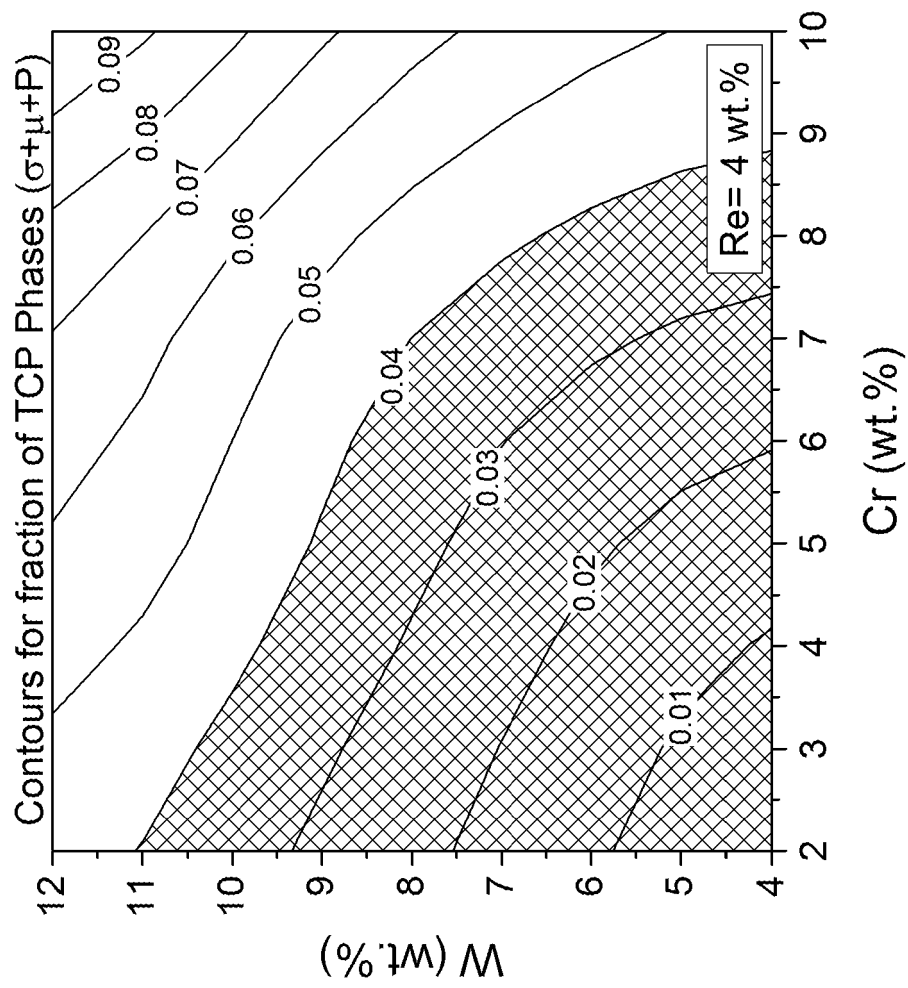


Figure 11

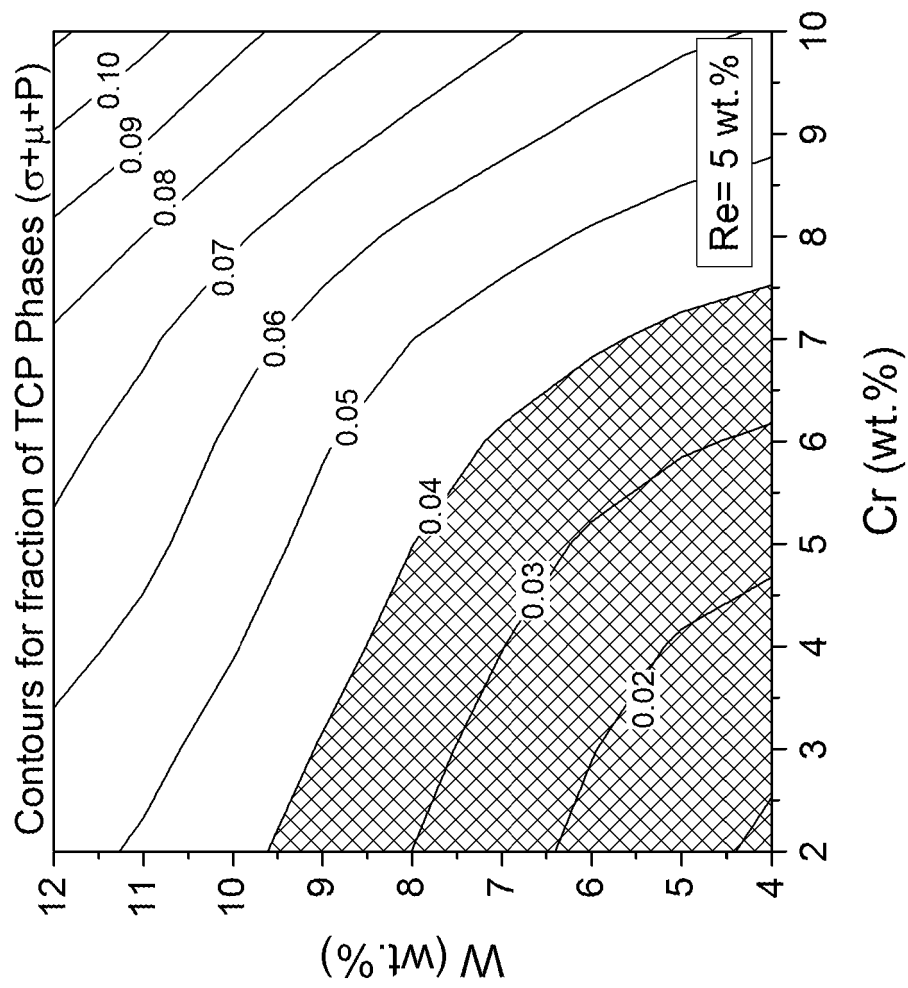


Figure 12

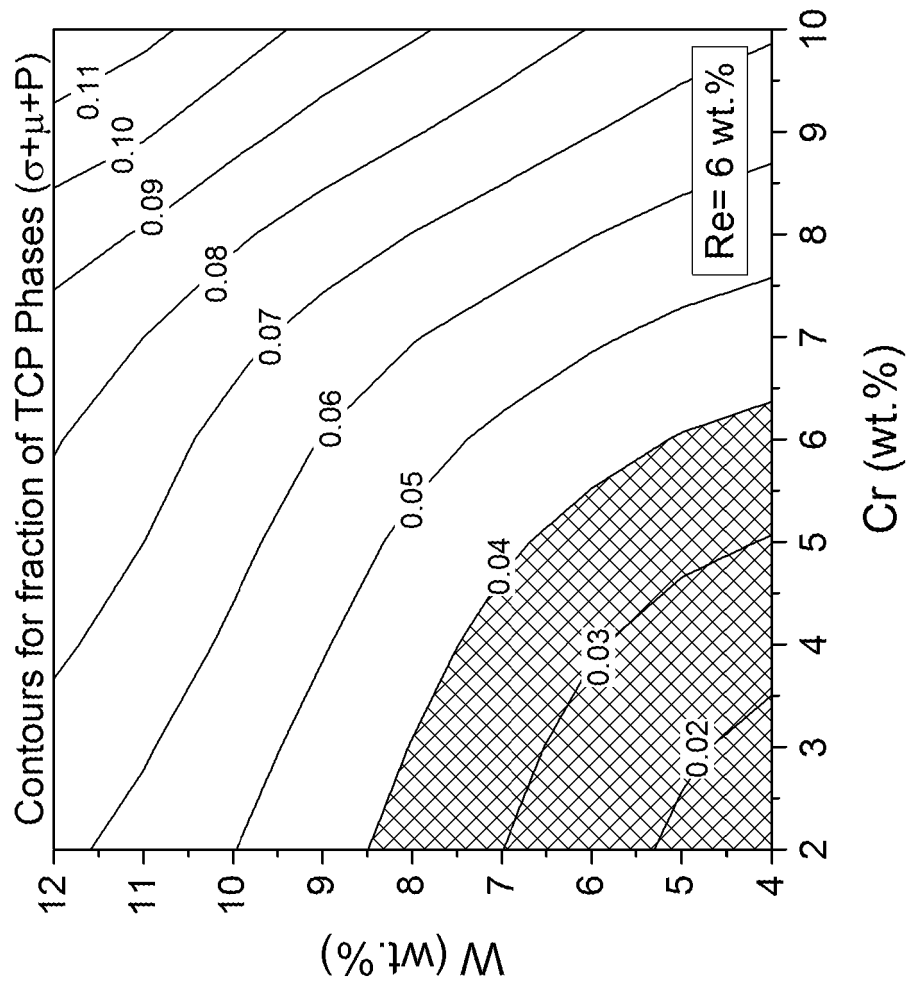


Figure 13

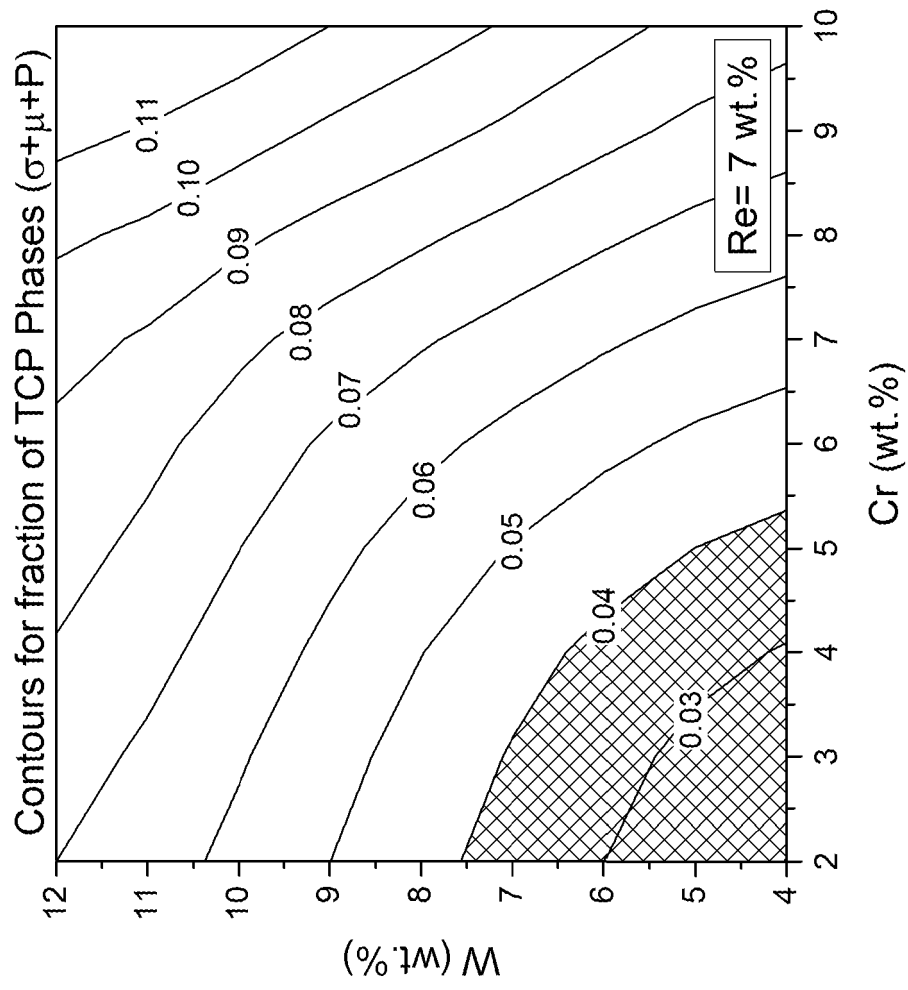
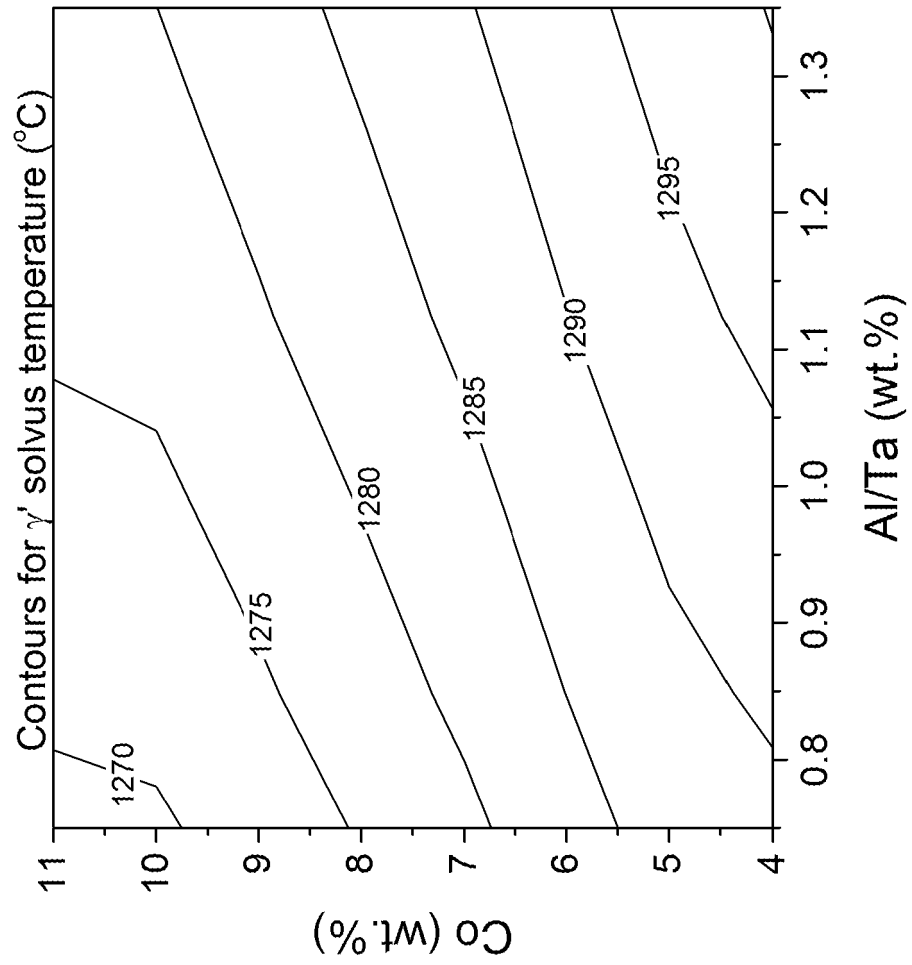


Figure 14

*Figure 15*

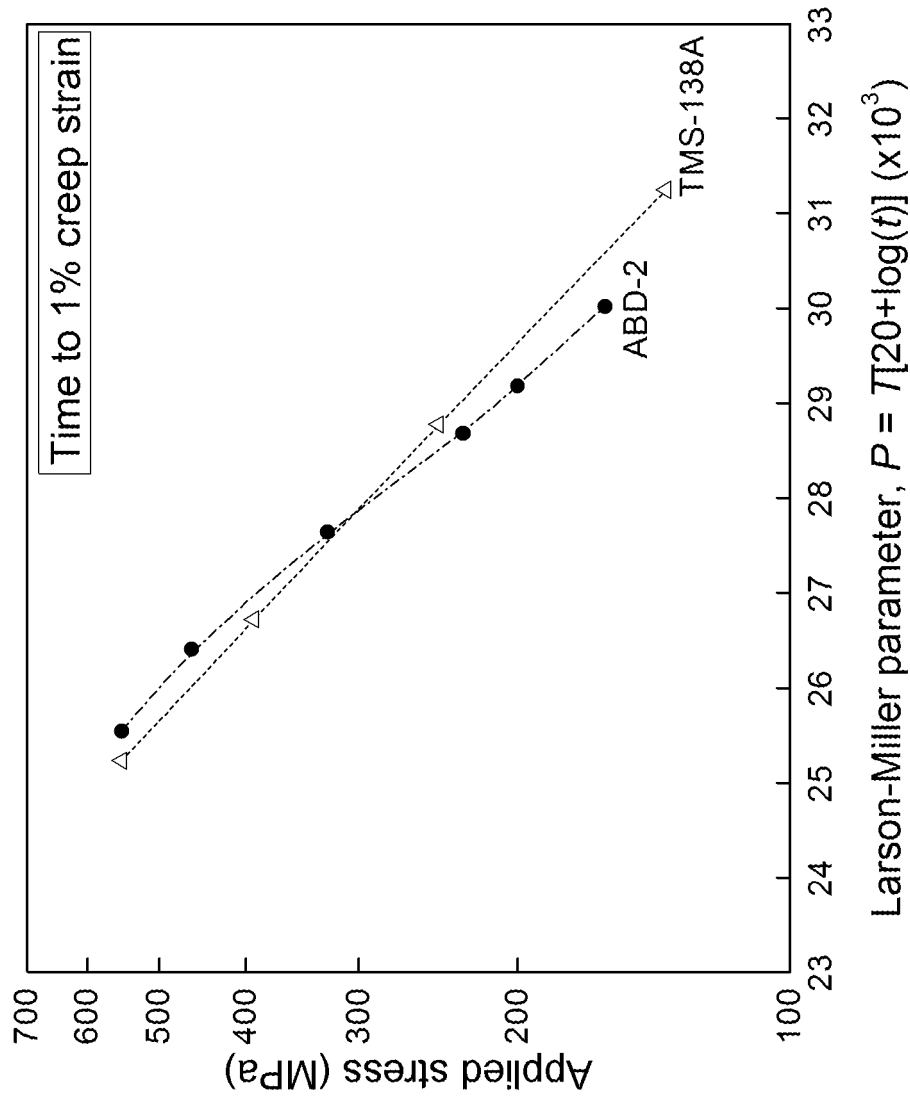
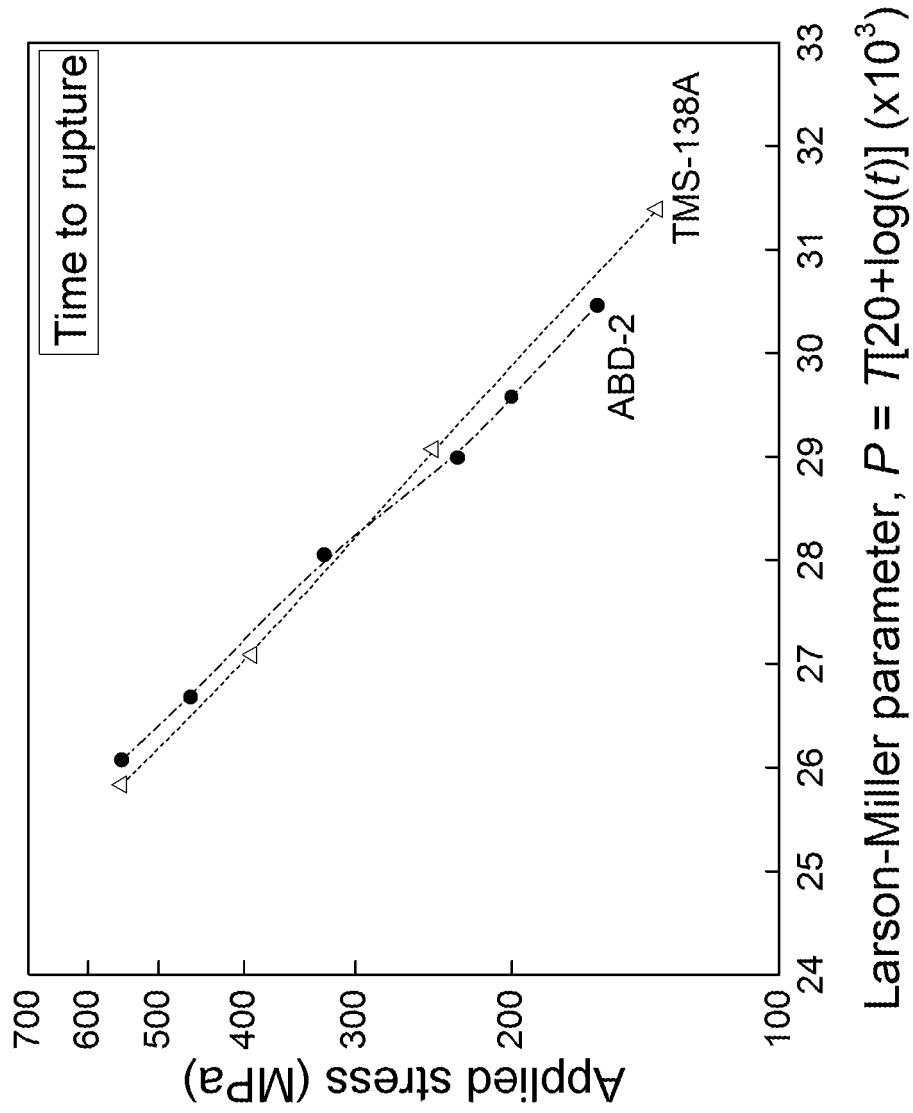


Figure 16



Larson-Miller parameter, $P = T[20+\log(t)] \times 10^3$

Figure 17

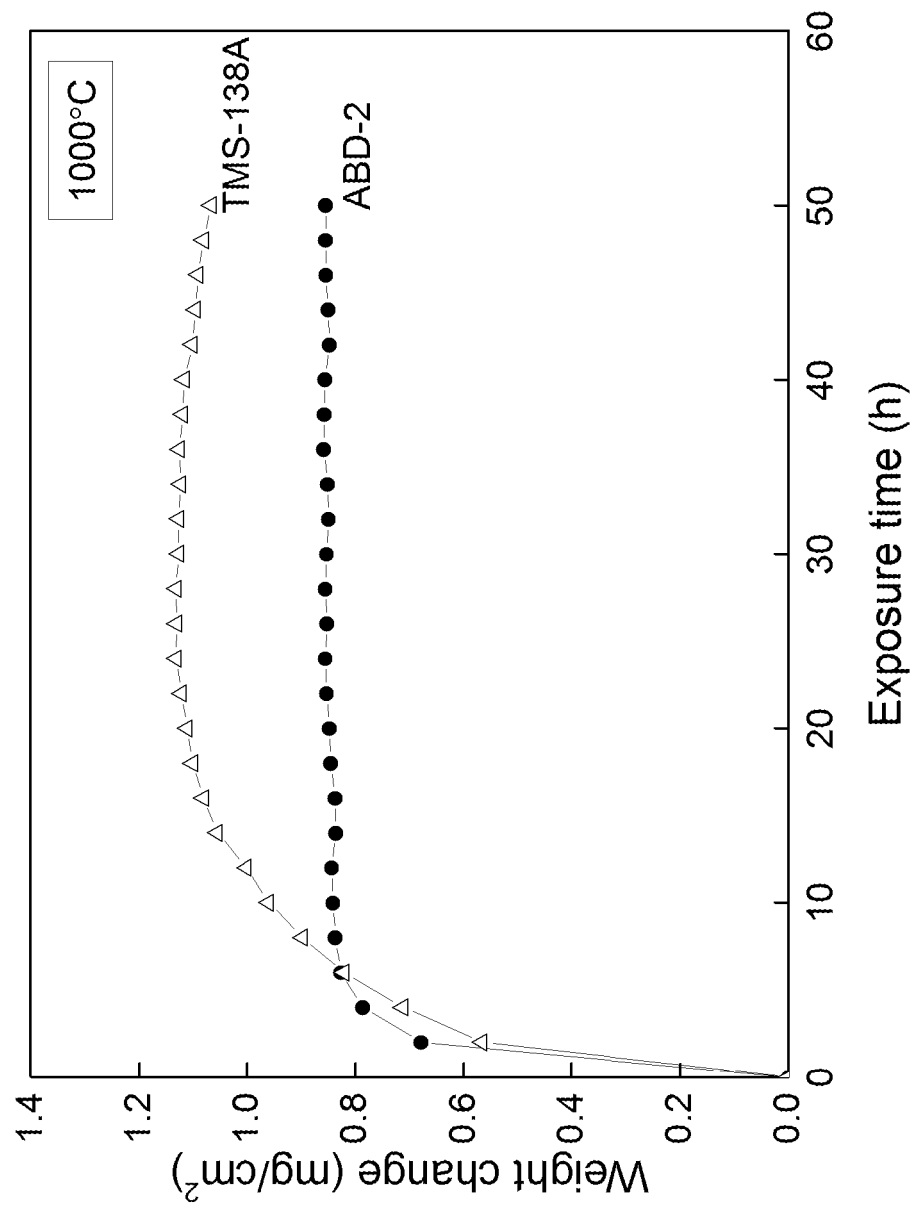


Figure 18