Influence of Alloying Compositions on the Properties of Nickel-Based Superalloys: A Review

Dileep Kumar Ganji and G. Rajyalakshmi

Abstract Superalloys were initially intended to take care of the demand in the materials execution prerequisites of space vehicles, turbo chargers, supplies of heat treatments, turbine motors of aircrafts and numerous others. Among the iron, nickel and cobalt-based superalloys, Ni as primary constituent is gaining lot of significance because of the presence of good mechanical properties including oxidation resistance at high temperatures, and also resistance to creep with precipitation strengthening. Nickel-based alloys also offer repetitivity to strengthen the phases either by solid solutioning or by hardening precipitated phase which enhances strength at peak temperatures. Also, the nature of solid solutions, pressures and environments, phase stability at different temperatures, grain shape, size and distribution are the important parameters for the study of superalloys based on nickel. The performance of these will largely depend on the composition of the elements used for alloying. To impart all the required characteristics for a particular application, alloying elements should be considered in appropriate proportions. With this review, future research endeavour might focus on the modelling and development of nickel-based superalloys for high-temperature applications along with the characterization studies of these superalloys with optimum composition of the constituent elements for better performance.

Keywords Elemental compositions · Oxide formers · Carbide formers · Selection of superalloys

1 Introduction

In the identification of an alloy for turbine blades, including the mechanical properties, environmental corrosion resistance also should be considered as one of the major aspects. When alloys are used at elevated temperatures, they are undergoing

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inevitable oxidation and in some cases, the formed oxide is protective so that further degradation of the material will be stopped or slowed down. However, if the working environment is too aggressive for the material, the corrosion will take place. Of course, designers in industry would prefer if corrosion could be completely avoided and a lot of efforts have been put to improve corrosion properties, in different ways. The morphologies and types of oxides or corrosion products are greatly influenced by the environment. Commonly, in industrial gas turbine blades, sulphides form due to the very oxidizing hot exhaust gases and this also carries some impurities. Thus, understanding of the corrosion mechanisms in different environments will help to reduce the occurrence of corrosion. A detailed review was made in the present paper on the influence of alloying compositions on the nickel-based superalloys. This effort can further be used to develop new materials through computational techniques which may rule out long lead times in designing novel materials together with the products, instead of compromising with the products besides the shortcomings of pre-existing materials.

In the last 60 years, many efforts were put for the development of materials applied in gas turbines by improving the processing methods and optimizing the chemical compositions. The nickel-based superalloys that can exploit in hot components of gas turbines always contain a certain amount of Al and Cr, which can form protective oxides of Al_2O_3 and Cr_2O_3 preventing further removal of the material in the aggressive environments. However, during long-term exposure, the depletion of the oxide layers or evaporation of Cr_2O_3 may lead to further depletion of the alloying elements. This finally causes material degradation and will eventually influence the mechanical properties of the alloys.

2 Characteristics of Superalloys

Superalloys has a wide application in aircraft gas turbines (disks, casings, combustion chambers, exhaust systems, thrust reversers, vanes, cases, blades, bolts and shafts), steam turbine power plants (blades, stack gas re-heaters), nuclear power systems (valve stems, springs and control rod drive mechanisms), metal processing (casting dies, hot-work tools and dies), reciprocating engines (turbochargers, hot plugs and exhaust valves), space vehicles (aerodynamically heated skins and ducting rocket engine parts), medical applications (prosthetic devices and dentistry uses), heat-treating equipment (furnace mufflers, conveyor belts, trays, fixtures and fans), petrochemical and chemical industries (bolts, fans, reaction vessels, valves, piping and pumps) and in many others. Due to its exceptional importance in aircraft and gas turbine engines, lot of research is being done on the elemental composition of the nickel-based alloys which will impart the desired properties for the specific high-temperature applications. Even after long exposure times above 650 °C (1200 °F), the superalloys have the ability to maintain their strength to the highest extent leading to many applications [1].

Superalloys constitute the major alloying elements like Fe, Ni, Co, Cr and are based on Group VIIIB elements and usually consists smaller amounts of W, Mo, Ta, Nb, Ti and Al. The heat-resistant superalloys are broadly classified into nickel-based, iron-based and cobalt-based.

Superalloys constitute face-centred cubic nickel as the primary constituent and may be up to a weight per cent of 40 and additions of five to ten other elements. In nickel-based heat-resistant alloys, the nickel weight per cent may be in the range of 37–80. Superalloys can also be manufactured through cast and in powder metallurgy forms. Cast alloys are rather used in aero engines due to better creep properties with the presence of large grains and accordingly suit them as one of the exceptional alloys for stress rupture limitations in typical applications. Table 1 shows the general composition of alloying elements in three different categories [2].

Most notable characteristic of alloys based on Ni is its usage in the load-bearing applications at temperatures of 80% of their melting temperatures, which is superior to all other alloys used in engineering. These alloys become stronger at high-temperatures, provide good corrosion and oxidation resistance, also have good resistance to rupture and creep. Even these will be best suited to the components of gas turbines such as turbine wheels and blades, and also turbine disks which will be affected by long-term rotational stresses at higher temperatures, i.e. superalloys exhibit good fatigue behaviour at very higher temperatures [3]. These also should maintain excellent chemical and mechanical properties at these temperatures besides withstanding the mechanical forces. Rotating hundreds of times per second in addition to the higher loads in the blades of modern jet engine is one of the most extreme environments, which is very difficult for any of the engineering materials to work, but this has been possible with the advent of Ni-based superalloys.

Table 1 Weight per cent of alloying elements in Fe-Ni, Co- and Ni-based superalloys

Fe-Ni-based										
Element	Ni	Fe	Cr	Ti	Al	Mo	Nb	Co	W	C
Weight %	9–44	29–67	0–25	0–3	0.3–1	0–3	0–5	0–20	0–2.5	<0.35
Co-based										
Element	Co	Ni	Cr	Ti	Al	Mo	Nb	Fe	W	C
Weight %	40–62	0–35	19–30	0–3	0–0.2	0–10	0–4	0–21	0–15	0–1
Ni-based										
Element	Ni	Ti	Cr	Co	Al	Mo	Nb	W	C	
Weight %	37–79.5	0–5	5–22	0–20	0–6	0–28	0–5.1	0–15	<0.30	

Also, minor proportions of Zr, Mn, La, Cu, Si, Mg, B, Ce, Hf, V and Ta can be included

3 Selection of Superalloys

Alloy selection is generally directed at optimizing the properties like creep strength, tensile strength, low- and high-cycle fatigue responses, fracture toughness, creep rupture behaviour and cyclic rupture behaviour [4].

Commonly controlled alloy elements could be as many as 14 or so in some alloys. Nickel and cobalt as well as chromium, tungsten, molybdenum, rhenium, hafnium and other elements used in superalloys are often expensive [2]. Steels will be affected with higher corrosion at elevated temperature applications. Ordinary steels and titanium alloys are not suitable when temperatures go above about 1000 °F (540 °C). To achieve highest temperatures with strength as the major consideration, nickel-based superalloys will be the best choice. Most wrought superalloys have considerable amounts of chromium in order to provide corrosion resistance. The oxidation resistance of nickel superalloys enhanced with the decrease in chromium content and increase in aluminium content. In the nickel-based superalloys, aluminium content increases with the reduction in chromium to keep the oxidation resistance similar to that of original levels or can be even increased. Refractory metals possess high melting points than superalloys, but they do not exhibit similar characteristics as that of superalloys [5]. Figure 1 shows the recent applications of Ni-based superalloys.

The main reason for the usage of superalloys aerospace gas turbine engine parts is because of high yield and ultimate tensile strength, good resistance to corrosion and oxidation in addition to excellent creep resistance at peak temperatures as these are exposed to high-service temperatures.

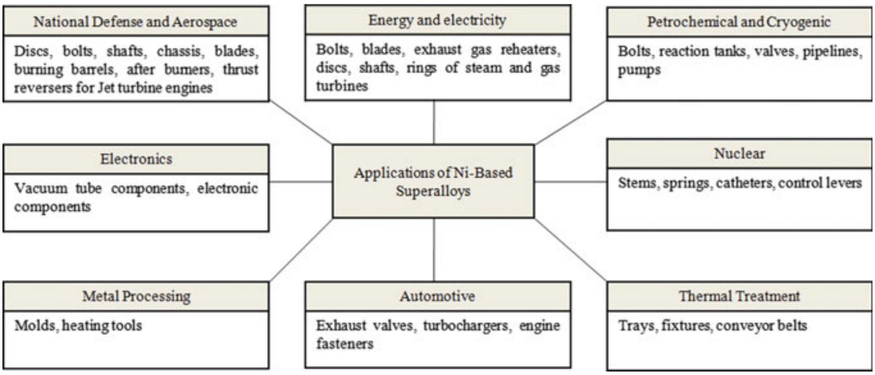

Fig. 1 Applications of Ni-based superalloys

4 Properties of Nickel-Based Alloys

Ni-based superalloys are principally utilized for the production of turbine blades used in turbine engines owing to their exceptional performance of mechanical properties at peak temperatures. Nickel-based superalloys are also capturing a lot of significance, with their applications in marine, chemical industries, boilers, aerospace and nuclear reactors. Many characteristics together with superior mechanical and chemical properties at higher temperatures, high melting point, high toughness and ductility, resistance to corrosion, resistance to thermal shocks, thermal fatigue are primarily liable for wide spectra of applications. These alloys are applicable in industrial chamber applications like muffles/liners in extreme temperature kilns, ball bearings, bearing races, springs, heart valves, etc. Some of the physical properties of nickel are represented in Table 2 [2].

The properties of the Ni-based superalloys can be adapted for specific applications by the addition of exotic materials like metals, metalloids and non-metals. In general, aluminium, niobium, chromium, cobalt, tantalum, molybdenum, iron, tungsten, zirconium, titanium, rhenium, vanadium, yttrium, boron, carbon or hafnium are used. These additions in proper proportions will optimize the properties required for high-temperature applications [6].

Titanium, aluminium and steel alloys loose their specific strength at higher temperatures and will be more ductile in nature. But nickel-based alloys exhibit better

Table 2 Physical properties of nickel

Property	Value
Atomic weight	58.71
Crystal structure	FCC
Lattice constant at 25 °C (nm)	0.35238
Density at 20 °C (g cm^{-3})	8.908
Melting temperature (°C)	1453
Specific heat at 20 °C (kJ kg^{-1} K^{-1})	0.44
Thermal conductivity (Wm^{-1} K^{-1})	
at 100 °C	82.8
at 300 °C	63.6
at 500 °C	61.9
Electrical resistivity at 20 °C (μΩ cm)	6.97
Coercive force (Am^{-1})	239
Saturation magnetization (T)	0.617
Curie temperature (°C)	353
Residual magnetization (T)	0.300
Modulus of elasticity (GPa) in tension	206.0
Shear modulus (GPa)	73.6
Poisson’s ratio	0.30

specific strength with the raise in temperature and can withstand up to 0.8 times of its melting point temperature, and hence 40% of the aircraft engine is being manufactured with nickel-based alloys [7].

5 Effects of Alloying Elements in Nickel Alloys

For superalloys, nickel, chromium, iron and molybdenum are considered to be the primary alloying elements. Also, elements such as aluminium, tungsten, copper, carbon, titanium and sulphur in small proportions will also impact some of the characteristics of the material to be alloyed. Nickel in general enhances strength at higher temperatures, resistance to carburization, oxidation, nitridation and halogenation. It provides metallurgical stability too and improves stress corrosion and cracking at elevated temperatures. Alloying with chromium enhances the resistance to higher temperature oxidizing and sulphidation. The presence of molybdenum considerably enhances the resistance to non-oxidizing acids, like hydrochloric (HCl), hydrofluoric acid (HF) and phosphorous acid (H_3PO_4). Iron controls thermal expansion and improves resistance to carburization. Tungsten additionally provides resistance to localized corrosion, imparts strength and weldability. Carbon will hamper corrosion resistance however adds strength at higher temperatures. Aluminium as an alloying element forms aluminium oxide scale at higher temperature and provides resistance to attack by oxidization, chlorination and carburization. Along with Ti, it upholds age hardening in certain alloys. The susceptibility to intergranular corrosion can be reduced by adding Ti with C, as it forms chromium carbide after heat treatment [8, 9]. The resistance to sulphidation and carburization by the addition of Co due to the solubility of carbon in nickel-based alloys [10]. A consolidated list of materials that provide the basic mechanical properties like hardenability, strength, toughness and machinability when alloyed with different metals is shown in Table 3 [3].

Minor amounts of the rare-earth metals like yttrium improves the resistance to oxidation either the alloys based on nickel or cobalt. Yttrium provides the alloy with comprehensively persistent aluminium oxide film. This film provides resistance from oxidation, carburization and chlorine attack through 2200 °F (1205 °C). Because of the γ' nature of the alloy, it has excellent strength properties through 1700 °F (925 °C) [11].

Main requirements in materials for gas turbines and related high-temperature applications are high melting point, micro-structural stability at high temperature, high-temperature performance, good oxidation/corrosion behaviour, low density, high stiffness and easy to process. Table 4 gives the information pertaining to the properties that can be imparted by adding alloying elements with nickel in superalloys [12, 13].

In most of the materials, with the increase in temperature, there may be a fall in the yield stress, as the metal becomes softer at higher temperatures. As observed in Al-Ni-based superalloys, the yield stress will be constant initially and then increases gradually to a temperature of about 700 °C, providing for its use in high-temperature applications.

Table 3 Materials that impart different mechanical properties

Hardenability	Strength	Toughness	Machinability
Molybdenum	Chromium	Calcium	Lead
Carbon	Cobalt	Cerium	Manganese
Titanium	Manganese	Chromium	Phosphorus
Manganese	Molybdenum	Magnesium	Selenium
Chromium	Copper	Molybdenum	Sulphur
Boron	Carbon	Nickel	Tellurium
Phosphorus	Nickel	Niobium	
	Niobium	Tantalum	
	Phosphorus	Tellurium	
	Silicon	Vanadium	
	Tantalum	Zirconium	
	Tungsten		
	Vanadium		

Table 4 Properties imparted by addition of alloy elements in Ni

Nickel when alloyed with	Provides
Chromium, Molybdenum, Iron, Tantalum, Tungsten	Higher strength
Boron, Zirconium, Carbon	Creep resistance
Chromium, Aluminium, Tantalum	Oxidation resistance
Aluminium, Titanium	High temperature strength
Hafnium	Ductile at intermediate temperatures, Prevents oxides flaking

Oxidation and hot corrosion are because of the alloy degradation modes that relate with atmosphere and comparatively tough to manage. Dangerous high-temperature corrosion (hot corrosion) is because of the contaminants in environment like sulphur, sodium, halides and vanadium. Owing to the catastrophic failure of the components, this hot corrosion will reduce rapidly and enhance the load-carrying capability of the material. Vast studies have been made by the researchers to study the phenomena of hot corrosion, particularly in aircraft turbine engines [14–16].

Due to the unique presence of the combined mechanical and physical properties, nickel-based alloys are considered to be the maximum composition as structural materials in the turbine engines. In Table 5, the properties of superalloys are listed. In the development of nickel-based superalloys, optimization of the tensile properties, fatigue, creep and cyclic growth is of paramount importance [17, 18].

With a FCC matrix stabilizer, the elements like chromium, molybdenum, tungsten, cobalt, iron, tantalum, tungsten and rare-earth metal like rhenium will act as solution strengtheners in solid phase. Carbide formers in nickel-based alloys are tantalum,

Table 5 Physical properties of nickel-based superalloys

Properties	Typical ranges and values
Density	7.7–9.1 g/cm^3
Melting point	1320–1450 °C
Elastic modulus	Room temperature: 210 MPa
	800 °C: 160 MPa
Thermal expansion coefficient	8–18 × 10^{-6}/°C
Thermal conductivity	Room temperature: 11 W/mK
	800 °C: 22 W/mK

tungsten, molybdenum, niobium, titanium and hafnium. The elements that can be used for the raise in solvus temperature of precipitate hardening and intermetallic compounds are cobalt, titanium, aluminium and niobium. Oxidation resistance can be imparted with the elements like chromium, aluminium, yttrium, lanthanum and cerium. To refine the grain boundaries, boron, zirconium, carbon and hafnium can be utilized. Boron and tantalum can be used to impart creep properties, whereas cobalt, chromium and silicon can provide sulphidation resistance. As the components manufacture using nickel-based superalloy can withstand callous environments, they are the idyllic materials in various applications like valves, heat processing equipments, marine assemblies, processing of the chemicals, pumps, aerospace, military, oil and gas industries [19]. Superalloys are the only materials that can exhibit the desired mechanical properties with increase in temperature. There is a gradual increase within the rotary engine entry temperatures, and this phenomenon is anticipated to continue. Therefore, there is a need to develop superalloys to withstand average temperatures of 1050 °C and as high as 1200 °C. This may be nearly equal to 80% of the melting point temperature of the material.

5.1 Strengthening of Solid Solution

Chromium and aluminium are vital as they provide oxidation resistance. Minute amount of yttrium facilitates the oxide scale for sticking to the substrate. The higher creep strength and ductility are due to the reduction of grain boundary changes and the mechanism of failure is because of grain decohesion. Also, the carbide formers like W, Mo, Cr, Co, Nb, C, Ti, Ta and Hf will have their presence in these alloys. The slippery at grain boundary is due to the formation of precipitates of carbides at the grain boundaries. Cobalt, niobium, iron, tungsten, chromium, tantalum, aluminium, vanadium, molybdenum and titanium also are solid solution strengtheners, both in γ and γ' [20].

High percentage of disordered solid solution elements like Cr, Mo, Co and W were present in the γ-phase with a continuous matrix of face-centred cubic phase [21]. This is soft in nature. In γ' phase, the principal strengthening phase is Ni_3

(Al, Ti), which is considered as a precipitating phase in which the crystal planes of the precipitate are in accordance with the γ matrix. This is represented in Fig. 2. The phase precipitates homogeneously all through the matrix and have long-time stability due to its nearness in matrix/precipitate lattice parameter (~ 0–1%) besides the chemical compatability. The γ'-phase is somewhat hard in nature [22].

At high temperatures, solid solution strengthening is mainly due to elastic (misfit) and modulus interactions between matrix and foreign atoms, while other contributions can be ignored [21], interstitials usually have a stronger strengthening effect than substituted atoms (relative per unit concentration), due to the tendency to produce non-spherical distortion in the lattice.

In Table 6, a few elements typically found in superalloys are listed together with their atomic radii and elastic properties. In a Ni-30Cr matrix, best candidates based on differences in size and moduli are primarily Re, W and also Nb, Mo and Ta [23–25]. Each increment of 10 wt% of tungsten and molybdenum decreases the rate of creep

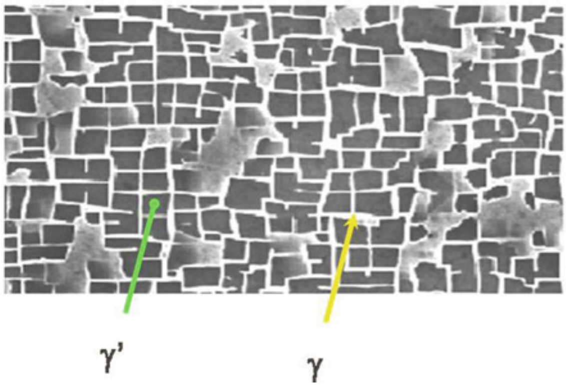

Fig. 2 γ-phase and γ'-phase [22]

Table 6 Relevant properties of some elements for solid solution strengthening

Element	Atomic radius (Å)	Young's modulus (GPa)	Shear modulus (GPa)
Ni	1.62	207	76
N	0.75	–	–
Co	1.67	211	83
Fe	1.72	200	81
Al	1.82	68	25
Cr	1.85	279	115
Re	1.97	469	176
Mo	2.01	330	120
W	2.02	400	175
Ta	2.09	185	69
Nb	2.09	103	37

such that tungsten strengthens to a fairly greater extent than molybdenum does [26], which is probably due to the difference in their elastic properties. Re has also been studied extensively as solid solution strengthener in nickel-bases alloys, and it is also found to dramatically slow down diffusion at high temperatures [25]. Ta and Nb are often alloyed in order to precipitate intermetallic precipitates. If these elements are to be used as solid solution strengtheners, then it is also important to consider the relative stability of their nitrides. Ta and Nb form very stable nitrides. Even though, Mo and W form stable carbides, they are not very strong nitride formers. In case of Ta, for instance, in a Ni30Cr alloy containing nitrogen, the matrix will be depleted because of the precipitation of nitrides [27].

Nickel forms a primary solid solution with copper and can be soluble completely with iron. 35% Cr, 20% each of W and Mo, and 5–10% each of manganese, titanium, aluminium and vanadium can be used to dissolve the same. The tough, ductile face centred cubic lattice matrix will dissolve the elements is varied combinations to form solution hardening along with improved oxidation and corrosion. The relation between the difference of atomic size and between the nickel and its alloying elements and the degree of solution hardening decides the ability of solute to hamper with the motion of dislocation [28].

The elements from Groups II, III and IV, like boron and carbon, tend to form borides and carbides and segregate at grain boundaries. It should be emphasized here that the grain boundary strengthening elements are favoured in polycrystalline alloys, but they are suppressed in single-crystalline materials [29].

γ-phase exhibits FCC structure, and in general, it forms a continuous matrix phase with other phases residing inside it. The elements consisting of γ matrix like iron, cobalt, chromium and some refractory metals like molybdenum and tungsten belongs to Group V, VI and VII. The γ' forms as a precipitate phase with FCC structure and is observed as spherical or cuboidal particles. The elements partitioning to γ' mainly belong to Group III, IV and V such as Al, Ti, Nb and Ta. The γ' precipitates are coherent with matrix and contribute to the strength of the precipitation hardened alloys [30].

The alloys might be improved by adjusting their composition; however, they can also be improved by innovations in processing, such as directional solidification or single crystal technology [31]. Unlike the polycrystalline alloys, the single-crystalline alloys are free from grain boundaries. The lack of grain boundaries leads to an increase in the incipient melting temperature, and therefore, it helps to get fine-scale precipitation of γ' when heat treated at 1240–1330 °C. In the applications for gas turbine blades, the lack of grain boundaries improves the creep and fatigue performance in service [32].

5.2 Carbides

Even though nickel is not carbide former, it can dissolve many elements enabling it to form carbides in the nickel constituent alloys (MC, M_6C, M_7C_3, $M_{23}C_6$ in which

M stands for alloying element). W, Ta, Ti, Mo, Nb forms MC carbides which are typically large and undesirable. Mo and W form M_6C carbides which can precipitate as small platelets in the grain boundaries. Cr forms M_7C_3 and can be useful when precipitated as discrete particles. Cr, Mo and W form $M_{23}C_6$ which can enhance creep rupture properties [33].

Ni-based superalloys are basically preferable when used at 760–890 °C, whereas Fe–Ni superalloys at the lower temperatures of 650–815 °C. Due to the absence of γ'-phase, cobalt-based alloys have still lower strength characteristics than Ni superalloys at medium and lower temperatures [34]. The relationship of creep strength for Fe-, Ni- and Co-based superalloys is shown in Fig. 3 with different types of strengthening [35].

Also, the stress rupture strength of the superalloys based on nickel are outstanding when compared with other materials used in the structures of aircraft like Mg, Ti and Al alloys as shown in Fig. 4 [36]. Rapid creep is observed in Mg, Al and Ti alloys above 100, 150 and 350 °C, whereas Ni-based alloys can resist even when it is used at a temperature of 850 °C.

Attributable to their splendid properties, like thermal stability, corrosion resistance, strength to fatigue under adverse environments, aero engines are made up of Ni-based superalloys by a weight per cent of 50 when compared to other materials [37–42]. Nonetheless, these materials represent a significant test for machining

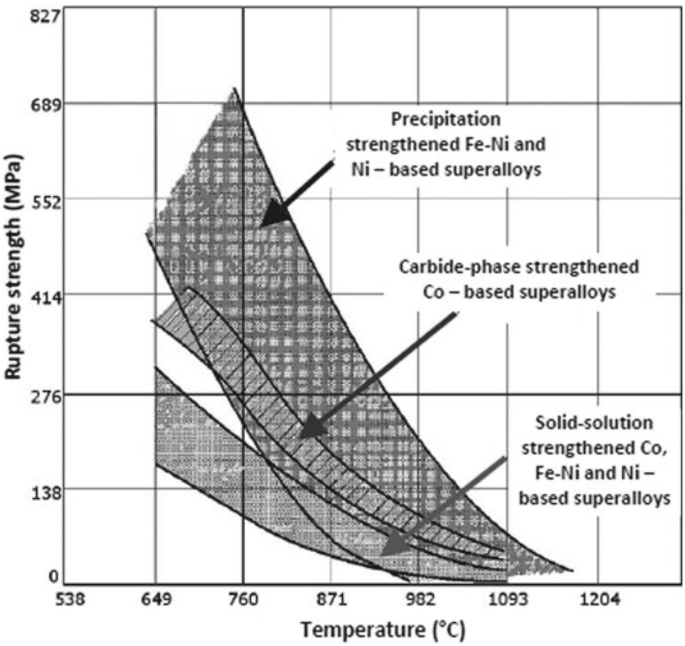

Fig. 3 Stress rupture of wrought Ni, Fe–Ni and Co-based superalloys with the strengthening mechanism [35]

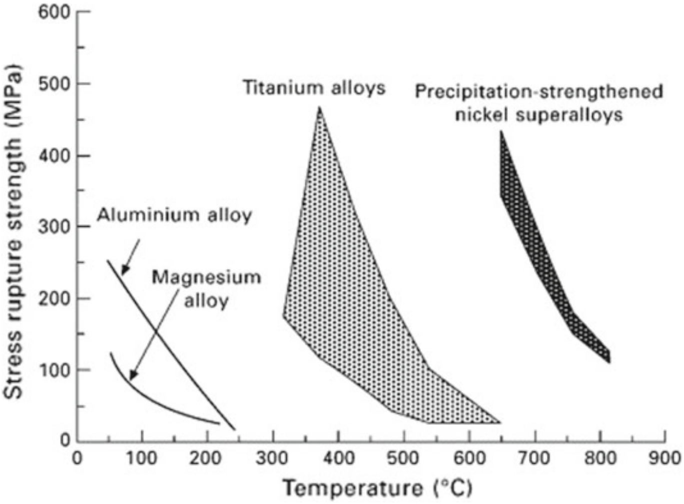

Fig. 4 Stress rupture characteristics of Mg, Ti, Al alloys and Ni-based superalloys [36]

because of its low thermal conductivity, hot hardness, tendency to work harden, existence of carbide particles in the microstructure, tool material chemical affinity [43–47]. Hence, noteworthy research consideration is drawn towards the manufacture of air craft engines and some other critical parts where safety is a prime consideration. Due to the formation of carbides in the microstructure of nickel-based alloys, it is difficult to machine [48]. The major components of gas turbine like compressor, combustor and turbine are manufactured through precision casting and then excess material can be removed through grinding, thereby desired surface finish can be obtained. Other machining processes may include turning, milling, drilling, boring and shaping of the spline couplings [49–51]. At present, electrical discharge machining, laser machining and electrochemical machining are being employed in many industries for hole-making processes besides twist drilling [52].

5.3 Oxidation Behaviour

The properties of Ni-based superalloys are often tailored to an explicit extent through the addition of the many different elements. Table 7 shows the effect of adding different alloying elements to nickel [53]. Alloying will improve the oxidation resistance of pure metals. With 10–30% chromium in nickel, iron or cobalt, the ensuing oxidation resistance is adequate at temperatures of use. An inclusion of 15% aluminium to iron additionally improves its oxidation resistance. Additions of Mo, V, Hf, W, Ti, Zr and S have considerably improved the oxidation resistance by forming a lot of stable complicated oxides [54]. Additions of yttrium in about less than 1% to chromium, scale back nitrogen penetration. Alloying will enhance the oxidation resistance of

Table 7 Alloying elements for various effects

Effect	Alloying elements
Strengtheners of solid solution	Mo, Cr
Stabilizers of FCC matrix	W, C, Ni
Carbide formers	Cr, Ti, Mo
γ' Ni_3 (Al, Ti) formers	Ti, Al, Ni
Hexagonal η (Ni_3Ti) formers	Zr, Al
Sulfidation resistance	Cr
Precipitate hardeners	Nb, Al, Ti
Rupture ductility	B
Corrosion resistance	La, Y
Oxidation resistance	Cr

metals that develop low-melting volatile oxides (rhenium, tungsten, molybdenum and vanadium) [55].

Figure 5 shows the composition of alloying elements in some of the commercially available nickel-based superalloys.

The variation of ultimate tensile strength (MPa), 0.2% yield strength (MPa), elongation and stress rupture at 1000 h (MPa) characteristics with change in temperature for Haynes-556, Haynes HR-120, Hastelloy X and Haynes-230 are shown in Fig. 6.

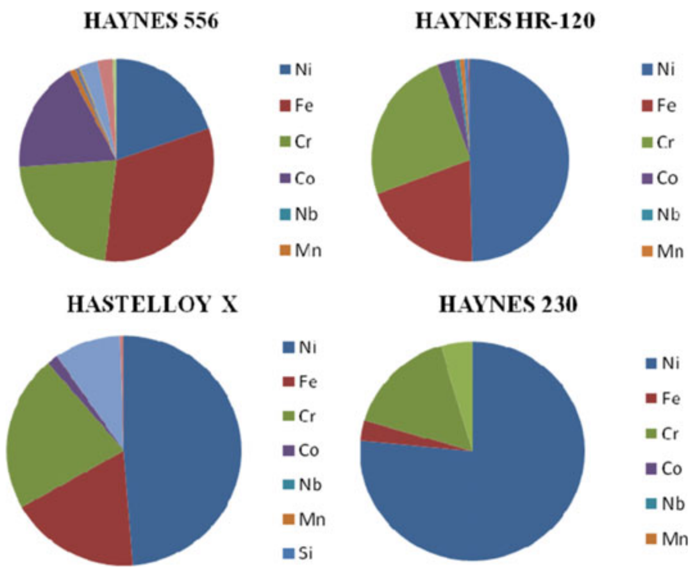

Fig. 5 Composition of various Ni-based superalloys

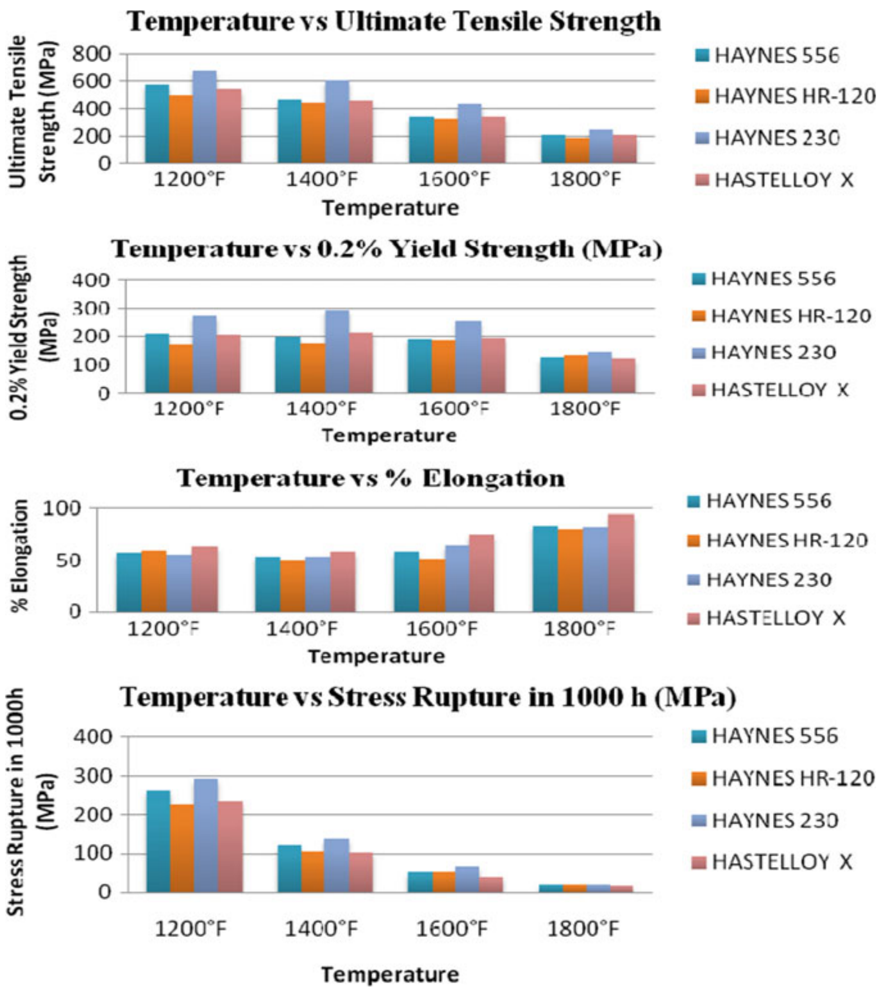

Fig. 6 Composition of various Ni-based superalloys

The Ni alloy with maximum composition of Fe, Cr and Co gives better mechanical properties when compared to other alloys even at higher temperatures.

At present, ruthenium was also being alloyed with nickel-based superalloys to forestall the formation of harmful topologically close-packed phases. Also, Ru can strengthen γ-phase and γ′-phase in comparison with Re due to a weaker partitioning of the γ matrix [39, 40, 56]. Table 8 presents the composition of the alloying elements for the formation of carbides and oxide layers.

The grain growth and mechanical deformation are closely related to surface roughness. This also will cause strain hardening and induce residual stresses [35, 57]. Shape parameters, fatigue durability and surface textures of nickel-based superalloy also need to be addressed through further investigations [52]. 0.05–0.2% carbon content

Table 8 Element compositions

Alloying elements	Composition range	Effect on properties
Mo	0–12	Due to the formation of carbides, these elements will enhance the mechanical strength of base alloy. Generally, these elements are at substitutional positions for solution strengthening
Ta	0–12	
W	0–12	
Nb	0–5	
Ti	0–6	
Si	0–5	Forms oxide scale on the surface of the alloys to protect surface
Al	0–6	
Cr	5–25	

can be added along with the refractory and reactive elements like tantalum, titanium, and hafnium, this forms carbides such as TaC, TiC or HfC. These carbides will decompose during heat processes and leads to lower carbides which will generate grain boundaries [17].

6 Future Work

The necessity of materials to work in the hot gas regions of gas turbines, like the blades/vanes, is very demanding. They need to be competent to operate at peak temperatures under both high and fluctuating stresses, and at the same time withstand severe operating environments. Due to the poor quality of fuels often used in industrial gas turbines, the turbine blades are exposed to hot combustion gases containing contaminants such as a mixture of inlet gases, combustion fuel, sulphur containing species, water vapour etc. As a result, the gas turbine materials will not only be oxidized, but could also suffer the more deleterious hot corrosion [58].

The plan and improvement of newer materials to cater very high-temperature needs is constantly a challenge between accomplishing better oxidation resistance and also creep strength and keeping up sufficient pliability and strength at both low and high temperatures. Many of the constituent elements can dissolve in Ni-based superalloys and maintain a high degree of structural stability. Further, this review can be used to focus on the development of Ni-based superalloys, by tailoring the composition, morphology and volume fraction of the major phases to obtain an optimum balance of tolerance to low and high temperatures along with considerable creep and oxidation resistance.

The machined surface integrity of these superalloys is a significant as it persuades the performance of material. As these materials metallurgically designed to have significant strength at peak temperatures, the stresses induced during machining are also high. Also, these will work harden easily leading to rise in diffusion wear, and may lead to formation of heavy burrs. Compositional changes can be made to overcome these challenges.

Artificial intelligence tools can be employed to develop new Ni-based superalloys for turbine applications, which may presumably satisfy all target properties at the same time [59]. The aim is to predict the composition and process variables that may provide a material satisfying the multi-criteria target specification. Initially, a predictive model is to be constructed for every property as a function of the composition. Then, the probability that a supposed composition suits the desired specification will be computed from the space search of the composition.

7 Conclusion

Tantalum, aluminium and titanium provide strength to the alloy, as they form γ'-phase. The resistance to creep can be enhanced by strengthening the solid solution of γ-phase with the addition of minor amounts of Re, W and Mo. Re increases the creep properties. Also, Cr, Co, W, Ta also does the same by addition of small amounts, else leads to microstructure instability. The fraction of Re can improve the hardness of the γ-phase. Al, Cr and Co can be added to improve resistance to oxidation, sulphidation and corrosion. Zr, Hf, B and C form borides and carbides at the grain boundaries in poly-crystal superalloys for strengthening of grain boundary. As the grain boundaries are not present in the single-crystal superalloys, the fractions Zr, Hf, B and C are lower, or not present in the single-crystal superalloys. In most of the materials, with the increase in temperature, there may be a fall in the yield stress, as the metal becomes softer at higher temperatures. But, nickel-based superalloys consisting γ'-phase has an intermetallic compound Ni_3 (Al,Ti) and are temperature resistant. If there is a need for higher strengths at lower temperatures, such as in turbine disk applications, γ''-phase can be used to strengthen the alloys by adding Nb or V forming Ni_3Nb or Ni_3V. The melting point of the Ni-based superalloys can be improved with the simplified alloy chemistry. So, alloys can be developed through varying compositions of the elements through modelling to cater the needs of modern high-temperature applications.

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