In harsh working environments where there can be very high temperatures and heavy loads, like in the inside of the combustion chamber of a rocket, industrial gas turbines, space vehicles, and so on, a special class of material will be needed for making the required parts. This special class of materials is called superalloys. There are many types of superalloys based on the major alloying element. But, among these, Ni-superalloys stand out significantly due to their superior mechanical and physical characteristics. Thus, they are widely used in situations where the working conditions are unbearably harsh for ordinary materials. And, due to this, a lot of research have been done on Ni-superalloys for improving them and studying their properties. This extensive research work has led to the development of many generations of Ni-superalloys, with alloys getting better and better with each passing generation. Among all generations, the 5th and 6th generations of Ni-superalloys are the most recently developed ones. With the development of 5th and 6th gen alloys being very recent, there are not many studies conducted on them. With the current bloom in aerospace, energy, and thermonuclear research fields, the need for materials such as Ni-superalloys that can withstand absurdly harsh environments is increasing. That is one of the reasons why reviewing existing studies pertaining to recently developed new generation alloys is very important. It can help us in finding out the future possibilities for research so that we can develop new alloys or improve the existing ones. In this review paper, various aspects of these alloys such as fatigue properties, creep properties, oxidation resistance properties, corrosion resistance properties, element composition of these alloys and their impact on the above factors, use of various manufacturing methods, and the presence of additives have been extensively studied.

1. Introduction

The aerospace, aeronautical, and automotive industries are booming today, and coupled with the growing energy demands, the demand for materials that can work in very harsh conditions has been increasing. This seems to be a major issue when selecting material and designing parts for applications such as parts of vehicles used for space flight, parts that make up the turbojet engines of airplanes that are used for high-speed atmospheric flight, and gas turbine blades used in high-energy output power plants. In all these cases, the components used are subjected to extreme temperatures, pressures, and even extreme loads acting on the bulk of the material. Some examples of these are as follows:

(i) Blades of gas turbines used in heavy industries, such as power generation plants or nuclear plants, where working components are exposed to high temperatures along with alternating tensile and compressive loads that are very high in magnitude

(ii) The inner wall of the combustion chambers of rocket engines where the material used should have high creep, fatigue, and oxidation resistance properties combined with the ability to also withstand very high temperatures that can even cross 1,000°C
(iii) The turbine blades of turbojet engines that are subjected to cyclic loading at elevated temperatures

This is where the development of Ni-based superalloys has been a great boon. It has helped in particularly developing alloys with high-temperature workability, superior creep properties, highly enhanced fatigue properties, high-temperature corrosion and erosion resistance, and high-temperature oxidation resistance. These characteristics of Ni-superalloys make them a go-to candidate for high-temperature applications where working conditions are extremely harsh.

2. Objective of the Study

Ni-superalloys were first developed in the early twentieth century. But widespread use was only seen in the 1960s and 1970s. But the alloys developed then were extremely premature and not as efficient as the high-performance Ni-superalloys we have today. Over the years, a lot of modifications have been done to these alloys in order to develop new Ni-superalloys with constantly improving characteristics and the ability to work at higher temperatures. This was seen to be mainly achieved by modifying the alloying element compositions and controlling the manufacturing methods, techniques, and manufacturing conditions and parameters. New generations of superalloys were developed eventually over the years with each new generation attaining superior characteristics in comparison to previous generations. These developments were carried out by modifying the alloying element composition and even by introducing certain new elements into the mix. And, depending upon this elemental makeup or compositions, Ni-superalloys can be categorized into six different generations with the 6th generation Ni-based superalloy being developed quite recently in the early twenty-first century. The objective of this study is to compare the most recently and newly developed 5th and 6th gen Ni-superalloys to the previous generation superalloys and to learn how and by what amount they have improved. The study also aims at identifying how further development can be done in this field, thus leading to the development of Ni-superalloys that are better than already existing or developed alloys and even developing a whole new generation of Ni-superalloys.

The various properties such as creep, effect of alloying element composition, oxidation resistance, and many others of new generation superalloys specifically 5th and 6th gen Ni-superalloys have been reviewed and compared with data provided by papers that examined previous generation superalloys. Table 1 shows the list of some 5th and 6th gen Ni-superalloys and some of their predecessors used in the papers reviewed in this article, their composition, and generation.

3. Classification of Ni-Superalloys

Ni-superalloys can be categorized into six different generations today, with the 6th generation having been developed quite recently. This classification is done based on the alloying elements used and their composition. A lot of studies [4, 5, 12, 13] have talked about this classification. Alloying elements present in 1st generation Ni-superalloys are mainly Cr, Co, Mo, Al, Ti, Ta, W, and sometimes Nb, V, Y, or Ca for enhancing certain aspects of these alloys such as creep, oxidation resistance, and so on. Ti, Ta, Nb, and V help in strengthening the γ’ phase precipitates by substituting the Al atoms in Ni₃Al. They also help in promoting the formation of Al₂O₃ surface oxide scales that help in preventing the further oxidation of the underlying superalloy component. Most of these alloys were only used in creating polycrystalline components using conventional casting techniques. Therefore, elements such as B, Zr, C, Cr, Mo, W, Nb, Ta, Ti, and Hf that help with the formation of carbides were used to strengthen the grain boundaries (GBs) as they have a tendency to precipitate there and thus decrease the tendency for sliding of GBs and can also help in suppressing certain defects [4, 5, 12-18]. Elements such as Cr, Al, and Mo were also seen to help with oxidation resistance at elevated temperatures, and refractory elements such as W and Ta were seen to help increase the workable temperature of these alloys [1-5]. But, when the concentration or composition of some of these alloying elements were seen to exceed a certain amount, it was seen to cause embrittlement of the γ matrix. But this problem was seen to be solved by the addition of a small amount of Re, thus giving birth to the 2nd generation of Ni-superalloy. Second gen Ni-superalloys are alloys derived by adding a certain amount of Re into the mix of alloying elements that make up the 1st gen superalloys. The Re concentration in these alloys was seen to be between 2 and 3 wt%. Re additions were seen to greatly enhance the strength and elastic modulus of the γ matrix and also improve creep properties. This was seen to help raise the working temperature of 2nd gen Ni-superalloys, improve their strength, and also extend their creep lives. Second gen superalloys were used for making polycrystalline and directionally solidified components. The 3rd generation of Ni-superalloys was characterized by the inclusion of Re in high amounts (up to 6 wt%). This along with a slight Mo increase was seen to improve the creep properties drastically. But, at these high Re concentrations, the solid solution limit was exceeded, and this was seen to lead to the formation of TCP phases that were detrimental to creep properties, at elevated temperatures. Third gen superalloys opened up the route to the production of single crystal (SC) superalloy components. The 4th generation of Ni-superalloys was synthesized by adding Ru to 3rd gen superalloys. This was done as Ru was seen to stabilize the microstructure and also suppress the TCP phase formation. It was also seen to significantly enhance the creep properties and workable temperatures. Fourth gen superalloys were seen to be primarily used in making SC components, so these alloys did not have any GB strengthening elements in their composition. Fifth generation of Ni-superalloys was seen to be derived from 4th gen superalloys by increasing the Ru concentration to up to 6 wt%. This was seen to better stabilize the microstructure and enhance creep and also helped include a higher concentration of refractory elements due to better stability. The inclusion of higher amounts of refractory elements was seen to enhance the workable temperature greatly. And alloys that can
withstand and work just fine in the range of 1,000–1,100°C were developed. The main drawback of 4th and 5th gen superalloys was their comparatively very low oxidation resistance. This was the issue tackled by the development of 6th gen superalloys. Sixth gen superalloys were an improved version of 5th gen superalloys that had excellent creep properties, high workable temperature combined with high oxidation resistance. This was seen to help attain a highly significant improvement in the creep life and strength. Sixth gen Ni-superalloys in addition to the elemental composition of the 5th gen superalloys were characterized by a higher amount of oxidation-resistant elements such as Cr. Sixth gen superalloys like 5th gen superalloys were also used only in SC applications.

### 4. Effect of Alloying Elements and Their Composition on 5th and 6th Gen Alloy Properties

Ni-superalloys are classified into various generations based on their alloying element composition, and the composition of these alloying elements can play a vital role in influencing the properties of these alloys. Various studies have been done in order to examine the influence of the composition of these elements on 5th and 6th gen superalloys. One such study [19] investigated the properties of newly developed 5th gen Ni-superalloy TMS-196. Fourth and fifth gen superalloys have good creep but bad oxidation resistance, and TMS-196 was developed to resolve this issue. It was developed with TMS-173 as a base. TMS-196 was developed by taking the composition of TMS-173 and then decreasing the amount of Re an element that can suppress oxidation resistance to some extent and increasing the amount of Cr that forms an oxide Cr2O3 and also promotes the formation of the oxide scale Al2O3 that can prevent further oxidation of alloy. This was seen to increase the oxidation resistance of the newly developed TMS-196. But, with a decrease in Re, an element that enhances creep properties, the creep strength and life of the alloy would be expected to fall behind its predecessor. But this was solved by adjusting the compositions of Mo and W. This adjustment was seen to help retain excellent creep properties by introducing a negative lattice misfit of very high magnitude in the γ-γ' interface. With the excellent creep properties, high negative lattice misfit, and superior oxidation resistance that was achieved by the TMS-196, its creep strength and life were seen to be extended significantly, and an improvement in the workable temperature of the alloy was also seen. The oxidation resistance of TMS-196 was seen to be comparable to that of 2nd gen Ni-superalloys such as Rene-N5, a Ni-superalloy with high oxidation resistance. And the mass change/loss that took place during creep was also seen to be low due to this enhanced oxidation resistance. This increase in the oxidation resistance was mainly attributed to the increased Cr content.

Another study investigated the influence of elemental composition by comparing a wide variety of Ni-superalloys from all generations. The investigations confirmed the clear influence that the composition of elements such as Ru and Cr had on the properties of 5th and 6th gen superalloys. Fifth gen superalloys are characterised by their high Ru content (up to 6 wt%). The high amount of Ru was seen to increase the microstructural stability and suppress TCP phase formation that is promoted by the high content of creep enhancing Re element. The microstructural stability that was provided by the high Ru content was also seen to enable further additions in the composition of other refractory elements. Thus, aiding in the enhancement of alloys’ creep properties, a result of the increased composition of Ru and other refractory elements greatly amplifies the negative lattice misfit that is present between the γ matrix and the γ' strengthening phases' interface. As such, the composition of Ru was seen to have a vital role to play in the development and improvement of 5th and 6th gen superalloys. The study also showed that in cases of some alloys such as TMS-196 and TMS-169, the increased Cr content provided these alloys with superior oxidation resistance and thermomechanical fatigue (TMF) properties.
Another study [20] examined the influence of Re composition on alloy properties and how their composition has helped in the superiority of 5th and 6th gen Ni-superalloys. The most important effect of Re was seen to be enhancing the creep properties of Ni-superalloys. With an increase in Re content with each new generation, significant improvement in the creep properties and workable temperature of alloys were noted. A good example of this is the increase in creep strength, life, and workable temperature in the alloys, 2nd gen CMSX-4, 3rd gen CMSX-10, and 5th gen TMS-169, with said properties improving with each passing generation. Moreover, moderate amounts of Re were also seen to improve fatigue strength and increase corrosion resistance. Re was also seen to help in slowing down the coarsening of the strengthening precipitates. Re was also seen to strongly segregate into the γ′ matrix, and Re was not seen to be present in amounts that can be detected in the precipitated γ′ phase. Creep properties exhibited by an alloy can be highly influenced by the rate of diffusion of the alloying elements at high temperatures. This is why the slow diffusion rate of Re observed at very high temperatures helped in enhancing the creep properties in high Re containing 5th and 6th gen Ni-superalloys. But the addition of Re was seen to stimulate the generation of TCP phases that are harmful to the superior characteristics that the superalloys are sought after. But 4th and 5th gen Ni-superalloys solved this problem by including moderate to high levels of Ru additions. Ru was seen to stabilize the microstructure and inhibit the TCP phase formation, thus improving creep. And, apart from suppressing TCP phase formation, the very high Ru content in 5th and 6th gen superalloys and the microstructural stability it gave these alloys were seen to enable further addition to the composition of Re and some other refractor elements, thus improving creep properties vastly. High Re content was also seen to induce greater negative lattice misfit at the interface of the γ and γ′ phases. And the improved negative misfit helped in increasing the creep strength and life of these Ni-superalloys greatly. The points regarding Ru and its effects were also supported by another study [4, 13]. Another study [21] talked about a 5th gen Ni-superalloy called TMS-162 that was developed with TMS-138 as the base alloy. This study particularly explained how the increased Ru and Mo compositions seen in TMS-162 together affected the alloy properties, namely, its creep properties. Compared to TMS-138, the newly developed superalloy TMS-162 had its Mo and Ru compositions increased by 1 and 4 wt%, respectively. The increase in these elements was seen to highly enhance the creep properties, by slowing down the creep rates. The creep speed/creep rates in TMS-162 were seen to be comparatively significantly lower along with the longest time to rupture because of the finer and smaller network dislocations in the γ- γ′ interface and the high negative lattice misfit, both of which are a result of the increase in the Mo content. And Ru was seen to aid in suppressing TCP phase formation and also help in including additional Mo content without disturbing the microstructural stability.

One study [22] investigated the influence that varying Ta, Ru, and Nb elemental compositions can have on the creep properties of a 5th gen Ni-superalloy called TMS-173. For this purpose, various variations of the alloy TMS-173 were made by manipulating the composition of the elements Ta, Ru, and Nb. The elemental composition of the variations and the original base alloy TMS-173 are shown in Table 2. TMS-173 has significantly high-strength and relatively superior creep life. But, after creep testing for a very long time at elevated temperature, TCP phase formation was observed in the alloy's tissue. TCP phases can cause damage to the alloy’s creep and other high-temperature properties. Thus, one variation has its Ru content increased from 5 to 6 wt%, to see how the TCP phase suppressing and microstructure stabilizing Ru can affect the creep properties of the alloy. In another variation, it was seen if reducing the Ta content could give a similar result and affect creep. Ta was also seen to be present in the TCP phases.

And, finally, how compensating the decrease in Ta by introducing Nb would affect the creep properties was also studied by using a variant having slightly decreased Ta content with Nb addition. All samples after heat treatment showed similar precipitation structure, and the γ′ grain sizes were found to be almost the same, with large eutectic regions that were about 0.3 mm in size being observed. Figure 1 below shows the variation in creep life of different samples made from various modified alloys at 900°C temperature and 392 MPa stress. Substituting Ta with Nb, increasing Ru content, and decreasing the Ta content were all seen to significantly extend the time to creep rupture, with the TMS-173 sample with decreased Ta content showing the highest time to rupture (almost 30% increase). The increases in time to rupture were seen because all the changes succeeded in reducing the TCP phase formation with a reduction in Ta suppressing the TCP phase formation the highest. And, as a result, no TCP Phases were formed in this sample. For 1,100°C and 137 MPa conditions, the sample where Ta content was reduced and substituted with Nb was seen to exhibit the longest time to creep rupture (about a 50% increase compared to the base alloy). In other samples, the coarsening of the γ′ precipitate was seen to be higher than in the sample containing Nb, thus breaking after forming a raft structure. That is why despite the samples with increased Ru and decreased Ta not having any TCP phases and the sample with Nb having them, the sample containing Nb still had a longer life at 1100°C and 137 MPa conditions. It was also seen that the two samples that did not have any TCP phases formed widely spaced γ-γ′ interfacial dislocation networks when compared to the sample containing Nb. This was seen to cause faster creep rates in the former and thus lead to a shorter creep life till rupture. On the other hand, the dislocation network in the sample containing Nb was much finer, and thus, it had a reduced creep rate and a longer creep life at very high temperatures. The changes in creep rates have been illustrated graphically in Figure 2.

The base alloy, which is TMS-173 without any changes in its alloying composition, had a much finer dislocation network compared to the samples with reduced Ta and increased Ru contents but had a very low creep life because of the relatively high amount of TCP phases formed. At low-temperature high-stress regimes, the amount of TCP phase...
formed was seen to have a great deal of influence in deciding creep life. But, when under low-stress and high-temperature conditions, compared to the existence of TCP phases, the fineness of the dislocation networks was seen to be the dominant factor in deciding creep life. The influence that high Mo and Ru contents can have in promoting the formation of finer and more regular dislocation networks with decreased dislocation network spacing was also supported by some other studies [8, 13, 23].

One study [13] also pointed out that the above factors combined with being able to include higher amounts of refractory elements to alloys due to the high Ru content and the microstructural stability that it provided were not only seen to greatly enhance creep properties but also seen to increase the workable temperature of 5th gen Ni-superalloys by at least 50°C in comparison to 4th gen superalloys. With each increasing generation of Ni superalloy, the element composition changes with a lot of refractory elements and rare earth elements being added into the mix. This is particularly spot-on in the case of 5th and 6th gen Ni-superalloys that have high Re contents and Ru contents. While these additions and changes to the alloying element composition enhance the microstructural stability, creep, fatigue, physical, and other properties, they can also make the alloy less thermally conductive. Fifth gen superalloys have only a little more than about 5% of the thermal conductivity of nickel. The study also showed that 5th gen alloys have a lower Cr content when compared to previous generation alloys, and this was seen to have a slightly negative impact on its oxidation resistance. This was especially seen in the case of 5th gen alloys such as TMS-173 and TMS-162. Fifth gen superalloy TMS-196 was developed particularly to tackle this issue. The role of Cr in oxidation resistance was also supported by another study [10]. This study showed that by increasing the Cr and content and reducing the Mo and W contents, we can retain the creep properties and at the same time improve oxidation resistance.

Another study [24] investigated the composition rules for Ni-superalloys and what their impact is on the alloys’ creep properties. In order to study the composition of the alloy, a uniform cluster formula for \([\text{Al-Ni}_{12}]\{\text{Al, Cr}\}_m\) was developed. The study focuses on SC Ni-superalloys from the 1st to 6th generations of the TMS family, for analyzing the alloy developments’ composition rules with the help of a cluster formula approach. Depending on this, how the lattice misfit present at the interface between the \(\gamma\) and \(\gamma'\) phases affects the lifetime of an SC superalloy component to rupture due to creep failure was established. Moreover, how the \(\gamma'\) precipitates are strengthened by these misfits between lattices was also investigated in this study. While studying the TMS family of Ni-superalloys that belonged to all six generations, the cluster formula was used to investigate the variation in \(Z\), which is the total atom number for a cluster formula unit. \(Z\) value was seen to decrease (approximately from \(Z\) value of 17 to 15.5) as the Ni-superalloys’ generation increased from 1st to 3rd and then increase (approximately to \(Z = 16\)) as we moved from the Ni-superalloys’ of 3rd to 6th generations. Two other families of SC Ni-superalloys that belonged to the PWA and CMSX series were also subjected.
to analysis using the cluster formula. The value of $Z$ was seen to follow the same trend in both PWA and CMSX families just like in the TMS family of SC Ni-superalloys. The composition of the elements belonging to the Al series was found to be a constant value in all superalloys that belonged to the TMS family, irrespective of their generation. The main job of the elements that belonged to the Al series was seen to be in forming the $\gamma'$ nano-precipitates and to maintain a large amount of volume fraction of the precipitated $\gamma'$ phase. Unlike the elements of the Al series, the composition of elements that belonged to the Cr series, denoted in the cluster formula by the atom number $G_{\text{Cr}}$, was observed to greatly vary from 1st to 6th generation alloys. The same tendency for variation was also seen to appear in “$n_{\text{s}}$,” the cluster formula unit's glue number. The fine-tuning of the composition of elements that belong to the Cr series was seen to mostly help in achieving a moderate amount of $\gamma'/\gamma$ lattice misfits in order to attain an optimal creep-resistant property. Also, the addition of Ru was seen to fix the instabilities caused in the microstructure by high Re composition that enhanced creep properties greatly. Thus, the addition of both Ru and Re elements in appropriate amounts was seen to be the case in late 4th–6th generation SC Ni-superalloys. Therefore, the composition of all the elements from the Al, Cr, and Ni series must be fine-tuned concurrently so that an equilibrium between the mechanical properties and corrosion or oxidation resistance is achieved. Based on interactions between dislocations and precipitates, the mechanism involved in the strengthening of the precipitates can be of two types, the particle shearing mechanism and the Orowan bowing mechanism. While examining the microstructure, it was seen that when the precipitates were very big in size and incoherent with the matrix, the strengthening was seen to have been achieved by using the Orowan mechanism. And the shearing mechanism was seen to cause precipitate strengthening when these precipitates were seen to be small in size and coherent in nature with the matrix. With the $\gamma'$ precipitates' size being big enough in the TMS series, it was observed that order strengthening ($\Delta \sigma_{\text{OS}}$) contributed to a greater deal of increase in strength in comparison to modulus mismatch and strengthening due to coherency ($\Delta \sigma_{\text{CS}}$ and $\Delta \sigma_{\text{MS}}$). Also, the increase in strength caused by the total increase in modulus mismatch and coherency strengthening in CMSX-4 was found to be significantly larger compared to the increase in strength due to order strengthening. It was also noted that the strengthening effect seen as a result of the $\Delta \sigma_{\text{Orowan}}$ has a close relationship with the particle size $r$, lattice misfit $\delta$, and the precipitates' volume fraction $f$. But $\delta$ was seen to be more influential than other factors. It was observed that when the $f$ value was kept constant, the biggest increase in yield strength will be attained when the condition ($\Delta \sigma_{\text{CS}} + \Delta \sigma_{\text{MS}}$) = $\Delta \sigma_{\text{Orowan}}$ was achieved and an optimized particle size of $r_0$ was present. Most often, it was seen that when the lattice misfit was comparatively bigger, higher strength of sample was recorded, in addition to a stronger $\gamma'/\gamma$ interface. These improvements were seen to help in preventing the precipitated $\gamma'$ phases from being cut by dislocations so that the rate of creep strain would be reduced and the lifetime to rupture improved. However, an exaggerated lattice misfit was seen to aid in accelerating the precipitated $\gamma'$ phases' coarsening and thus led to a decrease in the samples' lifetime to rupture. The study also highlighted that despite the smaller value of lattice misfit seen in the 6th generation SC Ni-superalloy TMS-238, it still possessed the highest value for lifetime till rupture among all the samples. Even when compared to the 4th generation TMS-138 and the 5th generation TMS-196 both of which had higher lattice misfits, it was still seen to exhibit a superior rupture life due to the comparatively larger volume fraction. This bigger volume fraction of TMS-238 alloy was seen to help attain a much larger strength increment with the help of the Orowan mechanism, which would result in making a big enough particle size that is calculated for optimality and is much larger than the value measured experimentally. The study pointed out that this reveals the strong influence that coherent strengthening has and how much enhanced it is as a result of particle coarsening, which greatly differs from the Orowan strengthening. Thus, increasing the precipitated $\gamma'$ phases' volume fraction was seen to be another way to improve the strength of the alloy. This observation was seen to occur because of the development of finer and narrower $\gamma$ channels that act as an obstacle in the movement of dislocations, as a result of the increased value of volume fraction. From the $z$ values in the cluster formula, although the $Z$ of TMS-196 is almost equal to that of TMS-238, the atom numbers of the Al series and Cr series of elements are different for TMS-196 and TMS-238, respectively. But the Ru and Re concentrations were observed to be maintained at a constant value in the Ni series. It is the fine-tuning of the composition of elements that belong to the Cr and Al series/family that induces a change in the $\gamma'/\gamma$ lattice misfit and thus in turn the size of precipitated particles and the max strength exhibited. Thus, it was seen to be very important to control the matching of alloying elements within the cluster formula unit frame so that a moderate $\gamma'/\gamma$ lattice misfit could be attained so as to optimize the mechanical properties of Ni-superalloys. Most often, for the sake of achieving $\gamma'$ nano-precipitates that have a cuboidal shape and an appropriate size, the lattice misfit was seen to be maintained within a specific range. It was also observed that the lifetime to creep rupture increased with an increase in the magnitude of a negative lattice misfit. And this result was seen because, when we have a greater negative lattice misfit, it could result in the development of a relatively very large amount of interface strength that can help in obstructing and hindering the movements of dislocations. In addition, suitable adjustments in the composition of SC Ni-superalloys were made for enhancing high-temperature mechanical properties and also the resistance to corrosion and oxidation. TMS-6, a 1st generation alloy, acts as a base alloy for TMS-277, TMS-285, TMS-286, and TMS-278. For the first 3 SC Ni-superalloys, in addition to element Re in TMS-6, a small amount of Nb was added as a substitute for Ta so that we can enhance the hot corrosion resistance and reduce the density of TMS-6 simultaneously. Moreover, the forming of Al2O3 scales was seen to be greatly promoted by the presence of Si, and thus, a small amount of Si was seen to be included in the
elemental composition of TMS-286, and the formation of these oxide scales was seen to improve the oxidation resistance. And, during the production of TMS-278, a minor amount of the element Mo was seen to be added into the elemental composition of TMS-6, which was considered as the base alloy for development. The Mo additions were seen to significantly improve the TMF lifetime of the alloy. The Si element was added into the TMS-138A to obtain the TMS-138A-Cr + Si and TMS-138A-Mo + Si SC alloys by reducing the amount of Cr and Mo. On the one hand, the oxidation resistances of TMS-138A-Cr + Si and TMS-138A-Mo + Si are significantly superior to that of their base alloy TMS-138A due to the addition of Si.

Similarly another paper [25] also talked about the influence or use of different alloying elements in Ni-superalloys. This study focused on presenting an extensive and elaborate review on how the alloying elements present in an SC Ni-superalloy used for making turbine blades used in very harsh environments with exposure to extreme stress, corrosion, and oxidation influence the properties and behaviour of the alloy. The study showed that with the development of new high-strength superalloys, the newer alloys developed were seen to have lower value of Cr elemental composition and increased value of Re elemental composition. This causes a reduction in the alloys’ environmental resistance, particularly oxidation resistance. The interactions taking place between the elements in Ni-superalloys that had more than 15 elements in their elemental makeup were seen to be very complex and not clearly understood. And it was also revealed in the study that most often in cases on newer Ni-superalloys, if the conditional requirements for alloying were not taken care of in detail, it leads to TCP phase formation that is very brittle in nature. And its formation was harmful to many physical and mechanical properties of the alloy. The making of new superalloys was seen to require achieving a good balance between strength and environmental resistance. And this was seen to be a big challenge. The study also showed that chromium, aluminium, and tantalum are important elements that help in improving the strength and resistance to very harsh environments. But it was also noticed that the presence or addition of Al above a certain limit/composition was seen to cause the formation of incipient melts at the time of heat treatment processes, done in order to achieve an optimum distribution and size of the \( \gamma' \) phase. The study also revealed that increasing amounts of Rh and Re in newly developed superalloys greatly increased the alloys’ strength and creep properties. It was also seen that very high concentrations of these elements severely reduce the environmental resistance. It was also revealed that Hf and Y seem to improve oxidative and corrosive resisting properties of the alloy. Another study [12] showed that Hf additions also improved ductility and reduced porosity.

Another study [26] discusses the distribution of the element Ru around Re, Mo, and W elements found in the \( \gamma \) matrix in 5th generation Ni-superalloys. In this paper, 3DAP microanalysis was used to study the elemental distribution of Ru in the disordered \( \gamma \) matrix of 5th gen SC Ni-superalloys. Bar-shaped samples of TMS-196 and TMS-173 were used for the study. The tests revealed that the \( \gamma' \) phase has more Al and Ta, whereas the \( \gamma \) phase has more Co, Cr, and Re. It was revealed in the study that layers of Al atoms found were parallel to Al atomic layers that are nearly parallel to the \( \gamma/\gamma' \) phase interface. The radius of a Ru atom compared to the radius of a Ni atom was seen to be much larger. This causes local strain fields to take place around the Ruthenium atom’s lattice point present in the \( \gamma \) phase. The same was also seen to be true for other elements such as Re, Mo, and W, which can be found in abundance in the TCP phases. Each atom of Re, Ru, W, and Mo moves towards one another in the \( \gamma \) phase for the sharing of strain fields. These phenomena were seen to aid in the reduction of \( \gamma/\gamma' \) phases’ free energy and significantly improve the solubility limit of rhenium, tungsten, and molybdenum in the \( \gamma \) phase. The study also supported the fact that the TCP phase precipitated is suppressed on adding ruthenium. If it is assumed that each ruthenium, molybdenum, tungsten, and rhenium moves towards each another, the experimental result seems to be higher than that of the binomial distribution. This showed that the present condition of block size being 100 atoms, no specific concentration deviation of Ru around Re, Mo, and W was observed.

5. Creep Properties of 5th and 6th Generation Ni-Superalloys

Creep properties are some of the most important mechanical aspects of 5th and 6th gen Ni-superalloys as they are mainly developed with enhanced creep in mind. With improvement in creep properties, the creep life, strength, temperature workability, and many other mechanical and performance factors will improve. Thus, creep properties and what influences them in depth in order to develop new and better alloys and how they figure out the most optimal application of the developed alloy must be studied. One of the most influential factors affecting creep is element composition and additions both in previous generation alloys [27, 28] and newer 5th and 6th gen Ni-superalloys. The main reason behind the greatly enhanced creep of 5th and 6th gen alloys seems to be the high concentration of refractory elements and high content of phase stabilizing Ru [2, 4, 10, 12, 13].

One study [24] examined in detail how the composition of certain alloying elements influences the creep properties of Ni-superalloys and establishes superiority in the case of 5th and 6th gen Ni-superalloys. In order to study the composition of the alloy, a uniform cluster formula for [Al-Ni12] (Al, Cr) m was developed. The study focuses on Ni-SC superalloys from the 1st to 6th generation of the TMS family, for analyzing the alloy developments’ composition rules with the help of a cluster formula approach. Depending on this, how the \( \gamma/\gamma' \) lattice misfit affects the lifetime of an SC superalloy component to rupture, due to creep failure was established. While studying the TMS family of Ni-superalloys that belonged to all six generations, the cluster formula was used to investigate the variation in Z, which is the total atom number for a cluster formula unit. Z value was seen to decrease (approximately from \( Z = 17 \) to \( Z = 15.5 \)) as the Ni-superalloys’ generation increased from the 1st to the
3rd and then increase (approximately towards \( Z = 16 \)) as we moved from the Ni-superalloys of 3rd to the 6th generations. The value of \( Z \) was seen to follow the same trend in both PWA and CMSX families just like in the TMS family of SC Ni-superalloys. The composition of the elements belonging to the Al series was found to be a constant value in all superalloys that belonged to the TMS family, irrespective of their generation. The main job of the elements that belonged to the Al series was seen to be forming the \( γ′ \) nano-precipitates and to maintain a large amount of volume fraction of the precipitated of the \( γ′ \) phase. The fine-tuning of the composition of elements that belong to the Cr series was seen to mostly help in achieving moderate amounts of \( γ/γ′ \) lattice misfits in order to attain optimal creep-resistant properties. Also, the addition of Ru was seen to fix the instabilities caused in the microstructure by high Re composition that enhanced creep properties greatly. Thus, the addition of both Ru and Re elements in appropriate amounts was seen to be the case in late 4th–6th generation SC Ni-superalloys. Therefore, the composition of all the elements from the Al, Cr, and Ni series' must be fine-tuned concurrently in order to achieve a balance between the mechanical properties. The study highlighted that despite the smaller value of lattice misfit seen in the 6th generation SC Ni-superalloy TMS-238, it still possessed the highest value for lifetime till rupture among all the samples. Even when compared to the 4th generation TMS-138 and the 5th generation TMS-196 both of which had higher lattice misfits, it was still seen to exhibit a superior rupture life due to the comparatively larger volume fraction. This bigger volume fraction of TMS-238 alloy was seen to help attain a much larger strength increment with the help of the Orowan mechanism, which leads to the production of a large calculated optimal particle size, much larger than the value measured experimentally. From the cluster formula, although the \( Z \) of TMS-196 is almost equal to that of TMS-238, the atomic number of the aluminium and chromium series are different for TMS-196 and TMS-238, whereas the Re and Ru content in the Ni series remains the same. It is the fine-tuning of the composition of elements that belong to the Al and Cr series/family that changes the \( γ/γ′ \) lattice misfit and thus in turn the maximum strength and its corresponding particle size. Thus, it was seen to be very important to control the matching of alloying elements within the cluster formula unit frame so that a moderate \( γ/γ′ \) lattice misfit could be attained so as to optimize the mechanical properties of Ni-superalloys. Most often, in order to achieve cuboidal \( γ′ \) nano-precipitates of an appropriate size, the lattice misfit was kept within a specific range. It was also observed that the lifetime to creep rupture increased with an increase in the magnitude of a negative lattice misfit. And this trend was exhibited by the alloy due to the greater negative lattice misfit aiding in the development of, a relatively very large amount of interface strength that can help in obstructing and hindering the movements of dislocations.

Another study [1] discussed the creep behaviour of a newly developed 5th gen Ni-superalloy TMS-196 and compared its performance to that of a few currently available commercial Ni-superalloys, namely, Rene-N5, CMSX-4, and CMSX-10. The parameters for creep testing were a temperature of 1,000°C and a stress of 245 MPa. TMS-196 was seen to exhibit maximum strength along with really good phase stability and resistance towards oxidation. It was also seen that the alloy had a very high lattice misfit at elevated temperatures. The misfit for the alloy was measured to be \(-0.39 \) at 1,100°C, and this misfit was seen to prompt the forming of \( γ/γ′ \) rafts in the microstructure during creep at high temperatures. Compared with other alloys studied, the misfit seems higher, and the network dislocations found were also seen to be numerous and much finer, thus improving the creep life. An impressive, 47°C improvement in creep temperature in comparison to CMSX-4 was observed in TMS-196. Another study [19] investigated the improved creep properties of the same TMS-196 superalloy in comparison to its predecessor and the alloy used as the base in developing it, TMS-173. The creep performance of TMS-196 was also compared with some widely used commercial Ni-superalloys such as TMS-75 and Rene-N5. TMS-196 was developed with TMS-173 as the base alloy, by manipulating its alloying element composition. The Re content was reduced and the Cr amount increased as Cr promoted oxide scale formation and increases oxidation resistance. And the compositions of Mo and W were adjusted to retain great negative lattice misfit in the \( γ-γ′ \) interface and maintain good creep properties, thus achieving a balance between creep and oxidation resistance. This allowed the newly developed TMS-196 to perform better than TMS-173 and other previous generation alloys. During creep testing (1,000°C, 245 MPa) of the new alloy along with TMS-173, it was seen that TMS-196 was seen to have a creep life of 850 h, which is approximately about 20.4% more than that of TMS-173. When the newly developed TMS-196 was subjected to another creep test with a high-stress regime and a lowered temperature condition (800°C, 745 MPa) when compared to the first creep test the alloy was seen to exhibit a creep life of more than 1,450 h that was significantly higher compared to the creep life exhibited by TMS-173 and its predecessor. But, under high-temperature low-stress conditions (1,100°C 137 MPa), the alloy was seen to not perform as good as TMS-173 but was still seen to produce results comparable to that of 3rd gen superalloy TMS-75. Data regarding the oxidation behaviour in terms of mass change on cyclic oxidation and creep properties have been graphically represented in Figure 3. Figure 3(a) shows oxidation behaviour, and Figures 3(b) and 3(c) represents creep behaviour that takes place while testing under the conditions of 1,000°C/245 MPa and 800°C/735 MPa, respectively.

Another study [29] investigated the advantages in adding of Ir to SC Ni-superalloys and various possibilities of developing new Ni-superalloys that also have Ir in their elemental makeup. An alloy design program (ADP) was used to study the newly designed alloy. And the alloy chosen is called TMS-238, which acts as a base. A newly developed alloy design program was used for an alloy having Ir. The ADP was seen to be made of two different subprograms, namely, the search and analysis programs. The job of the analysis program was seen to be collecting data regarding structural and mechanical properties from the composition of the
alloying elements. And the search program’s job was seen to be finding a desirable combination of alloying element composition that can give us the desired result. It was seen that on giving the alloying element composition, temperature conditions, and applied stresses as inputs to the program, different properties of the alloy were seen to be provided. Characteristics such as chemical compositions of both \( \gamma \) and \( \gamma' \) phases, structural properties, \( \gamma' \) phases’ volume fraction, and \( \gamma / \gamma' \) lattice misfit are found using test temperature and composition of the alloy. Then, the mechanical properties, such as lifetime to creep rupture, are predicted by regression equations. ADP was also seen to be able to make use of the equations used in predicting TMF (thermomechanical fatigue) in order to predict fatigue and oxidation resistance properties. Observations from the study showed that adding small quantities of Ir was a successful tactic to improve the creep rupture capabilities of 6th gen SC Ni-superalloy, TMS-238, by 20°C from 1,117°C. The study showed that using ADP can make it possible for developing a new generation SC Ni-superalloy with excellent creep properties, with small quantities of Ir present in the elemental makeup. Creep strengthening factors in high temperatures and lower stress are studied by prediction equations. In this regard, regression coefficients of those formulas are of high use. By adding Ir, the alloys’ creep strength was not seen to significantly be affected or improve. But the forming of TCP phases was seen to be greatly suppressed, thus allowing a lot better creep rupture capability.

Another study [3] examined in depth an advanced alloy design program (AADP) and its use in improving TMS-238 alloy. The coefficient of regression for the element Ru was seen to be very small under every creep condition that was used in this study. This suggested that Ru additions to Ni-superalloys are highly efficient in the suppression of the formation of TCP phases by expanding the solubility limit. However, Ru additions were not seen to enhance creep strength under all the testing conditions. For an alloy sample experiencing high-stress and low-temperature environment, Re additions were seen to play the most important role in enhancing the creep strength. It was also noted in the study
that it was not possible to successfully find out the effect that every alloying element can have on the alloy's oxidation resistance properties because of the high standard deviation errors of the regression coefficients. But the effect a few elements have was successfully interpreted. Al additions were seen to help in minimizing the weight gained because of the formation of oxides, and $b_{ij}$ was seen to show a negative value of the regression coefficient, which can be usually observed in correspondence to the oxidation behaviour of other Ni-superalloys. The opposite was seen for Mo that showed a huge positive value that can suggest that Mo has a tendency to reduce the resistance to oxidation of Ni-superalloys. Re also was seen to have a negative coefficient. Three new alloys were designed with the goal of enhancing the creep strength without compromising the resistance to oxidation of the alloy, TMS-238. TMS-238mod-A is an alloy that has a bigger value of γ′ volume fraction and a slightly more negative lattice misfit present at the interface of the γ matrix and γ′ precipitates. This was seen to have been achieved by decreasing the composition of Co. TMS-238mod-B was seen to be an alloy that has a higher Ta composition that aided in the strengthening of the γ′ phase. TMS-238mod-C was seen to be an alloy that had better 2-phase stability and a larger negative lattice misfit present at the interface of the γ matrix and γ′ precipitates. This was seen to be caused by the increased Ru content. Enhancements observed in the creep strength were justified with the help of AADP calculations. In the equation used for predicting the lifetime to creep rupture, the Co element's coefficient was seen to be slightly negative. This indicates that TMS-238 mod-A, which had decreased Co content, had a more prolonged lifetime to creep rupture when compared to TMS-238. This was experimentally validated. But the mechanism that Co follows to have this kind of influence is still unknown and requires more extensive studying to find out. While studying TMS-238mod-B, the enhancement in a lifetime to creep rupture was seen to be caused by the increased Ta content that aided in improving solution strengthening of γ′ phase and also the rafting that takes place as a result of bigger negative lattice misfit present at the interface of the γ matrix and γ′ precipitates. The enhanced lifetime until creep rupture that was exhibited by TMS-238mod-C was seen to be caused due to the rafted structures forming as a result of the very high negative value of γ/γ′ lattice misfit induced by the increase in the Ru composition.

Another study [23] discusses how the strengthening provided by γ/γ′ interfacial dislocations can influence creep. TMS-162, a 5th generation Ni-superalloy, was used for this study. Lattice misfit is an aspect of Ni-superalloys that plays a vital role by influencing their performance. A vital linear relationship between alloy strength and lattice misfit can be observed in Ni-superalloy between temperatures of 25 and 800°C. Developing alloys having γ/γ′ structure and high negative lattice misfit increases the temperature capability because γ/γ′ alloys have high creep resistance than the creep resistance of the bulk form of either γ or γ′. At elevated temperatures, γ′ phase precipitates having cuboidal shape were seen to transform into the plate-like linked structures indicating rafting taking place. The direction of orientation of these plate-like precipitates was seen to be perpendicular to the direction in which the stress is applied. Thus, the inhibition of dislocation climbs aided by the presence of the rafted structure was seen to be the creep mechanism exhibited by the alloy at elevated temperatures. The network of interfacial dislocations present in the alloy was also seen to suppress the γ′ phase precipitates from getting sheared. The interfacial misfit between the γ′ and γ-phases helping in the strengthening of a superalloy is an important concept to be considered while deciding on alloy design. High-temperature creep strength and creep deformation under low-stress conditions were seen to be highly influenced by the lattice misfit present at the interface of the γ and γ′ phases. This study studied the creep behaviour of TMS-75, TMS-138, and TMS 162 and also examined how it was affected by the lattice misfit and the interfacial dislocation networks. The creep life was seen to be the longest for TMS-162 followed by TMS-138 and finally TMS-75. This was seen to be caused by the very fine dislocation network found in TMS-162 that was produced as a result of the TMS-162 having the highest content of Mo and Ru. This was seen to lower the creep rates and extend the creep life in TMS-162. In all these alloys, the minimum creep rate was seen to have an almost linear relationship with the lattice dislocation network spacing, thus indicating that high-temperature creep is highly dependent on dislocation networks. The dislocation networks being widely spaced was seen to allow easy moving and slipping of the lattice planes and thus lead to creep rupture faster. The fineness of these networks in TMS-162 was seen to help resolve this issue and extend creep life and also increase temperature capabilities.

In another study [7], the mechanism for creep deformation in SC Ni-superalloys containing Ru, which takes place under high-temperature low-stress (1,100°C and 137 MPa) and low-temperature high-stress (800°C, 735 MPa, and 607 MPa) conditions, were examined. TMS-75, TMS-75 + Mo, TMS-75 + Ru, TMS-138, and TMS-162 were the alloys used for the study. TMS-162 was seen to have been examined under moderate temperature and stress conditions during creep testing (1,000°C, 245 MPa). Among all the five alloys, while undergoing high-temperature and low-stress conditions for creep testing, the newly developed Ni-superalloy TMS-162 has the smallest minimum creep rate and a longest lifetime to creep rupture. On the other hand, the alloy TMS-75 + Ru was seen to display the biggest minimum creep rate and shortest lifetime to creep rupture. TMS-162 was observed to have the smallest amount of spacing between interfacial dislocations. These dense interfacial dislocations can prevent glide dislocations by cutting the rafted γ/γ′ structure. Interfacial dislocation networks in TMS-75 + Ru and TMS-75 are irregular. In TMS-75, TMS-75 + Ru, and TMS-75 + Mo, the interfacial dislocation spacing is distributed in a wide range, whereas in TMS-138 and TMS-162, the dislocation spacing has a narrow distribution range. With the increase in the negative lattice misfit, the interfacial dislocations tend to become homogeneously arranged, due to the stronger elastic interaction between the dislocations closer to each other. And the interfacial dislocations being distributed in a
Superalloys have superior properties that promote the generation of TCP phases that can be detrimental to the superalloys. At the time of the primary creep stage, the formation of rafted structures in the alloy was observed at 1,100°C and 137 MPa. Meanwhile, rafting was seen to occur much slowly in 1,000°C and 245 MPa testing conditions. The cause for this disparity was seen to be the influence temperature has on the alloys’ diffusion rates. During the steady creep stage, the alloy when tested under moderate temperature and stress conditions was seen to exhibit a very large minimum creep rate value in comparison to testing the alloy under high-temperature low-stress conditions. Measurements that were obtained via TEM showed that the γ'/γ' interfacial dislocation spacing observed in alloys tested under moderate temperature and stress conditions is lesser in comparison to the values obtained from studying alloys tested under high-temperature low-stress conditions. This result was seen to occur because of the larger amount of stress that was applied to the tensile sample in the former case in comparison to the latter. At low-temperature and high-stress creep testing conditions, the Mo additions to the alloy were seen to help in reducing the SF energy. Meanwhile, Ru additions were seen to have no significant influence on the SF energy. But, due to Ru having an hcp structure, adding it to the elemental makeup of Ni-superalloys may help in reducing SF energy even if by a very tiny amount. To sum it up, Ru and Mo additions to Ni-superalloys were seen to aid in reducing the SF energy. But adding the element Ru was observed to be the most important factor when it comes to strengthening of a superalloy when it comes to testing done at high-stress low-temperature environments.

Another study [20] investigated the importance of Re in creep enhancement in the case of newly developed 5th and 6th generation Ni-superalloys. The most important effect of Re was seen to be enhancing the creep properties of Ni-superalloys. With an increase in Re content with each new generation, significant improvement in the creep properties and workable temperature of alloys were noted. A good example of this is the increase in creep strength, life, and workable temperature in the alloys, 2nd gen CMSX-4, 3rd gen CMSX-10, and 5th gen TMS-169, with said properties improving with each passing generation. Re was also seen to help in slowing down the coarsening of the strengthening precipitates. The creep properties of an alloy can be highly dependent on the rate of diffusion of the alloying elements at high temperatures. This is why the slow diffusion rate of Re at elevated temperatures combined with the finer precipitates formed was seen to enhance the creep properties in high Re containing 5th and 6th gen Ni-superalloys. But the addition of Re was seen to promote the generation of TCP phases that can be detrimental to the superior properties that the superalloys are sought after. But 4th and 5th gen Ni-superalloys solved this problem by including moderate to high levels of Ru additions. Ru was seen to stabilize the microstructure and inhibit the TCP phase formation, thus improving creep. And, apart from suppressing TCP phase formation, the very high Ru content in 5th and 6th gen superalloys and the microstructural stability it gave these alloys was seen to enable further addition to the composition of Re and some other refractor elements, thus improving creep properties vastly. High Re content was also seen to increase the negative lattice misfit in the γ- γ' interface; this was seen to increase the creep strength and life of these Ni-superalloys greatly.

Another study [21] investigated the superiority of creep properties of a 5th gen Ni-superalloy called TMS-162 that was developed with the 4th gen alloy TMS-138 as a base. The 5th gen Ni-superalloy TMS-162 was developed to have superior characteristics to that of TMS-138. Mo and Ru saw an increase by 1 and 4 wt%, respectively, in the newly developed TMS-162. Creep testing at a high-temperature low-stress regime (1,100°C, 137 MPa) showed that TMS-162 has vastly superior creep life compared to TMS-138 and another 3rd gen superalloy, CMSX-10. Compared to TMS-138 and CMSX-10, the creep speed of TMS-162 was seen to be very slow. TMS-162 was seen to have a workable temperature of 1,100°C and a greatly superior creep life at 1,000 h, with the time taken to reach 1% creep strain by TMS-162 being 2.5 and 5 times that of the time taken by CMSX-10 and TMS-138, respectively. Shorter creep speeds and longer creep lives were also observed for TMS-162 under low-temperature high-stress regime (800°C, 735 MPa). The creep speed/creep rates in TMS-162 were seen to be comparatively significantly lower along with the longest time to rupture because of the finer and smaller network dislocations in the γ- γ' interface and the high negative lattice misfit, both of which are a result of the increase in the Mo content. The creep properties of changing the composition of elements Ta, Ru, and Nb on TMS – 173 are discussed in another paper [22]. For this purpose, various variations of the alloy TMS-173 were made by manipulating the composition. The elemental composition of the variations and the original base alloy TMS-173 are shown in Table 3. TMS-173 has significantly high-strength and relatively superior creep life.

But, after creep testing for a very long time at elevated temperature, TCP phase formation was observed in the alloy’s tissue. TCP phases are harmful to high-temperature properties, especially creep properties. Thus, one variation has its Ru content increased from 5 to 6 wt% to see how the TCP phase suppressing and microstructure stabilizing Ru can affect the creep properties of the alloy. In another variation, it was seen if reducing the Ta content could give the similar result and affect creep. Ta was also seen to be present in the TCP phases. And, finally, how compensating for the decrease in Ta by introducing Nb would affect the creep properties was also studied by using a variant having slightly decreased Ta content with Nb addition. All samples after heat treatment showed similar precipitation structure, and the γ' grain sizes were found to be almost the same, with large eutectic regions that were about 0.3 mm in size being observed. At 900°C temperature and 392 MPa stress, Figure 4 shows the variation in creep life.

Substituting Ta with Nb, increasing Ru content and decreasing the Ta content was all seen to significantly extend the time to creep rupture, with the TMS-173 sample with
<table>
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<th>Table 3: Elemental compositions of the various alloy mixtures used [22].</th>
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<td>Cobalt (%)</td>
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<td>TMS-173</td>
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<td>TMS-173 + Ru</td>
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<td>TMS-173-Ta</td>
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<td>TMS-173-Ta + Nb</td>
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decreased Ta content showing the highest time to rupture (almost 30% increase). The increases in time to rupture were seen because all the changes succeeded in reducing the TCP phase formation with a reduction in Ta suppressing the TCP phase forma-
tion the highest. And, as a result, no TCP phases were formed in this sample. For 1,100°C and 137 MPa con-
ditions, the sample where Ta content was reduced and substi-
tuted with Nb was seen to exhibit the longest time to 
creep rupture (about a 50% increase compared to the base 
 alloy). In other samples, the coarsening of the γ′ precipitate 
was seen to be higher than in the sample containing Nb, thus 
breaking after forming a raft structure. That is why despite 
the samples with increased Ru and decreased Ta not having 
any TCP phases and the sample with Nb having them, the sample 
containing Nb still had a longer life at 1,100°C and 137 MPa 
conditions. It was also seen that the two samples that did not 
have a TCP phase formed widely spaced γ-γ′ interfacial 
dislocation networks when compared to the sample contain-
ing Nb. This was seen to cause faster creep rates in the 
former and thus lead to shorter creep life till rupture. On 
the other hand, the dislocation network in the sample contain-
ing Nb was much finer, and thus, it had a reduced creep rate and a 
longer creep life at very high temperatures. The base alloy, 
which is TMS-173 without any changes in its alloying 
composition had a much finer dislocation network compared to 
the samples with reduced Ta and increased Ru contents but 
had very low creep life because of the relatively high amount 
of TCP phases formed. At low-temperature high-stress re-
gime, the amount of TCP phase formed plays an important 
role in determining the creep life. But the fineness of dislo-
cation networks plays a huge role when the temperature is 
high and the stress regime is low.

The influence of Ru was elaborated by another study 
[12]. The same study also did a comparison of creep 
temperature capability between various Ni-superalloys of 
different generations. This study showed clearly just how much 
the working temperature has increased for present or latest 
Ni-superalloys in comparison to the first developed alloys. 
The data regarding this are presented in Figure 5. Figure 6 
portrays data collected from other studies [9, 30–32] that 
shows the creep life of superalloys from various generations.

Another study [6] used the newly developed 6th gener-
ation superalloy (TMs-238) to investigate the deformation 
of creep along with MX-4 alloy for comparison. Further-
more, its relation in enhancing creep strength under creep 
conditions of 735 MPa applied stress and 800°C temperature 
condition was carried out. Creep curves obtained in the 
study showed that the alloys took 2.9 and 195 h to attain 0.1% 
creep strain. Through creep rupture tests performed, it was 
found that the creep strength exhibited by TMS-238 was 
much larger compared to that of MX-4. After examining the 
microstructures of the two SC Ni-superalloys, MX-4 was 
seen to have slightly bigger sized γ′ precipitates, and also, the 
y channel width was small as compared with TMS-238. 
Meanwhile, the alloy was observed to have a regular shaped 
γ′ phase’s precipitate more uniformly distributed in the γ 
matrix. The mechanism under which creep happened varied 
with each alloy. The creep mechanism in MX-4 was 
explained by the γ′ phase’s precipitate undergoing shearing 
due to the higher creep rate exhibited in comparison to 
TMS-238, while the creep mechanism in TMS-238 was seen 
to be explained in terms of SFE. Under high-stress low-
temperature conditions, it was common to see the activation 
of a ⟨112⟩ {111} slip at the time of primary creep in SC Ni-
superalloys. The study also showed that the dissociation of 
dislocations within the γ matrix was influenced by the 
microstructure formed between γ and γ′ phases, stresses 
applied, SFE in the γ matrix, and the stress due to lattice 
misfit. Since both alloys were seen to have almost similar 
microstructural properties, the SFE of TMS-238 became 
the distinguishing factor that influenced the creep mechanism 
observed in TMS-238 SC Ni-superalloy. TMS-238 was seen 
to have significantly lower SFE compared to MX-4. The 
study also revealed that the alloy’s SFE was influenced by 
alloying elements and their compositions. The main com-
ponent aluminium’s γ′ phase in the Al content was seen to 
be the same for both alloys studied and thus was deemed to 
not be the main reason for the lowering of SFE seen in TMS-
238. Investigations also revealed that a reduction in the 
energy barrier was caused by the presence of Mo, Re, Cr, and 
Ru additions, while a slight increase in the energy barrier was 
seen to be cased Co. This helped in concluding that Re and 
Ru are more influential compared to Mo, Co, and Cr when it 
comes to reducing the γ matrix’s SFE per unit content. Cr 
and Mo were seen to have a stable bcc structure, while Co 
was seen to possess a stable fcc structure above approxi-
ately 4,501°C. Meanwhile, a stable hcp structure was seen 
to be exhibited by the elements Re and Ru. From fcc to hcp, 
the phase transformation and crystal structure are closely 
connected to each other. The sludge factor formation is 
favoured by the stable hcp lattice. This is why even though 
the content of Co and Cr is small, Re and Ru play a vital role 
in lower SFE in TMS-238.

6. Oxidation Resistance of Later 
Generation Superalloys

A lot of studies have revealed that there is a decrease in 
oxidation resistance with each passing generation. And this 
is seen to be caused by the reduction in Cr content in new
generation Ni-superalloys. Cr forms oxides and also promotes the formation of protective Al₂O₃ oxide scales that forms a layer over the base alloy and prevents it from further oxidation. Second generation Ni-superalloys can be seen to have better oxidation resistance than new 5th and 6th gen alloys. This was confirmed by one study [1] that compared TMS-196 and TMS-173, two of the best 5th gen Ni-superalloys with some alloys from the previous generations such as 2nd gen Rene’N5 and CMSX-4 and 3rd gen CMSX-10. This study also highlighted the TMS-196 alloy’s good oxidation behaviour that is comparable to 2nd generation Ni-superalloy Rene’N5, in terms of mass change after cyclic oxidation. After 1 h oxidation of TMS-173, TMS-196, and Rene’N5, the average thickness of the oxide film after the test was 18, 15, 7, and 5 mm, respectively. After five 1 h oxidation cycles, TMS-173 showed a drastic mass increase, but after that, a rapid decrease in mass was observed. No drastic mass increase or rapid mass decrease was shown by TMS-196, and the mass change of the sample tested was seen to be vastly higher in the case of TMS-173 when compared to TMS-196 at the end of testing (after 50 cycles). In another study [10], the comparison is made between the oxidation behaviour of TMS-196 to that of TMS-173. This study also confirmed the fact that the increased Cr content played a major role in improving the oxidation resistance of TMS-196. The study of 1 h isothermal oxidation at 1,100°C shows that the thickness of the Nio layer of TMS-173 and TMS-196 is thrice that of TMS-196. At the same time, TMS-196 has a thin Al₂O₃ at the substrate’s interface, whereas TMS-173 has internal columnar Al₂O₃ particles. Compared to the composition of TMS-173, the composition of TMS-196 saw a slight decrease in the Mo, W, and Re contents. This was also seen to help improve oxidation resistance. This was because having a high content of resistance was comparable to that of Rene’N5. The ability for oxidation resistance was measured by comparing the mass change that the alloy samples underwent during cyclic oxidation testing. And the mass loss was seen to be the highest for TMS-173. Another similar study [19] also investigated in detail the oxidation resistance properties of a TMS-196 Ni-superalloy. TMS-196 was developed with TMS-173 as the base alloy, by manipulating its alloying element composition. The Re content was reduced, and the Cr amount was increased as Cr promoted oxide scale formation and increased oxidation resistance. The compositions of Mo and W were adjusted to retain great negative lattice misfit at the γ- γ′ interface that helps maintain good creep resistance, thus achieving a balance between creep and oxidation resistance. This study also highlighted the TMS-196 alloy’s good oxidation behaviour that is comparable to 2nd generation Ni-superalloy Rene’N5, in terms of mass change after cyclic oxidation. After 1 h oxidation of TMS-173, TMS-75, TMS-196, and Rene’N5, the average thickness of the oxide film after the test was 18, 15, 7, and 5 mm, respectively. After five 1 h oxidation cycles, TMS-173 showed a drastic mass increase, but after that, a rapid decrease in mass was observed. No drastic mass increase or rapid mass decrease was shown by TMS-196, and the mass change of the sample tested was seen to be vastly higher in the case of TMS-173 when compared to TMS-196 at the end of testing (after 50 cycles). In another study [10], the comparison is made between the oxidation behaviour of TMS-196 to that of TMS-173. This study also confirmed the fact that the increased Cr content played a major role in improving the oxidation resistance of TMS-196. The study of 1 h isothermal oxidation at 1,100°C shows that the thickness of the Nio layer of TMS-173 and TMS-196 is thrice that of TMS-196. At the same time, TMS-196 has a thin Al₂O₃ at the substrate’s interface, whereas TMS-173 has internal columnar Al₂O₃ particles. Compared to the composition of TMS-173, the composition of TMS-196 saw a slight decrease in the Mo, W, and Re contents. This was also seen to help improve oxidation resistance. This was because having a high content of

Figure 5: Improvement in temperature workability exhibited by development of newer generation superalloys [12].

Figure 6: Advancement in creep life with the development of newer generation Ni-superalloys. TMS-196, a 5th generation Ni-superalloy with the highest creep life, is the most recently developed Ni-superalloy [9, 30–32].
these elements will lead to the formation of volatile oxides formed by these elements. The oxidation resistance of alloy can be highly harmed because of these oxides. Thus, a decrease in the composition of these elements reduced the formation of such oxides and thus improved the oxidation resistance. The results regarding the influence of Cr and the decrease in Mo, W, and Re contents were reconfirmed by yet another study [25] that deeply investigated the influence that the different alloying elements have on the alloy properties.

In another study [33], the oxidation behaviour of Ni-based superalloys having a high content of Re and Ru were investigated. The morphology of oxides and the effects of alloy elements, that is, Cr, Mo, and Ru, on the oxidation resistance of sample surface in those alloys were studied. The alloys contain more Ru and Re than 5th generation alloys, and the amount of Co, W, Al, Ta, Hf, and Ni are constant. Scanning electron microscopy (SEM) is used to observe the scales, as well as the cross-sectional microstructures, and electron probe micro-analyzer (EPMA) was used to analyze phase composition. ThermoCalc™ and Thermotech database, Ni-DATA7, helps for the prediction of thermodynamic properties. There were a total of five alloy variants used in this study. The first one Alloy A was the base alloy that was a high Ru and Re containing 5th gen Ni-superalloy, and the other four alloys’ Alloy B–E were variations of the base alloy. The elemental variations of these alloys are as follows:

(i) Alloy A: Base alloy
(ii) Alloy B: Alloy A + Mo additions
(iii) Alloy C: Alloy A + Cr additions—decrease in Mo composition
(iv) Alloy D: Alloy A + Ru additions
(v) Alloy E: Alloy A—decrease in Cr composition

In the first 30 cycles, all alloys except for Alloy E showed similar weight change behaviour: The alloys showed parabolic oxidation behaviour and rapid increase of the weight change in the first few cycles and then changed to slight increases of the weight change after 5 cycles. On the other hand, Alloy E showed a large mass gain after 1 cycle and started to show continuous weight loss after 3. This consecutively lasted till the end of the cyclic oxidation test, which indicates that Alloy E showed the poorest oxidation resistance among the all tested alloys. After 200 cycles, the change in weight of Alloy C is the least of all, whereas it is large in Alloy E, while other alloys (Alloy A, B, and D) showed moderate change. The main difference between Alloys A and E is their Cr content, meaning that Cr reduction in high Re- and Ru-containing alloys significantly degrades the oxidation resistance. Cr reduction significantly decreases Al activity. This corresponds with the differences in weight change between Alloys A and E. Since the Al content is constant in this study, Al activity has been varied depending on the amount of other elements. Cr is very effective to improve oxidation resistance and promote more Al2O3 formation on the specimen surface. Alloy C contains the highest amount of Cr among the tested alloys and showed the best oxidation resistance in this study. It can therefore be concluded that Cr addition is effective to improve the oxidation resistance of alloys containing a high amount of Re and Ru. Alloys A, B, and D showed moderate weight change during cyclic oxidation. All the alloys showed a similar weight change until 50 cycles and then started to show different behaviour. Within the three alloys, alloys B and D showed better oxidation resistance than Alloy A, the base alloy in this study. Alloy B, Mo added alloy into Alloy A, showed smaller weight change within the three alloys after 200 cycles. Also, a comparison of Al activity and weight change indicated that Al activity increased with Mo addition. The addition of Ru resulted in an increase in Al activity, and Alloy D showed better oxidation resistance than Alloy A. Change in Al activity with Ru addition is larger than with Mo addition, Alloy B, and the weight change during the first 30 cycles in Alloy D is smaller. Comparing the change in Al activity between elements, the increase of Al activity by Ru addition is 6.2% in Alloy D, whereas Mo increased the Al activity in Alloy B by 2.7%. This indicates that the oxide formed on Alloy D has better quality than that on Alloy B, suggesting better adhesion between substrate and oxide, and resulted in less spallation of oxides. Consequently, Ru addition might be more effective to suppress degradation of oxidation resistance than Mo in high Re- and Ru-containing alloys. While investigating samples after putting them through a 200-cycle cyclic oxidation test, the type of oxides formed on the surface of each alloy was seen to vary from sample to sample. Some samples were seen to only one layer of oxides, and some were seen to form two layers of different oxides. Alloys A, B, and D were seen to form two layers of oxides with the 1st layer being a complex oxide formed by both NiO and Al2O3 and the 2nd layer being an oxide layer made of only Al2O3. Alloy C was seen to have only one layer of Al2O3 oxides formed on its surface, and Alloy E was seen to have formed only one layer of complex oxide made of both NiO and Al2O3. Another study [34] discussed the type of oxide layers formed and how each can have an influence over the oxidation behaviour of Ni-based superalloys. Only a small initial change of weight is seen on alloys that form Al2O3 oxide, while a huge amount of gain in mass was seen to be exhibited by Ni-superalloys that formed thick NiO oxides. NiO oxide is non-protective and porous in nature. Thus, it was seen that NiO oxides provided easy access to oxygen to the metal lying beneath it, and this was seen to help in continuing the oxidation of the alloy. The formation of NiO oxide causes a violent reaction for the oxide formation, which can lead to an unceasing loss in mass and thus cause very low resistance to oxidation. On the contrary, these alloys show a less violent reaction than the alloys forming a thick NiO oxide. This is because the adherence of Al2O3 is better than that of NiO, which acts as a protective layer. This was seen to have a highly significant impact when it came to the oxidation resistance of newly developed 5th and 6th generation Ni-superalloys.

Another study [35] examined how the 6th generation Ni-superalloy TMS-238 that was developed with a 5th gen alloy as the base by concentrating on both creep and oxidation improvement was improved further to significantly further enhance the alloy’s oxidation behaviour. This study aims to enhance the oxidation resistance of the SC Ni-superalloy
TMS-238 while retaining the creep properties, with the help of a CaO crucible for melting. Cyclic oxidation tests and creep tests have made it possible to understand the influence that melting original alloy material in a CaO crucible can have on its high-temperature properties. Results that were obtained from the cyclic oxidation tests showed that melting alloy in a CaO crucible aided in an adhesive oxide scale forming on the sample during oxidation tests. This scale formation was seen to enhance the TMS-238 alloy’s resistance to oxidation. After completion of cyclic oxidation tests investigation revealed the presence of few voids beneath the oxide scales in both TMS-238 and TMS-238-CaO. Voids seen in TMS-238-CaO showed that the Al₂O₃ layer prevents oxide scales in both TMS-238 and TMS-238-CaO. Voids seen in TMS-238-CaO showed that the Al₂O₃ layer prevents the transport of metallic elements from the substrate to surface through oxide layers. Due to this, the resistance of TMS-238-CaO towards oxidation was seen to have been significantly enhanced. From the Ellingham graph, the free energy CaS formation is less than that of other metallic sulphides. Therefore, the dissolved Ca present in the molten alloy was seen to combine S present to form CaS. This was seen to help in preventing S from getting segregated onto the interface between the metal and the oxide scales. This was seen to help improve the oxide layers’ adhesive nature and thus enhance oxidation resistance. Similar results were obtained while melting other SC Ni-superalloys such as CMSX-4 too. Thus, it was concluded using a CaO crucible for melting of alloy can enhance the resistance of the Ni-superalloy towards oxidation without compromising on their superior creep properties. A similar study [11] examined in depth the cause for the enhancement in the oxidation resistance that was exhibited by TMS-238, melted in a CaO crucible. Sulphur undergoes elemental segregation at the junction between the oxide scale and substrate. This segregation was seen to be more prominent in an ordinary TMS-238 sample than in a TMS-238-CaO sample. Segregation of elemental sulphur was observed in both types of samples, but the increase in sulphur content in the TMS-238/Al2O3 interface was seen to be relatively much higher in comparison to the other sample. This revealed the fact that the segregation of sulphur in an ordinary TMS-238 sample is stronger when compared to one prepared by melting in a CaO furnace. The 3DAP results showed a considerable amount of difference in the peak concentration of sulphur at the junction, and no Ca segregation was observed. A very clear disparity in oxides’ fragmentation and oxidation resistance was seen in the tests performed in the study. The amount of sulphur segregation seen in the sample was seen by melting of alloy in a CaO crucible was seen to be comparatively much less. Thus, proving that, the reason for the improvement in the resistance towards oxidation exhibited by TMS-238-CaO is the segregation of elemental sulphur being suppressed. Subgrain boundaries of TMS-238-CaO were examined using BSE images. Investigating the images and the results obtained from the elemental maps plotted the presence of inclusion of CaS was confirmed. The CaS was seen to have been formed as a resulting reaction between S and the Ca dissolved in the alloy during its melting in the CaO crucible. This was seen to decrease the amount of sulphur present at the interface and thus reduce the segregation of sulphur. This reduction was seen to improve the adhesion of the oxide scales onto the substrate interface and thus greatly enhance the alloy’s resistance to oxidation.

7. Physical and Mechanical Characteristics of 5th and 6th Generation Nickel-Based Superalloys

The advantage of using Ni-superalloys is their physical and mechanical properties, which are very high. These include a variety of properties such as hot corrosion behaviour, thermomechanical fatigue, tensile properties, elastoplastic characteristics, and fatigue properties. Studies in this field are very important as they can help us determine the strengths of newly developed Ni-superalloys belonging to the newer generations, their precise applications, uses, and further improvement and development of existing or new alloys. A few papers that focus on such mechanical and physical properties of 5th and 6th generation Ni-superalloys in comparison to that of previous generation alloys have been reviewed in this paper.

In one such study [9], at 700 and 900°C, creep property and hot corrosion were studied from 1st to 6th generation alloys. First generation single crystal alloys (René N4, PWA 1480, TMS-1700), 2nd generation alloy (René N5), and 3rd generation alloy (CMSX-10 N) are highly corrosive, whereas 2nd generation alloy (CMSX-4, TMS-244), 3rd generation alloy (CMSX-4 plus), and 6th generation alloy (TMS-238) showed good corrosive resistance. Even though the superalloys having sufficient content of Cr exhibited good corrosive resistance, the increased content of Mo and W prevented the chromium oxide formation, which acts as a protective layer. The Cr, Mo, and W content in CMSX-4, TMS-244, CMSX-4 plus, and TMS-238 is relatively low, but they have Re. These results showed that increasing the Re content is more effective than increasing the Cr content to ease the effect of Mo and W leading to corrosion of the alloy. Among all the Ni-superalloys used in this study, TMS-196 and TMS-238 showed superior creep hot corrosive resistance properties. Creep strength and corrosive resistance are poor in 1st generation alloy. After 2nd generation, corrosive resistance of the materials improves abruptly. Between the alloys CMSX-10 N and CMSX-4 plus, corrosive resistance differs greatly. After it in 4th generation alloys, the creep strength too gets increased, while the corrosive resistance remains the same. TMS-238 has Cr₂O₃ and Al₂O₃ at the surface. The study also revealed that CMSX-10 N has poor hot corrosive resistance as nickel oxide containing sulphide was formed sample’s surface, while TMS-238 does not get affected much. Regression analysis done on type II alloys showed that cobalt, chromium, niobium, and rhenium prove effective in the corrosive resistance of type-II corrosion, whereas molybdenum, tungsten, and titanium reduce corrosive resistance. In this, the material’s dependence on Nb is less. In type-I corrosion, a protective Cr₂O₃ layer is formed, thus preventing corrosion that was excluded from the analysis.

Another aspect of Ni-superalloys is the elastoplastic deformation they can undergo. Various studies have been
done to understand this mechanical aspect of Ni-superalloys. One such study [36] talks about the elastoplastic deformation and its influencing factors of VZhm8 alloy. Consequently, pressure anisotropy accompanies bulk deformation. The difference in pressure is 22% for VZhm8 alloy at uniform bulk deformation. For simulating the dynamic load of test cylinders, the finite element method is used. Three-dimensional modelled continuity and motion equation is used for dynamic loading. Strains found in a tetrahedral element that is being rigidly rotated in space are recalculated by the Jaumann device. The rigid wall’s cylinder impact is estimated by numerical simulation. The anisotropic material’s stress-strain relationship depends on both kinematic and geometrical characteristics of the loading and position of central axes with respect to the principal system. This is due to the usage of different constant parameters that showed their impact on the auxeticity of VZhm8 alloy. Another similar study [37] dealt with the same mechanical aspect, elastoplastic deformation, while using the same material. In this study, elastoplastic deformation and dynamic properties in a Ni3Al superalloy (VZHM8) under impact loading are studied. Numerical simulation of dynamic loading made of VZHM8 was performed along [001]. The direction of loading lines up with [001] direction. For 1st calculation, all three axes (computed) coincide with the crystallographic directions ([010] and [100]), and for 2nd calculation, only the direction of impact loading ([001]) coincides, and the next two directions were rotated by 45° perpendicular to impact direction’s ([011] and [011]) plane. The wave pattern deforms in all three directions due to the rotation of the two axes. The variation in compressibility of elasticity in all loading directions must be taken into account when performing mathematical modelling. It is finally observed that in VZHM8 alloy, the change in principal axes and initial orientation results in a change in elastoplastic deformation. The elastic precursor was observed to remain unchanged.

Another study [38] that used the same material as the above two studies looked into the influence of auxeticity on elastoplastic deformation. The deformation process of heat resistance alloy VZHM8 (nickel aluminium alloy, rhenium, and ruthenium doped) is studied in this work using numerical simulation. This program considers utmost elastic properties such as auxeticity into account. For studying, two principal axes with respect to crystallographic axes are used: (1) the loading is applied along the [001] axis, while the other two with the [010] and [100] directions; (2) the loading direction lines up with the [011] direction and the other with the [100] axis. The radius increases to a particular value corresponding to the moment of cylinder rebounding from the rigid wall; when the cylinder was loaded along OX and OY axes as well as [001] direction, the deformation too takes place along OX and OY axes, and the values are same in both axes, making the problem axisymmetric. Considering the second situation, the direction of loading lines up with [011] direction; rebounding is due to the increase of cylinder radius with respect to the OX axis and decrease of it with respect to the OY axis. The reduction of cylinder radius is due to the influence of the plane’s negative Poisson’s coefficient. Even after neglecting the identical elastic properties, the time is taken by the cylinder to rebound changes because of changes in the loading direction with respect to crystallographic axes.

Another mechanical aspect of Ni-superalloys that has developed greatly over the years with the development of new generation alloys is fatigue behaviour. An in-depth study of this aspect can help in improving the life, strength, and durability of these alloys and even help develop new alloys with a much better life, strength, and durability. One such study [39] examines the influence of deformation twins and their thinning on the thermo-mechanical fatigue performance of TMS-196 and compared the results with TMS-82+. During TMF, testing formation of deformation twins was observed in both alloys. But the amount of twins formed in TMS-196 was seen to be significantly higher and much finer and thinner than the ones formed in TMS-82+. Nearly after 1.5 cycles of TMF testing, deformation twins originate at the γ/γ′ interface. Slip dislocation segments produced in the TMF process get deposited in the γ/γ′ interface of the γ channel to remove the strain formed due to lattice misfit that occurs between γ and γ′ phases, which acts as nucleation sites for the twins. TMS-82+ and TMS-196 have nearly 0.39% and 0.65% lattice misfits, respectively. Apart from that, the size of γ′ in TMS-82+ is greater than that of TMS-196. It is also observed that TMS-196 has a larger interface area between γ and γ′, thus favouring the deposition of slip dislocations. Hence, it can be concluded that TMS-196 has more dislocations than TMS-82+ in TMF cycling. This makes TMS-196 form more twins during the TMF process. This trend was attributed to the increased Re and Ru amount in TMS-196 that was mainly responsible for the high negative lattice misfit that helped in the deposition of slip dislocations. Due to the strengthened alloying effect in TMS-196, shear resistance is larger for twinning. Apart from that, as γ′ size in TMS-196 is smaller, twins having the same size should pass through more γ/γ′ interfaces than in TMS-82+. It helps in increasing the twinning shear resistance further. At the same time, when thicker and thinner twins are considered, the thicker one has larger shear resistance. A balance between total interfacial energy and shear resistance must be maintained to ease the deformation twin’s growth. Even though TMS-196 has a great amount of twin nucleation sites, its twinning shear resistance is high, which creates numerous and fine deformation twins in the alloy. The fracture morphology after TMF failure is greatly influenced by the size of the deformation twins. TMS-82+ has a flat fracture surface creating a possibility for brittle fracture mode, whereas TMS-196 has a rough fracture surface revealing ductile-like fracture characteristics. This ductile-like fracture behaviour was seen to help avoid immediate instant failure and prolong TMF life. Another study [40] examined tensile and fatigue life variabilities of SC Ni-based superalloys: the 3rd generation CMSX-4 Plus, the 6th generation TMS-238, and a newly developed TROPEA containing Pt. The researchers selected nine different Ni-alloys in order to understand the influence of
chemical composition on alloys better. At VHCF, the pore size plays a huge role than other metallurgical defects when VHCF is considered. TMS-238 has smaller pores than CMSX-4 Plus and TROPEA. Variations in pore size were seen to be influenced by the thermal gradients, mold thickness, and withdrawal rates used. The results are compared with the database of Institut Pprime. TMS-238 showed high performance, almost equalling AM1/MCNG HIPed specimens’ lifetime. Under fully reversed conditions, the chemical composition does not create any impact on VHCF lifetime. However, its impact is expected at high temperatures and positive stress ratio, where creep and fatigue damage coexist. At LCF, the LCF loops are the reason to create the difference in the LCF life of the alloys. At the first cycle with a maximum applied stress of 950 MPa, TMS-238 has a noticeable plastic deformation, while the others have nearly zero deformation. Even since TMS-238 obtains a fully elastic loop, slip localization is caused because of plastic deformation in cycle 1, which leads to earlier crack initiation in the pores. TROPEA and CMSX-4 Plus have nearly twice the LCF life of TMS-238 at 950 MPa. The cyclic behaviour of all the alloys was compared at iso-maximum stress with YS value to study the LCF durability. TROPEA and CMSX-4 Plus are reaching elastic loops after at least five cycles, whereas TMS-238 gets stabilized since cycle 2. This is the reason for the steep hardening of TMS-238. Influence of tensile properties: in the same paper, the influence of chemical composition on different single crystal Ni-superalloys that have the same precipitate size and crystalline orientation is studied. The studies revealed that the ratio between the atomic percentage of \( (Ti + Ta) \) concentration and Al concentration is mainly related to YS variation. Such elements are known to form \( c' \) precipitates, thus increasing the APB energy that contributes to resistance of precipitate shearing. But, as there is no Ti in TMS-238, elements such as Ta should be replaced in \( c' \) precipitate. When the ratio of the concentration of \( (Ti + Ta) \) compared with Al concentration is low, YS is lower, and when the ratio is high, YS too is high. Both superalloys proved a strong hardening and low ductility. It is due to the high density of subgrain/low angle boundaries at dendrite/interdendritic interfaces that is because of a fast cooling rate used at the end of the heat treatment solution. This causes pronounced dendritic stresses. In this case, early yielding, high hardening, and low ductility due to a lower mean free path for dislocation/slip bands are because of the high density of subgrain boundaries. Very minimum YS and great work hardening are observed in TMS-238. This unusual behaviour is largely due to the high misfit of the alloy. TMS-238 has a lower \( c' \) fraction than other elements due to its slightly low \( c' \) forming elements. Even though it has high Ta content, the overall Al-substitution element is low when compared to others that carried out well in the tensile test, such as CMSX-4 Plus, TROPEA, and PWA1484. Even though the cost of TROPEA and TMS-238 is nearly the same, TROPEA has proved good while considering YS, elongation at failure, and LCF at low temperatures. TROPEA alloy is the first alloy in which how minor additions of Pt to the alloy could impact mechanical properties is investigated. The results still show the potential of Pt bearing single crystal Ni-superalloy that exhibits very good tensile behaviour for turbine blade material, with a reasonable density.

8. Supply Risk Assessment of Developing New Generation Ni-Superalloys

The development of new generation superalloys comes with a lot of risks and challenges, especially supply risks. This is one of the reasons why carrying out significant research on the latest generation Ni-superalloys is almost impossible for individuals and the only people who can contribute to this field of research is big technological R&D companies that deal with defence or space fields or other research institutes. Addressing this issue can help us better manage resources and carry out new alloy development with maximum efficiency in a highly optimized manner. One study [41] has elaborated on some of the common risks and challenges one can face during the development of new generation Ni-superalloys. Semiquantitative estimates of the comparative supply risks related to superalloys with rhenium as primary interest are dealt in the current paper. The comparison of supply risks is done based on the superalloy’s chemical composition. These are mostly polycrystalline old alloys, “wrought,” “powder-processed,” “conventionally cast,” as well as “directionally solidified,” low Re containing alloys.


Al and Cr form a protective oxide layer that makes the element corrosive resistant. Re and Ru improve creep strength. Ru further increases the high-temperature rupture strength [42]. In all superalloys, Ni contributes to about more than 50% of the mass. Inconel-718; a wrought alloy is the only Ni-superalloy with Fe used here. At the same time, Fe and Nb appear only in the average for wrought superalloys. Typical 2nd generation alloys have only 3%wt rhenium. This increased to about 6%wt in the 3rd generation. The 4th generation has a small amount of Ru that is 5 %wt in the 5th generation. The elemental concentration for Ta, Co, Al, and W is rather constant over time. Mo and Ti are only used in minor quantities. The Cr concentration in superalloys decreased as generation went on but still increased again in the 6th generation alloy TMS-238 and also in low Re-containing superalloys.

8.2. Costs. The total raw material cost for earlier generation Ni-superalloys is on an average about 100 USD/litre of volume. Adding Re, from the 4th generation, further increased the material costs. Re contributes to 60% and Ru to 30% of the total raw material cost of TMS-238, thus increasing the cost to 2,400 USD/litre. Other elements contribute to only 10% of the total raw material cost [41].

8.3. Supply Risk Assessment Method. Augsburg method is used, with minor changes regarding the sector’s competitive index. Firstly, it evaluates the relative supply risk of elements
in Ni-based superalloys. Secondly, it adds supply risk “scores” at the alloy level. The relative supply risk is divided into risks of (1) supply reduction, (2) demand increase, (3) market concentration, and (4) political risk. A common scale of 0 to 100 is used for risk estimation. This scheme is used for comparing the results on the alloy with endurance temperature as a key parameter. Using a semiquantitative assessment scheme, the supply risks were evaluated. Re, Mo, and Co have the highest supply risk scores, whereas Ti and Al have the lowest. When comparing generations, they were found to be similar in terms of cost. Due to increased Re’s (up to 6%wt) share from 2nd generation, the supply risk slightly increases. Even after having a decreased Re composition, the new low Re generation still faces a higher supply risk than 1st gen SC or non-SC alloy types. It can be concluded that increased costs and the relatively small increases in the supply risk scores for 4th and 6th generation alloys are not too high. Only in the cost share approach, the supply risk seems to be higher, but alloy composition and fuel consumption too need to be considered. The higher generations are particularly suited to reduce costs for airlines from fuel consumption. It is thus important to manage the supply risks, rather than avoid them.

9. Future Scope

After reviewing papers that have studied the various aspects of 5th and 6th generation Ni-superalloys and by comparing the results to that of the previous generation Ni-superalloys, the following suggestion for future research can be made:

(i) Effect of alloying elements present and their composition was seen to play a very major role in deciding the properties of the alloys. Thus, future research on this matter can be highly beneficial for the development of new alloys and the improvement of existing ones. In particular, the effect of increasing Ru and Re beyond 6 wt% to develop an entirely new class of Ni-superalloys is still one unexplored possibility.

(ii) Throughout the review process, it was seen that additive manufacturing (AM) of 5th and 6th gen Ni-superalloys was not done anywhere. Thus, checking the feasibility of such processes and analyzing the pros and cons of AM for producing parts made of 5th and 6th gen Ni-superalloys are other unexplored possibilities.

(iii) It was also observed that the studies on the application of thermal barrier coats (TBCs) on 5th and 6th gen alloys are almost non-existent. Therefore, the application of TBCs on these alloys and the influence that will have on oxidation, creep, or fatigue properties is yet another unexplored possibility.

(iv) Another study that can be done in the future is to study in depth how elements that can cause TCP or incipient melt phases in the alloy microstructure can be replaced by certain other elements such as Ir, Nb, and so on, in order to suppress undesirable phases forming while retaining all other properties such as creep, fatigue, and oxidation resistance properties.

(v) Future studies can also be aimed at improving existing alloys to achieve better creep, fatigue, oxidation resistance, tensile, and corrosion resistance properties. Studies can also be done to develop new 5th or 6th generation Ni-superalloys or maybe even develop new 7th generation of Ni-superalloys.

(vi) The cost of making these alloys is one major hurdle to the fast progress in their development and technological advancement. Therefore, conducting research into how existent elements that are too costly can be substituted partially or completely, without damaging existing properties, is another possibility for further research.

10. Conclusion

Detailed reviewing of various papers that have studied the properties, development, and improvement of 5th and 6th generation Ni-superalloys has given us an in-depth understanding of these alloys, how they are made, what are their properties, the reasons behind their unique behaviour, what factors affect their performance, how they can be improved, and how new alloys can be made. Research that is focused on the 5th and 6th generation Ni-superalloys is very scarce, but it is imperative that we review all existing work in order to gain sufficient knowledge about the subject so that we will be able to proceed with further developments in this area. In-depth studying and understanding of the elemental makeup influence on elemental composition on alloy properties, and the material and physical alloy characteristics are imperative to achieve improvements in the development of new generation alloys and also to improve existing ones.

Data Availability

All data are included within the article.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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