

Superalloys, sustainability and applications

Fehim Findik^{1,2,*}

1: Metallurgy and Materials Engineering Department, Faculty of Technology, Sakarya Applied Sciences University, Sakarya, Turkey

2: Istanbul Aydın University, Mechanical Eng Dept, Engineering Faculty, Florya Halit Aydın Campus, Istanbul, Turkey

*Corresponding author E-mail: findik@subu.edu.tr

ABSTRACT

Superalloys are resistant to extreme mechanical stress at temperatures above 70% of their melting point. Superalloys have exceptional properties such as resistance to creep and thermal fatigue, mechanical strength at high temperatures, resistance to corrosion and oxidation, and resistance to phase separation with time. Superalloys are primarily based on nickel (Ni), but cobalt (Co)-based and iron (Fe)-nickel-based variants are also available. Superalloys are categorized based on their primary element: First, nickel-based superalloys are mostly used in superalloy applications. Second group is cobalt-based superalloys. For example, Haynes 188 and Stellite 6B are some of such superalloys. They can be used in various fields including gas turbine blades, dental implants, and industrial furnace parts applications. Third group is nickel-iron-based superalloys. They can be used in different application areas such as turbine disks and boiler components. In the presented article, exceptional properties of superalloys are identified and classified depending on the processing route and primary element. Then, the sustainability of superalloys is criticized for the sake of environmental perspective. The challenges and future perspectives of alternative alloy development and superalloys are also investigated to provide potential researchers with insights into the benefits and disadvantages of the virgin field of superalloys.

Keywords: Superalloys, Applications, Sustainability, Alternatives, Future

1. Introduction

Superalloys are resistant to extreme mechanical stress, at temperatures above 70% of their melting point. They are also a class of high-performance alloys designed to withstand corrosive or oxidizing environments. Superalloys have exceptional properties such as resistance to creep and thermal fatigue (thermal stability), mechanical strength at high temperatures, resistance to corrosion and oxidation, and resistance to phase separation over time (microstructural stability). Superalloys are primarily nickel (Ni) based, but cobalt (Co) based and iron (Fe)-nickel based variants are also available [1], [2], [3].

There are two types of classifications of superalloys. One of them is depending on processing route. For example, wrought superalloys (forged/worked into shape), cast superalloys (investment casting for complex shapes, e.g., single-crystal turbine blades) and powder metallurgy superalloys (for homogeneous microstructure in high-alloy compositions). The second classification is contingent upon primary base element. For example, nickel, cobalt or iron-nickel based superalloys.

Superalloys are categorized based on their primary base element: The first one is nickel-based superalloys are mostly used in superalloy's applications. For example, Inconel (718, 625), Hastelloy, Waspalloy are some of the nickel-based superalloys [4], [5]. In these superalloy compositions, there are several elements including Ni + Cr, Co, Al, Ti, W, Mo, Ta, and Re (Table 1, Figure 1). These superalloys are basically used in the turbine blades, jet engines, and nuclear reactors [6], [7], [8]. In order to increase the hardening of this kind of superalloys, solid-solution strengthening, and γ' (gamma-prime, $\text{Ni}_3\text{Al/Ti}$) precipitation hardening can be used (Table 2).

Table 1. Chemical composition of the alloy 625 powder [9]

Composition in weight percent (wt.%)										
Ni	Cr	Fe	Nb	Mo	Al	Ti	Co	C	Si	Mn
64.04	20.9	2.6	3.2	8.4	0.01	0.01	0.01	0.029	0.31	0.39

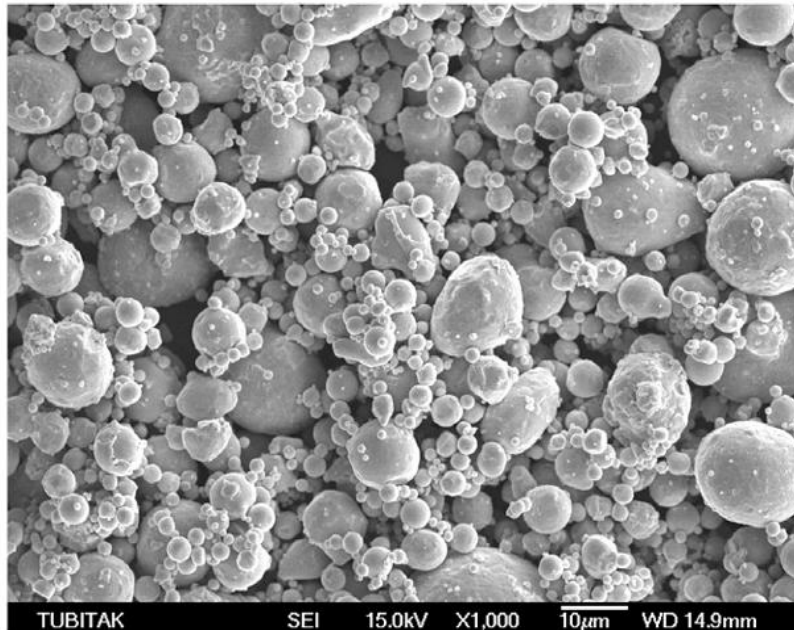


Figure 1. SEM micrograph of alloy 625 powder [10]

Table 2. Tensile strength and elongation values of injection molded Nimonic-90 samples [10]

Material/Condition	Yield stress/MPa	Tensile stress/MPa	Elongation/%
Sintered	690	858	11.4
Aged (C%: 0.127)	760	920	10.6
Nimocast-90	520	700	14
Wrought Nimonic-90	810	1235	33
PIM Nimonic-90	906	1249	22

The second group is cobalt-based superalloys. For example, Haynes 188 and Stellite 6B are some of these kinds of superalloys. They can be used in various area including gas turbine vanes, dental implants and industrial furnace parts applications. Within the compositions of these superalloys, there are several elements counting Co + Cr, Ni, W and C (carbide formers). This kind of superalloys have several advantages such as better hot corrosion resistance, and higher melting points than Ni-based superalloys. Strengthening could be done via carbide precipitation (e.g., Cr_{23}C_6) + solid-solution strengthening.

The third group is nickel-iron based superalloys. For instance, Incoloy (800, 925) and A-286 are some of the Ni-Fe based superalloys. In their compositions, there are several elements including Fe-Ni + Cr, Ti, Al (less common than Ni/Co). they can be used indifferent application area such as Turbine disks and boiler components.

The mechanical properties of superalloys describe how they respond to applied forces. Key metrics include tensile and yield strength as well as ductility: In tensile strength, the maximum stress a material can withstand while being stretched. In yield strength, the stress at which a material begins to deform permanently. Ductility is the ability of a material to deform under tensile stress, often measured by percent elongation [11], [12]. These properties are not fixed; they can be tuned through alloy design and heat treatment. For instance, the high-temperature yield strength of “Haynes 282”, a well-known nickel-based superalloy, is superior to many of its contemporaries. The alloy's strength comes from two main mechanisms including precipitation hardening and solid-solution strengthening:

In precipitation hardening, the formation of a high volume fraction of the γ' (gamma prime) phase (e.g., $\text{Ni}_3(\text{Al}, \text{Ti})$). These tiny particles act as obstacles to dislocation movement, which is the primary way a metal plastically deforms. On the other hand, in solid-solution strengthening, the addition of refractory elements like molybdenum (Mo) and tungsten (W). These atoms of different sizes distort the crystal lattice of the base metal, making it harder for dislocations to move [13], [14].

Research shows that by carefully adjusting these elements, properties can be significantly enhanced. For example, a modified alloy based on Haynes 282, which substituted tungsten for some molybdenum, showed a marked improvement in its mechanical performance. The table below (Table 3) provides typical mechanical properties for some common superalloys.

Table 3. Characteristic mechanical properties for some common superalloys.

Alloy Name	Alloy Type	Tensile Strength (MPa)	Yield Strength (MPa)	Elongation Break (%)	at Condition
Super Alloy 36TM	Fe-Ni based	490	240	42.0	Annealed prior to test
Super Alloy A-286	Fe-based	1035	759	25.0	Standard condition

In the other hand, at high temperatures, oxidation is a primary cause of material degradation. Superalloys resist oxidation by forming a slow-growing, dense, and adherent oxide layer on their surface that acts as a barrier, preventing further oxygen from attacking the underlying metal [15], [16].

The formation of this protective layer is highly dependent on the alloy's composition: Chromium (Cr) is crucial for forming a protective Cr_2O_3 (chromia) scale at intermediate temperatures (e.g., 800-1000°C). Haynes 282 relies on this mechanism. Aluminum (Al) becomes more important at very high temperatures (above 1000°C) because it forms an Al_2O_3 (alumina) scale, which is even more stable and grows slower than chromia. Minor additions of "reactive elements" like Y, Hf, or Zr can significantly improve the adhesion of the oxide scale, preventing it from spalling (flaking off). Elements like Titanium (Ti) can have a complex role. While sometimes beneficial, in some alloys like TROPEA, the addition of Platinum (Pt) was found to delay the formation of a protective alumina layer, actually hampering oxidation resistance in the short term.

Advanced alloy design seeks to balance these elements. For instance, new alloys based on Haynes 282 aim to improve oxidation resistance up to 800°C by using minor metalloid additions to compensate for necessary reductions in chromium content [13], [15]. Creep is the time-dependent and permanent deformation of a material when subjected to a constant load at a high temperature. For turbine blades and other high-stress components, excellent creep resistance is paramount [11]. An important problem of creep performance is improved through several microstructural strategies including stable strengthening phases, grain boundary engineering and phase stability: Stable Strengthening Phases: The γ' precipitates that provide strength must resist coarsening (growing larger) at high temperatures, as larger particles are fewer effective obstacles. Research has shown that substituting W for Mo in a Haynes 282 variant helped retard the coarsening of γ' precipitates, especially under stress. Grain Boundary Engineering: In polycrystalline alloys, grain boundaries can be sites for creep failure. Alloys like A-286 can be age-hardened to strengthen these boundaries. For the most demanding applications, single-crystal superalloys (like CMSX-4 or AMS20) eliminate grain boundaries entirely, vastly improving creep life. Phase Stability: Over long periods at high temperatures, brittle, needle-like phases known as TCP (Topologically Close-Packed) phases (e.g., σ and μ phases) can form. These phases deplete the matrix of strengthening elements and can act as crack initiators. Alloy design aims to suppress their formation [16], [17]. In Figure 2 high temperature capability of some Ni-based single crystalline superalloys are given.

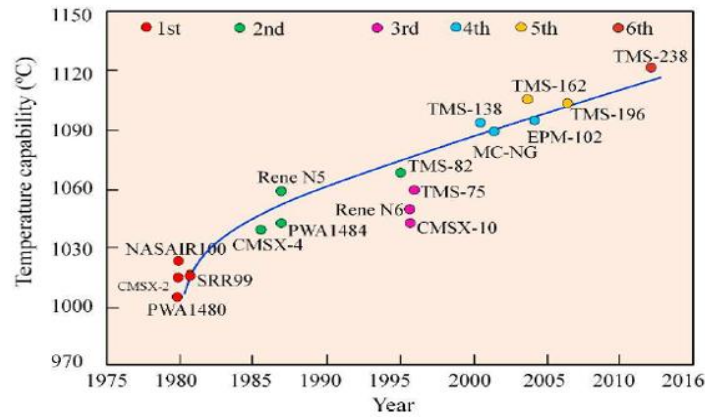


Figure 2. High temperature capability of some Ni-based single crystalline superalloys [18].

The following table (Table 4) compares the composition and design focus of modern single-crystal superalloys, where creep resistance is the primary goal.

Table 4. Composition and performance of modern single-crystal superalloys,

Alloy Name	Alloy Generation	Key Compositional Features	Design Focus / Performance
CMSX-4	2nd Generation	Contains ~3 wt.% Re (Rhenium)	Excellent balance of properties; serves as a baseline for oxidation comparison
CMSX-10K	3rd Generation	High Refractory content (Re, W, Mo)	Optimized for high-temperature creep strength
AMS20	3rd Generation	Computationally designed composition	Aims to balance the high creep strength of 3rd-gen alloys with the oxidation resistance of 2nd-gen alloys like CMSX-4
TROPEA	Pt-containing	Contains ~2 wt.% Platinum (Pt)	Pt addition increases mechanical properties, but can negatively affect early-stage oxidation

In the submitted paper, extraordinary properties of superalloys are defined and classified depending on the processing route as well as the primary base element. After that, sustainability of superalloys is criticized for the sake of environmental point of view. Alternative alloy development as well as challenges and future perspectives of superalloys are also investigated for the potential investigators to give them prediction for benefits and disadvantages of superalloys' virgin area.

2. Sustainability

Superalloys are critical for energy-efficient technologies (e.g., jet engines, power plants), but their sustainability faces challenges due to critical raw materials, recycling, waste reduction as well as coatings and repair:

2.1. Reducing critical raw materials

Superalloys are based on strategic metals such as cobalt (Co), rhenium (Re), and tantalum (Ta) that are sourced from expensive, geopolitically sensitive resources. Therefore, the goal of superalloys is to reduce such critical raw materials. Two examples of such reduction efforts can be given. The first is General Electric (GE) Aviation's rhenium reduction. Rhenium (Re) is a major reinforcing agent in Ni-based superalloys (e.g. CMSX-4), but its annual global production is extremely small. GE has reduced costs and supply risks by developing Re-free superalloys for turbine blades (e.g. René N515). As a result, some new alloys have reduced Re content from 3-6% to <1% without compromising performance. The second example is cobalt-free superalloys (ETH

Zurich and NASA). Cobalt is associated with some mining problems in the Democratic Republic of Congo (DRC). To remedy this, researchers have designed Co-free Ni-based alloys strengthened with high aluminum/titanium content (for example, NASA's GRX-810, an oxide dispersion strengthened alloy). As a result, GRX-810 offers 2,000 times better creep resistance than conventional alloys, eliminating Co-dependency.

2.2. Recycling

Superalloy scrap is valuable but difficult to recycle due to its complex composition. Two examples of innovations in recycling can be given. First, Safran (a French aerospace company) salvages used turbine blades from retired aircraft engines. Here, high purity Ni, Co and Re are extracted for reuse in new superalloys through electrochemical refining. As a result, metal recovery rates of up to 90% have reduced primary mining demand. Second, Haynes International's superalloy scrap sorting process uses laser-induced breakdown spectroscopy (LIBS) to rapidly identify and separate scrap alloys (for example, separating Hastelloy X from Inconel 625). As a result, high-performance scrap is prevented from being reused in low-grade applications.

2.3. Alternative alloy development

New alloys aim to reduce dependency on critical materials while maintaining performance. Examples of sustainable alternatives include high entropy alloys and oxide dispersion strengthened alloys. First, high entropy alloys (HEAs) can be used instead of superalloys. For example, HEAs such as CoCrFeMnNi (Cantor alloy) use abundant metals instead of Re/Ta. In this regard, Sandia National Labs recently developed nanostructured HEAs with high-temperature strength comparable to Inconel. As a result, the potential for a 50% lower CO₂ footprint in production is possible. In Figure 3, some high entropy alloys are shown.

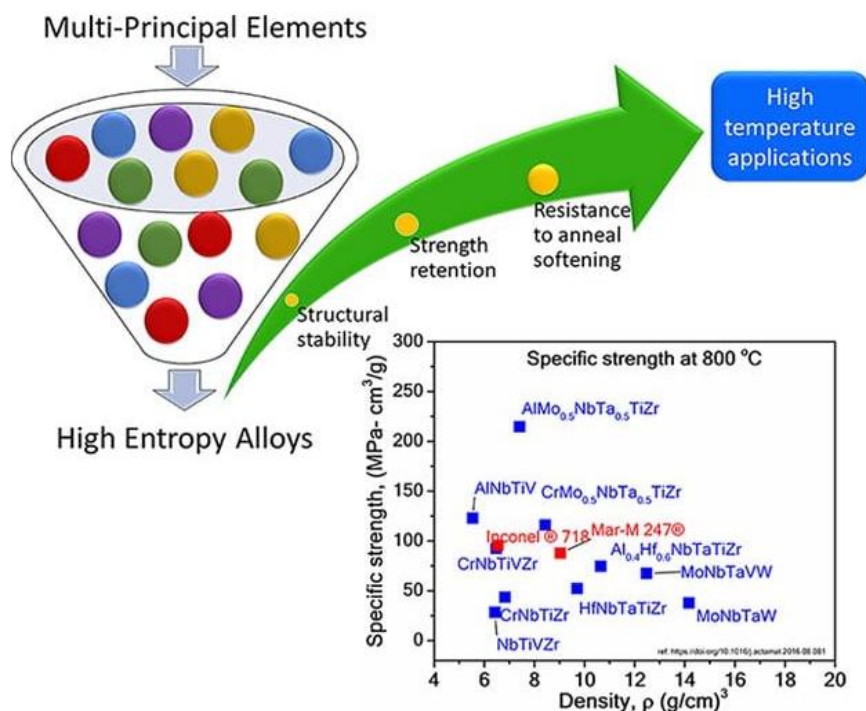


Figure 3. High entropy alloys [19]

The second example is oxide dispersion strengthened (ODS) alloys. Here, alloys such as MA754 (Ni-Cr with Y₂O₃) rely on oxide particles instead of rare metals for strength [5]. These alloys are used in nuclear reactors and gas turbines and reduce the Re/Co content. Some mechanical properties of high entropy and dispersion strengthened alloys are given in Tables 5 and 6. Also, in Figure 4, comparison between experimental and estimated yield strength for alloys is given.

Table 5. Some mechanical properties of high entropy alloys

Property	HEA Performance (Average/Max)	Comparison to Standard Steel/Alloys
Yield Strength	600 – 1,200+ MPa	Often 2–3x higher than standard structural steels.
Fracture Toughness	200 MPa·m^{1/2}	The "Cantor Alloy" (CrMnFeCoNi) remains one of the toughest materials known at cryogenic temperatures.
Operating Temp	Up to 1,200°C+	Refractory HEAs outperform Superalloys in jet engine environments.
Hardness	800 – 1,100 HV	Some HEA coatings reach hardness levels comparable to ceramics.

Table 6. Some mechanical properties of dispersion strengthened alloys

Property	ODS Alloy (e.g., MA956)	Conventional Superalloys
Max Operating Temp	Up to 1,300°C	Usually capped at 1,000°C – 1,100°C
Yield Strength (1,000°C)	~80–120 MPa	Often drops below 50 MPa
Creep Life Improvement	50% longer	Standard baseline
Thermal Conductivity	~25–30 W/m·K	Highly stable at extreme heat

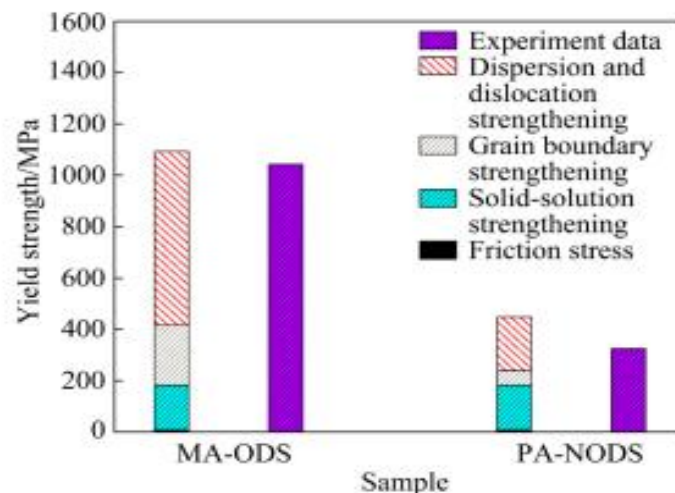


Figure 4. Comparison between experimental and estimated yield strength for alloys [20].

2.4. Additive manufacturing (AM) for waste reduction

Traditional machining of superalloys produces approximately 80% waste; AM minimizes this waste stuff. Two examples from industry can be given. First, Siemens Energy's 3D printing of turbine blades. This method used laser powder bed fusion (LPBF) to print Ni-based blades (e.g., Inconel 738LC) with internal cooling channels, reducing material usage by 40%. This results in lower energy consumption with 3D printing compared to casting + machining.

The second example is GE's additive-first approach. GE Aviation's LEAP engine features 3D-printed fuel nozzles from Co-based superalloy Haynes 282. The result is a 25% weight reduction and a 5x longer lifespan compared to traditionally manufactured parts.

2.5. Coatings and repairs to extend life

Instead of replacing deteriorated parts, advanced coatings and repairs reduce waste. Two examples are available. First, Pratt & Whitney's application of thermal barrier coatings (TBCs). Here, yttria-stabilized zirconium (YSZ) coatings on turbine blades have reduced fuel consumption by allowing higher operating temperatures. As a

result, blade life has been extended by a factor of 3-5, reducing replacement demand. Second, laser coating for component protection. Here, for example, Rolls-Royce used laser metal deposition (LMD) to repair worn turbine blades (e.g., Inconel 718) instead of scrapping them. As a result, new part production has achieved 60% cost savings and 75% lower CO₂ (Table 7).

Table 7. Key Takeaways on Sustainability

Challenge	Solution Example	Outcome
Cobalt dependency	NASA's GRX-810 (Co-free)	Ethical sourcing, equal performance
Rhenium scarcity	GE's René N515 (low-Re)	Cost reduction, supply security
Recycling complexity	Safran's closed-loop refining	90% metal recovery
Manufacturing waste	Siemens' 3D-printed blades	40% less material waste
Short component lifespan	Pratt & Whitney's TBCs	3–5x lifespan extension

As a result, superalloys are becoming more sustainable through material innovation (Co/Re-free alloys, HEAs), efficient recycling (closed-loop systems), additive manufacturing (waste reduction, complex designs) as well as life extension (coatings, repairs). Companies like GE, Safran, and Siemens are leading these efforts, proving that high-performance alloys can align with circular economy principles. However, scaling these solutions industry-wide remains a challenge.

3. Alternative element research

Alternative element research in superalloys focuses on reducing or replacing critical, costly or ethically problematic elements such as Co, Re, Ta while maintaining or improving mechanical properties, oxidation resistance and creep performance. The main strategies are reviewed below in terms of technical and industrial approaches.

3.1. Goals of alternative element research

As the first goal, cobalt can be reduced or replaced due to the price volatility of the element (~30–80K/ton) and ethical concerns in cobalt (Co)-mining. Second, rhenium (Re), which is extremely rare and expensive (\$3000/kg) since only 50 tons are produced per year, can be eliminated. As the third goal, lighter elements can be used instead of high-density tantalum (Ta) and tungsten (W) that increase weight. Fourth, sustainability can be improved by using abundant low-impact elements such as Al, Ti, Nb, Mo instead of rare elements.

3.2. Basic technical approaches

Here, the reduction/replacement of cobalt element, elimination of rhenium and substitution of heavy tantalum and tungsten will be examined. Co stabilizes the FCC matrix in Ni/Co based superalloys, but since it is risky in terms of supply chain, cobalt (Co) reduction/replacement can be done. For example, high aluminum/titanium Ni based alloys or iron-nickel (Fe-Ni) superalloys can be used as solutions. Al-Ti based alloys are used in combustion chambers, turbine blades and have 2,000 times better creep resistance than Inconel 718 (Table 8). Incoloy 330 (Fe-Ni-Cr) is an iron-nickel (Fe-Ni) superalloy and replaces Co with Fe; it maintains oxidation resistance. It has a lower melting point (~1,400°C for Ni based).

Table 8. Comparison of mechanical properties of alloy 718 with forged and cast alloys [21]

Condition	Yield Strength (MPa)	Tensile Strength (MPa)	Strain (%)
As sintered	506 ± 29	667 ± 25	5.8 ± 0.4
As aged	780 ± 36	1022 ± 58	5.3 ± 0.5
Cast Inconel 718	915	1090	11
Wrought Inconel 718	1185	1435	21

Re is an element that should be eliminated due to its high cost, although it increases creep resistance. As a solution, either ruthenium (Ru) or high niobium alloys can be used as a partial replacement. Here, Ru stabilizes the γ' and γ phases in a similar way to Re, but it is less rare. For example, the Ni-based TMS-238 alloy, which is used in high-pressure turbine blades and is Re-free and has 3% Ru element, can be given as an example. An example of a high niobium alloy is the Re-free and 2.5% Nb-based René 65 alloy used by GE for static

components in the GE9X jet engine. Here, the mechanism is that Nb forms stable carbides and γ' (Ni_3Nb). This increases the creep resistance of the system.

Finally, the replacement of heavy elements tantalum (Ta) and tungsten (W) will be discussed. Here, although Ta/W increases strength, these elements are very heavy and have high costs. Molybdenum (Mo) + niobium (Nb) binary alloys can be used as a solution to this problem. Here, as a mechanism, Mo provides solid solution strengthening; Nb helps γ' formation. For example, Ni-based Haynes 282 alloy containing 8.5% Mo and 0.3% Ta used in combustion linings and nuclear reactors can be given as a solution and this alloy replaces W/Ta-dominant alloys. As a second example, modified alloys can be obtained with vanadium (V). For example, Ni-Fe-Cr alloy 740H containing V instead of Ta can be given. This alloy is used in ultra-supercritical coal power plants and operates at a service temperature of 700°C.

3.3. Emerging material systems

In new material systems, high entropy alloys or refractories or alloys strengthened with oxide dispersion can be used as an alternative to superalloys.

Instead of superalloys, high entropy alloys such as CoCrFeMnNi or alloys such as aluminum-doped AlCoCrFeNi can be used. Among the advantages of these alloys is that the strength obtained by the absence of Re and Co is the same as Inconel 718 at 800°C. Among the disadvantages is that the oxidation resistance is weaker than Ni-based alloys. Secondly, high entropy refractory alloys such as NbMoTaW can also be used. These refractory alloys have higher melting points. For example, the melting temperatures of Ni-based superalloys are approximately 1,400°C, while the melting temperatures of these refractory alloys are above 2,500°C. Studies are ongoing to eliminate the disadvantages of these refractory alloys, such as brittleness at room temperature. Thirdly, instead of superalloys, alloys such as Ni-20Cr-0.6Y₂O₃ (MA754) strengthened with oxide dispersion can be an alternative. The creep resistance of these alloys, which are used in turbine blades and nuclear reactor coatings, has been increased thanks to Y₂O₃ nanoparticles.

3.4. Industry and research case studies

From industry and research case studies, we can mention Re and Co free alloys and environmentally friendly superalloys. For example, Re-free Ni-based Rene N515 alloy is used by GE in aviation. It is also used in GE90 engine blades and reduces Re usage by 50%. Also, Co free but Al/Ti containing Ni-Fe-Cr alloys are being investigated by Rolls-Royce for low pressure turbines. Finally, low Ta, high Mo Ni based LTES-1 alloy, which is 30% lower cost than Ta rich CMSX-4 and has similar creep performance, is used as environmentally friendly superalloy by Japanese NIMS (Table 9).

4. Future directions and emerging solutions

We can examine future studies in terms of alloy development, process, sustainability and surface engineering. In alloy design, high entropy refractory alloys can be mentioned with computational alloy development. Various alloys can be developed using package programs such as phase diagram modeling program CALPHAD in computational alloy development. For example, optimization was performed using machine learning to determine Al/Ti/Nb combinations for Co-free strength. As a result, GRX-810 alloy was developed by NASA and stable temperature strength at 1,100°C was achieved by strengthening the oxide dispersion in the new alloy. In addition, studies can be focused on new high entropy refractory alloys such as NbTaTiV and MoNbTaW, which have high melting points (melting points >2,500°C) compared to Ni-based alloys. However, problems such as room temperature brittleness of these new refractory alloys should be solved by research with applications such as B doping at grain boundaries.

More process-related innovations and solutions can be expected in the future. We can divide these innovations into two as additive manufacturing and rapid sintering at high temperatures. First of all, some preliminary studies have been conducted on 3D printing (additive manufacturing) and successes have been achieved. As

follows; additive manufacturing, which currently has disadvantages such as being slow and expensive, has superior performance in the production of critical parts. Many different methods are used in additive manufacturing. However, two specific methods can be mentioned as directed energy deposition and electron beam deposition. For example, turbine blades were repaired using Haynes 230 alloy and directed energy deposition method, which is an additive manufacturing method, and the amount of waste was reduced by 70%. Again, for low-pressure turbine blades, Ti-48Al-2Cr-2Nb (γ -TiAl) alloy, which is 50% lighter than Ni-based ones, was developed using electron beam melting method, one of the additive manufacturing methods.

Another method is the creation of new solutions for superalloys by high-speed, high-temperature sintering (Figure 4). Namely; hot isostatic pressing (HIP) method is a sophisticated method used in powder metallurgy. However, hours are required for sintering in the HIP method. Here, it is possible to sinter powders in seconds (<10s) with the Joule heating method, one of the ultra-fast high temperature sintering methods. With this method, super alloys that do not contain Re element with nano-sized precipitates can be obtained.

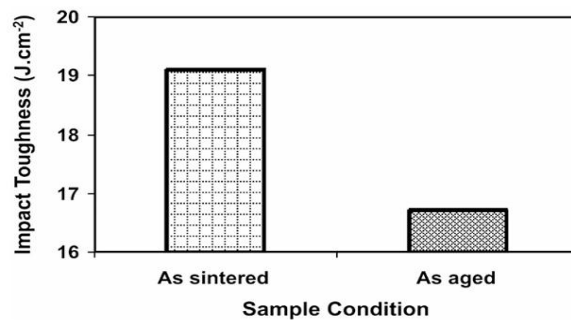


Figure 4. Impact toughness values of Ni-625 samples [22]

Sustainability initiatives include recycling and alternative material use. First; Re element can be recovered from scrap turbine blades via electrochemical dissolution. This method recovers Re element in conventional smelting, increasing efficiency by 95%. Second, bioleaching of Co/Ni uses bacteria to extract Co from mine waste, resulting in 50% less CO₂ emissions (Table 10).

In terms of future prospects for superalloys, we can also talk about coatings and surface engineering. Self-healing thermal barrier coatings and nanostructured coatings are two potential topics worth considering. Self-healing thermal barrier coatings, such as the YSZ + MoSi₂ developed at the Fraunhofer IKTS, form SiO₂ to bridge cracks at 1,200 °C. Nanostructured coatings, such as AlCrN/Si₃N₄ nanocomposites, provide twice the oxidation resistance compared to MCrAlY. All of these coatings could play an important role in surface engineering in the future.

Table 9. Industry & academic case studies

Organization	Initiative	Impact
GE Aviation	René N515 (Low-Re alloy)	50% less Re in GE9X engine blades
Rolls-Royce	UltraFan® engine (TiAl blades)	20% weight savings vs. Inconel
Oak Ridge Natl. Lab	AM of ODS alloys (FeCrAl-Y ₂ O ₃)	Nuclear reactors with 1,500°C tolerance
NIMS Japan	LTES-1 (Low-Ta alloy)	30% cost reduction vs. CMSX-4

Table 10. Grand challenges & roadmap

Timeframe	Focus Area	Milestones
Near-term (2025–2030)	Co/Re reduction	Commercialize GRX-810, René N515
Mid-term (2030–2040)	AM-processed RHEAs	Crack-free NbTaTiV alloys for hypersonics
Long-term (2040+)	Fully circular superalloys	100% recycled-content blades via AI sorting

In summary, creep/oxidation limits, critical element reduction, production and sustainability are important points in superalloys. For example, new generation coatings are pushing the boundaries of self-healing and oxide dispersion hardening alloys. In addition, it can be said that new alloys will replace Co/Re in superalloys by developing high entropy alloys with artificial intelligence support. Again, thanks to additive manufacturing, the production of waste-free geometric parts becomes possible. In addition, it is possible to reduce dependency on mining with biological washing and recycling.

In the future, superalloys can be transformed into multi-material systems such as Ni-based and ceramic composites [23], [24], [5]. In addition, progress can be achieved by making various collaborations in the industry (such as Siemens Energy), in the academic field (MIT's Alloy Development Laboratory) and in the government (such as the EU's Horizon 2030) related to superalloys.

5. Conclusions

Superalloys have exceptional properties such as mechanical strength at high temperatures, resistance to corrosion and oxidation, and microstructural stability over time. The results obtained from this study are given below:

- a. Superalloys are becoming more sustainable through material innovation (Co/Re-free alloys), efficient recycling, additive manufacturing and life extension through coatings.
- b. Alternative element research in superalloys focuses on reducing or replacing critical, costly elements such as Co, Re, Ta while maintaining or improving mechanical properties, oxidation resistance, and creep performance. In new material systems, high entropy alloys or refractories or oxide dispersion strengthened alloys can be used as alternatives to superalloys.
- c. In the future, superalloys can be developed into multi-material systems such as Ni-based and ceramic composites. In addition, progress can be made in superalloys through various collaborations in industry, academia, and government.

References

- [1] M. J. Donachie and S. J. Donachie, *Superalloys: A Technical Guide*, 2nd ed., ASM International, 2002, <https://doi.org/10.31399/asm.tb.stg2.9781627082679>
- [2] M. Durand-Charre, *The Microstructure of Superalloys*, Gordon and Breach Science Publishers, Amsterdam, 1997, <https://doi.org/10.1201/9780203736388>
- [3] C. T. Sims, *Superalloys: Genesis and Character*, Superalloys II, C.T. Sims, N.S. Stoloff, and W.C. Hagel, Ed., John Wiley & Sons, 1987, <https://doi.org/10.31399/asm.tb.sap.9781627083133>
- [4] J. A. Manriquez, P. L. Bretz, L. Rabenberg, and J.K. Tien, *The High Temperature Stability of IN718 Derivative Alloys*, *Superalloys 1992*, S.D. Antolovich et al., Ed., TMS, 1992, https://www.tms.org/superalloys/10.7449/1992/Superalloys_1992_507_516.pdf
- [5] K. A. Heck, J. S. Smith, and R. Smith, "Inconel 783: An Oxidation Resistant, Low Expansion Superalloy for Gas Turbine Applications", *J. Eng. Gas Turbines Power*, vol 120, no. 2, pp. 363–369, 1998, <https://doi:10.4028/www.scientific.net/MSF.546-549.1271>
- [6] R. J. Smith, G. Lewi, and D. Yates, "Development and Application of Nickel Alloys in Aerospace Engineering", *Aircr. Eng. Aerosp. Tech*, nol., vol 73, no. 2, pp. 138–147, 2001, <https://doi:10.1108/00022660110694995>
- [7] Mahmood Aliofkhazraei (Ed.), *Superalloys*, AvE4EvA Publishing, 2015 Open Access, <https://www.intechopen.com/books/4615>

-
- [8] C. R. Reed, *The Superalloys Fundamentals and Applications*, Cambridge University Press, Cambridge 2006, <https://patron.group/wp-content/uploads/2017/04/The-Superalloys-Fundamentals-and-Applications-2006.pdf>
- [9] O. Ozgun, O. Gulsoy, R. Yilmaz, F. Findik, "Injection molding of nickel based 625 superalloy: Sintering, heat treatment, microstructure and mechanical properties", *Journal of Alloys and Compounds*, vol. 546, pp. 192-207, 2013, <https://doi.org/10.1016/j.jallcom.2012.08.069>
- [10] O. Ozgun, O. Gulsoy, F. Findik, R. Yilmaz, "Microstructure and mechanical properties of injection molded Nimonic-90 superalloy parts", *Powder Metallurgy*, vol. 55, no. 5, pp. 413-422, 2012, <https://doi.org/10.1179/1743290112Y.0000000010>
- [11] J. Liu, H. Yang, X. Zhong et al., "Microstructure manipulation and high-temperature service performance enhancement of nickel-based superalloys", *J. Mater Res and Tech*, vol. 40, pp. 2930-2961, 2026. <https://10.1016/j.jmrt.2025.12.165>
- [12] X. Zhang, M. Zou, S. Lu et al., "A novel high-Cr CoNi-based superalloy with superior high- temperature microstructural stability, oxidation resistance and mechanical properties", *Int. J. Miner. Metall. Mater.*, vol. 31, no. 6, 2024. <https://10.1007/s12613-024-2843-6>
- [13] X. Yu, H. Zhuo, L. Wu et al., "A novel low-density Co-Ni-Al-Nb-based multicomponent superalloy with superior medium-to-high temperature mechanical properties and oxidation resistance", *Journal of Alloys and Compounds*, vol. 1040, pp. 183495-183505, 2025. <https://10.1016/j.jallcom.2024.183495>.
- [14] P. Maj, R. Sitek, J. Ciftci et al., "Impact of rhenium addition on microstructural characteristics and mechanical performance in powder bed fusion-laser beam produced Inconel 625 alloy", *Archives of Civil and Mechanical Engineering*, vol. 24, pp. 103-113, 2024. <https://10.1007/s43452-024-00901-0>.
- [15] M. Liu, X. Wei, Y. Zhao et al., "Oxidation-induced dissolution initiated from semi-coherent delta/matrix interface in Inconel 718 superalloy", *Acta Materialia*, vol. 306, pp. 121924-121934, 2026. <https://10.1016/j.actamat.2025.121924>.
- [16] I. Barwinska, M. Kopec, D. Kukla et al., "Thermal Barrier Coatings for High-Temperature Performance of Nickel-Based Superalloys", *Coatings* 2023, vol. 13, pp. 769-780. <https://10.3390/coatings13040769>.
- [17] X. Li, W. Wu, S. Xue, "A Review of High Temperature Durability and Laser Cladding Crack Suppression Techniques for Nickel-Based Alloys: Mechanisms and Strategies", *Applied Research*, vol. 4, no. e70035, pp. 1-33, 2025. <https://10.1002/appl.202400035>.
- [18] Y. Zhao, X. Zhao, Y. Fan et al., "Composition optimization in alloy design for Ni-based for single crystal superalloy", *Metals*, vol. 15, pp. 793-826, 2025. <https://10.3390/met15070793>.
- [19] M. F. Ashby, H. R. Shercliff, & D. Cebon, *Materials Engineering Science, Processing and Design*. Butterworth-Heinemann, 2007. <https://10.1016/B978-0-7506-8391-3.X5001-6>
- [20] W. He, P. Ke, J. Huang, F. Liu, et al. "Mechanical properties and microstructural evolution of nickel-based superalloys", *Trans. Nonferrous Met. Soc. China*, vol. 35, pp. 2304–2319, 2025. [https://10.1016/S1003-6326\(25\)67023-5](https://10.1016/S1003-6326(25)67023-5).
- [21] O. Ozgun, O. Gulsoy, R. Yilmaz, F. Findik, "Microstructural and mechanical characterization of injection molded 718 superalloy powders", *Journal of Alloys and Compounds*, vol. 576, pp. 140-153, 2013, <https://doi.org/10.1016/j.jallcom.2013.04.042>
- [22] O. Ozgun, R. Yilmaz, O. Gulsoy, F. Findik, "The effect of aging treatment on the fracture toughness and impact strength of injection molded Ni-625 superalloy parts", *Materials Characterization*, vol. 108, pp. 8-15, 2015, <https://doi.org/10.1016/J.MATCHAR.2015.08.006>
-

- [23] B. Geddes, L. Hugo, X. Huang, Superalloys Alloying and Performance, ASM International, Ohio 2010, <https://doi.org/10.31399/asm.tb.sap.9781627083133>
- [24] G. H. Gessinger, Powder Metallurgy of Superalloys, Butterworths London, 1984, <https://doi.org/10.1557/PROC-521-205>
- [25] S. E. Huron, R. C. Reed, C. Mark et al. (Eds.), Superalloys 2012, Wiley, New Jersey 2012, <https://www.amazon.com/Superalloys-2012-Eric-S-Huron/dp/0470943203>