Screening for an Alternative to Ni-Based Superalloys in Turbine Blades for the Power Industry

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Abstract. Turbine blades in the power industry operate under extreme conditions, requiring materials that can withstand high temperatures, mechanical stress, oxidation, and corrosion. Ni-based superalloys have long been the primary choice due to their exceptional balance of mechanical properties and resistance to harsh environments. However, as operational demands increase, Ni-based superalloys are reaching their performance limits, driving the search for alternative materials. This paper explores the process of screening a wide range of materials to identify the most suitable candidates for turbine blade applications. Through this process, the dominance of Ni-based superalloys is reaffirmed. After determining that Co-based superalloys are the best alternative, a comparative analysis is conducted to evaluate the strengths and limitations of both materials in the context of turbine blade applications. While Co-based superalloys demonstrate superior high-temperature performance, oxidation resistance, and creep resistance, they face challenges such as higher density and increased manufacturing costs.

Keywords: Turbine blade; material selection; superalloy; power industry.

1. Introduction

The development of advanced materials for turbine blades in the power industry has emerged as a critical area of research due to the increasingly stringent operating conditions faced by modern turbines. Turbine blades are subjected to extreme thermal environments and must endure substantial mechanical stresses. In addition, these components are required to exhibit resistance to both corrosion and oxidation, driven by the harsh conditions within gas turbines. Currently, Ni-based superalloys dominate the market for turbine blade materials, owing to their exceptional resistance to corrosion, optimal balance between strength and toughness, superior performance under high-temperature conditions, and remarkable resistance to fast fracture.

Fast fracture, also referred to as brittle or catastrophic fracture, describes the rapid propagation of cracks within a material once critical stress thresholds are surpassed. This phenomenon typically occurs with minimal or no plastic deformation, providing little warning prior to failure. Fast fracture is most likely when the applied stress exceeds the material's fracture toughness, particularly under low-temperature conditions, environments with high strain rates, or materials that possess pre-existing defects [1].

In the context of turbine blades, resistance to fast fracture is important. Given the prolonged operation of these components at high temperatures and under high rotational speeds, the likelihood of cracking is elevated. A material with high resistance to fast fracture ensures that even when cracks form, catastrophic failure of the blade is averted. Consequently, fracture resistance is a crucial performance criterion for turbine blades in modern gas turbines.

As turbine operation conditions become more extreme, the limitations of Ni-based superalloys, particularly in terms of oxidation and corrosion resistance, microstructural degradation under constant high temperature, and long-term mechanical performance, are becoming increasingly apparent [2-4]. While Ni-based alloys have served the industry well, the need for materials that can surpass their temperature and creep resistance has prompted a search for viable alternatives.

In this process, this research aims not only to identify the best possible alternative to Ni-based superalloys but also to thoroughly compare the mechanical and thermal properties of the candidate materials. Even if the alternative does not surpass Ni-based superalloys in every aspect, the material selection process itself is critical. The objective is to find a material that optimally balances performance, cost, and manufacturability for specific turbine blade applications. Ultimately, this approach provides valuable insights into the limitations and potentials of various materials, ensuring that the selected superalloy meets the demands of modern turbine operations.

2. Working Conditions of Turbine Blades

Turbine blades operate under extremely demanding conditions, making material selection critical for their performance and longevity. The airfoils of turbine blades experience longitudinal stresses of up to 20,000 psi (138 MPa) and temperatures between 650 °C and 980 °C. Meanwhile, the blade root, which attaches to the disk, endures tensile stresses as high as 40,000 to 80,000 psi (276 to 552 MPa) and temperatures up to 760 °C [5]. These components must maintain their mechanical strength while also exhibiting sufficient ductility to tolerate creep deformation and resist low-cycle fatigue deformation. This ductility is essential for securely seating the blade in the disk slot without permanent damage.

In addition to mechanical strength and ductility, turbine blade materials must possess high oxidation resistance due to constant exposure to high-temperature combustion products. During cyclic operation, the heating and cooling of turbine sections cause thermal gradients, inducing thermal stresses. Therefore, materials with high thermal conductivity, low thermal expansion, and superior strength are essential to resist thermal fatigue. Furthermore, these materials must exhibit long-term microstructural stability to maintain their properties over extended periods. Ideal materials for turbine blades should also have good impact strength, castability, and low density to reduce the overall weight of the turbine while ensuring reliability under extreme conditions.

3. Material Selection Process

3.1. Objective

The objective of the material selection process is to identify a superalloy that optimizes the critical mechanical and economic requirements for turbine blade applications.

Maximum Young’s modulus (E), maximum yielding strain/elongation, resistance to fast fracture and minimum price are at the heart. By balancing these factors, the selected material will not only meet the demanding conditions of turbine operation but also provide a sustainable and economically viable solution.

3.2. Constraints

The operating conditions of turbine blades provide crucial information that helps define the material requirements. These blades endure extreme temperatures and mechanical stresses, requiring a material that can not only withstand high temperatures but also resist deformation and fracture under constant stress, in particular, 1000 h Rupture strength > 138 MPa at 650 °C < T <980 °C and yielding strength > 276 – 552 MPa at 760 °C.

3.3. Free Variables

In addition to the defined constraints, certain free variables in the material selection process offer flexibility in achieving the optimal balance of mechanical and economic requirements. These free variables allow for adjustments in material composition to fine-tune properties such as strength, ductility, and oxidation resistance. The two key free variables considered in this selection process are the base of the alloy and other composites in the superalloy.

3.4. Material Selection

For the material selection, Granta software was utilized to screen for the materials that meet the specified requirements.

3.4.1 Step 1: setting limits

Three specific limits were applied, corresponding to the constraints mentioned earlier:

i) Nickel content: All materials with more than 30% Ni content by weight were filtered out to ensure that the remaining materials were not Ni-based superalloys.

ii) Maximum service temperature: The limit was set at 980 °C to ensure the material can perform at high temperatures.

iii) Yield strength: A minimum yield strength of 276 MPa was specified to ensure the material can withstand the mechanical stresses in turbine blades.

3.4.2 Step 2: plotting Young's modulus vs. elongation

The relationship between Young's modulus and elongation was plotted, as illustrated in Fig. 1. A horizontal line was drawn to represent the objective of maximizing Young's modulus, and a vertical line was drawn to represent the goal of maximizing elongation.

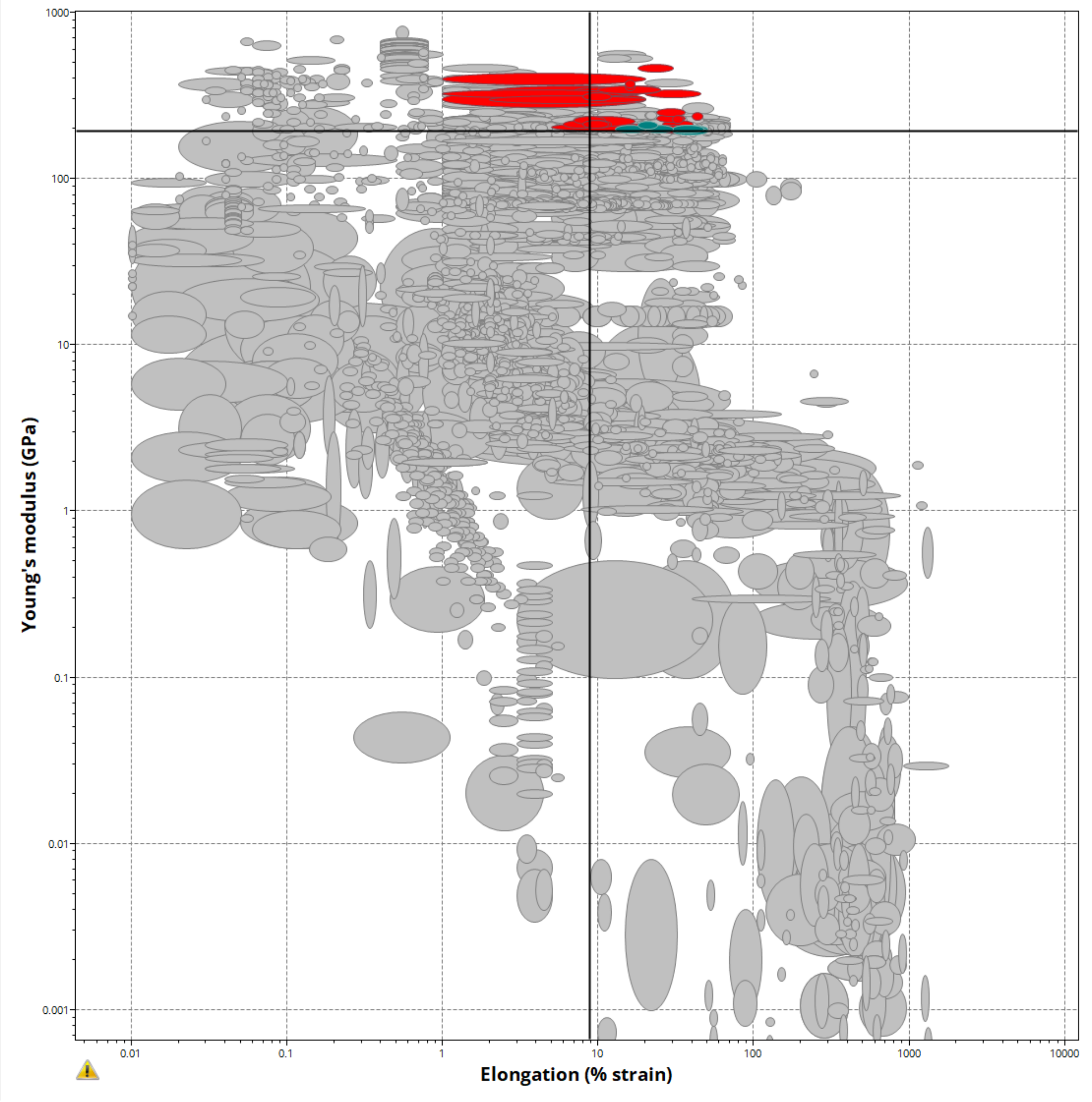


Fig. 1 Young's modulus vs elongation without Ni-based superalloy [Picture credit: Original]

After removing the limit on Ni content, the plot shows the properties of Ni-based superalloys (highlighted in the yellow ellipse) in comparison to other candidates.

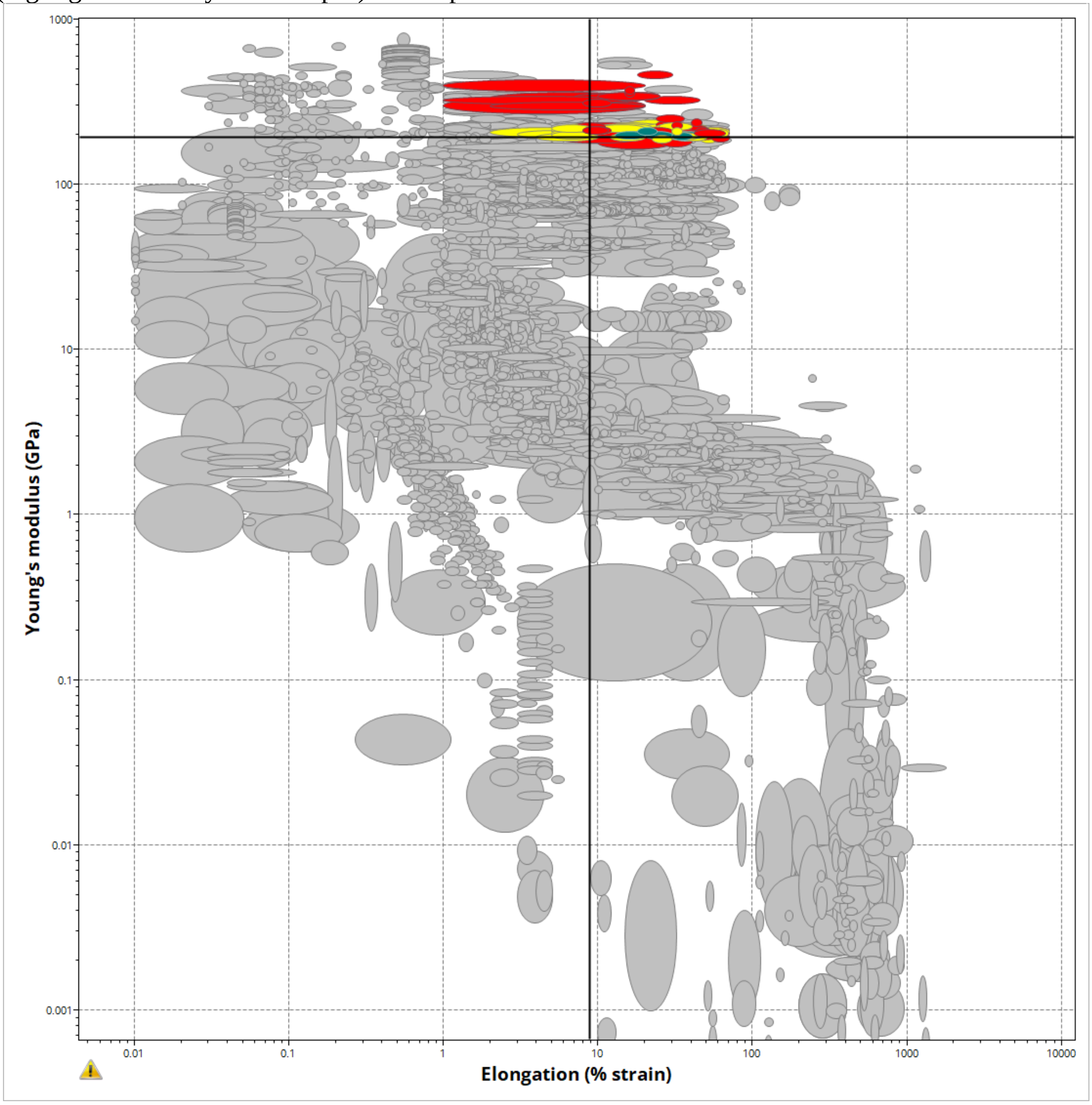
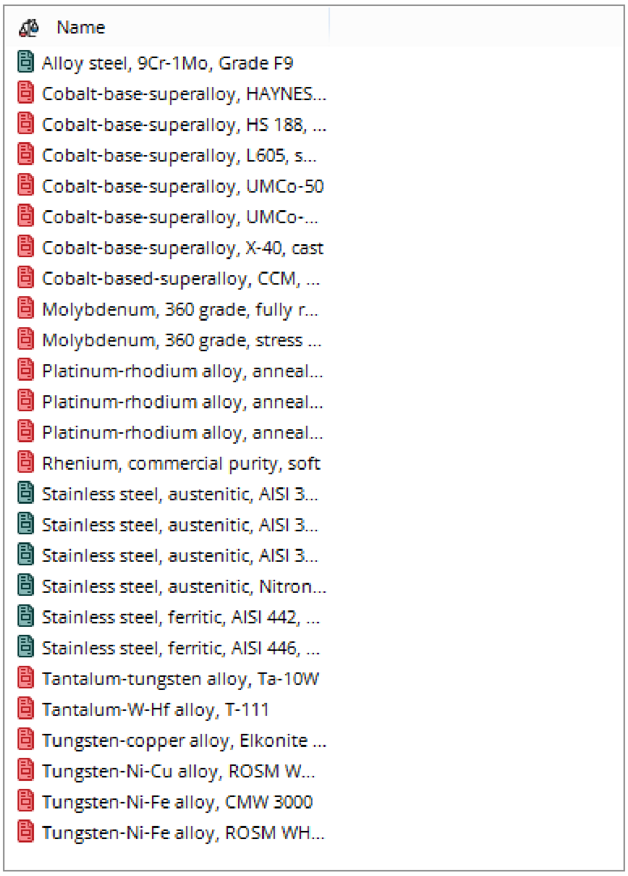


Fig. 2 Young’s modulus vs elongation with Ni-based superalloy [Picture credit: Original]

From Fig. 2, Ni-based superalloys excel in ductility, while their stiffness is comparable to other alloys. Below, in Fig. 3, the filtered list of remaining materials is included, which consists primarily of Co-based superalloys, molybdenum alloys, Ti-based superalloys, W-based superalloys, and stainless steel.



Name

Alloy steel, 9Cr-1Mo, Grade F9
Cobalt-base-superalloy, HAYNES...
Cobalt-base-superalloy, HS 188, ...
Cobalt-base-superalloy, L605, s...
Cobalt-base-superalloy, UMCo-50
Cobalt-base-superalloy, UMCo-...
Cobalt-base-superalloy, X-40, cast
Cobalt-based-superalloy, CCM, ...
Molybdenum, 360 grade, fully r...
Molybdenum, 360 grade, stress ...
Platinum-rhodium alloy, anneal...
Platinum-rhodium alloy, anneal...
Platinum-rhodium alloy, anneal...
Rhenium, commercial purity, soft
Stainless steel, austenitic, AISI 3...
Stainless steel, austenitic, AISI 3...
Stainless steel, austenitic, AISI 3...
Stainless steel, austenitic, Nitron...
Stainless steel, ferritic, AISI 442, ...
Stainless steel, ferritic, AISI 446, ...
Tantalum-tungsten alloy, Ta-10W
Tantalum-W-Hf alloy, T-111
Tungsten-copper alloy, Elkonite ...
Tungsten-Ni-Cu alloy, ROSM W...
Tungsten-Ni-Fe alloy, CMW 3000
Tungsten-Ni-Fe alloy, ROSM WH...

Fig. 3 List of candidates after step 1[Picture credit: Original]

3.4.3 Step 3: plotting resistance to fast fracture vs. price

Next, the relationship between resistance to fast fracture and price was plotted, as shown in Fig. 4.

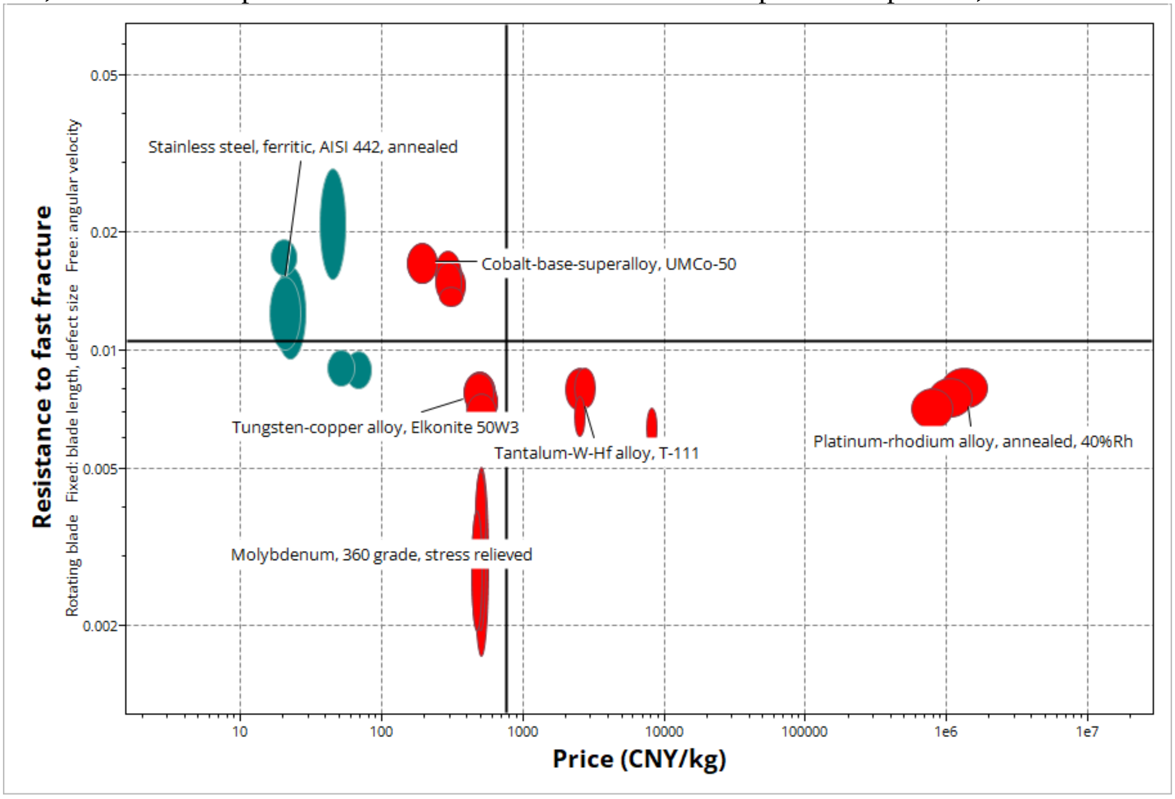


Fig. 4 Resistance to fast fracture vs. price without Ni-based superalloy [Picture credit: Original]

The remaining materials formed distinct clusters, as shown in Fig. 4, and their corresponding metal bases are labeled. Notably, Co-based superalloys and stainless steel exhibit significantly higher resistance to fast fracture compared to the other candidates while also being more cost-effective than the other alloys. Considering the extreme working conditions of turbine blades, the corrosion resistance of stainless steel would be insufficient in this case. As a result, Co-based superalloys were chosen as the final selection.

Additionally, the limit on Ni content was removed, and the same graph was plotted again to observe how Ni-based superalloys compare to the other alloys, as shown in Fig. 5.

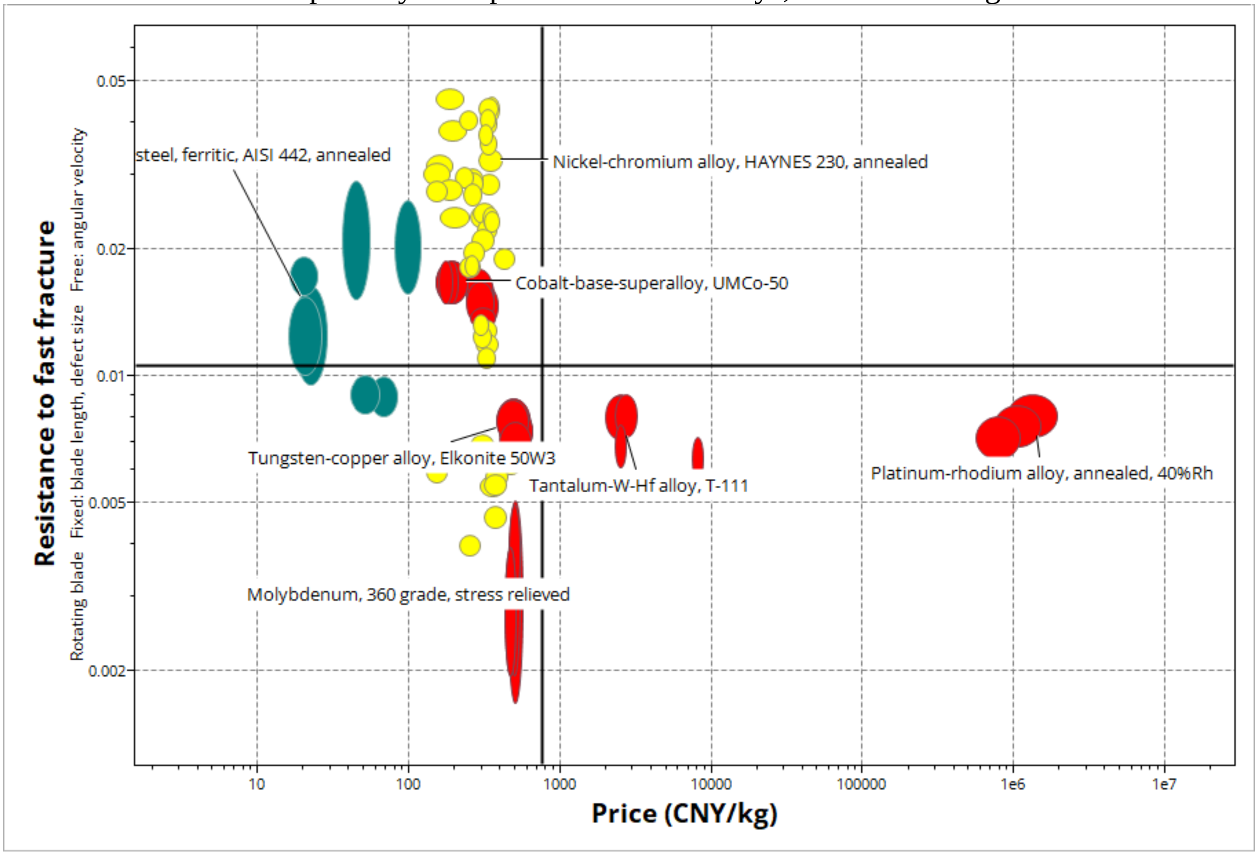


Fig. 5 Resistance to fast fracture vs price with Ni-based superalloy [Picture credit: Original]

From this comparison, it becomes evident that Ni-based superalloys can be the highest resistance to fast fracture, far surpassing the other candidates, including Co-based superalloys. This is likely one of the primary reasons why Ni-based superalloys remain the preferred choice for turbine blades.

3.5. Final Selection

on the material selection process outlined earlier, Co-based superalloys have emerged as the most suitable alternative to Ni-based superalloys for turbine blade applications. As a result, Co-based superalloys have been chosen as the final selection for the base of the alloy in this project, providing the necessary performance for high-temperature turbine applications while addressing some of the limitations of Ni-based alloys.

3.5.1 Data of existing Co-based superalloy

To find the Co-based superalloy that best meets the requirements, it is necessary to evaluate specific mechanical properties. As previously mentioned in the Constraints section, the materials must have a yield strength greater than 276 MPa at 760 °C and a 1000-hour rupture strength of more than 138 MPa at temperatures between 650 °C and 980 °C. These two key properties will help determine which Co-based superalloy is most suitable for turbine blade applications.

The reference used is Superalloys: A Technical Guide by Matthew J. Donachie, which provides detailed mechanical data for various Co-based superalloys. The focus was placed specifically on Co-based alloys that meet the criteria outlined in the constraints. The data presented here includes only the relevant Co-based alloys, which will guide the selection of the final alloy for this project.

Table 1. Effect of temperature on the short-time mechanical properties of selected wrought superalloys [6]

Alloy	Form	Yield strength at 760 °C (MPa)
AirResist 213	…	…
Elgiloy	…	385
Haynes 188	Sheet	290
L-605	Sheet	260
MAR-M918	…	…
MP35N	…	…
MP159	Bar	…
Stellite 6B	…	…
Haynes 150	…	…

Table 2. Effect of temperature on the short-time mechanical properties of selected cast superalloys [6]

Alloy	Form	Yield strength at 538 °C (MPa)
AirResist 13	…	330
AirResist 215	…	315
RSX-414	…	…
Haynes 1002	…	345
MAR-M 302	…	505
MAR-M 322(i)	…	345
MAR-M 509	…	400
WI-52	…	440
X-40	…	275

The first set of data tables consulted presents the short-time mechanical properties of Co-based superalloys. Table 1 represents wrought alloys, while Table 2 focuses on cast alloys. For this paper, the most relevant data are the 0.2% yield strength at 760 °C from the wrought alloy table (Table 1) and the 0.2% yield strength at 538 °C from the cast alloy table (Table 2).

Table 3. Effect of temperature on 1000h stress-rupture strengths of selected wrought superalloys [6]

Alloy	Form	1000 h-Rupture strength at 760 °C (MPa)
Haynes 188	Sheet	165
L-605	Sheet	165
MAR-M918	Sheet	60
Haynes 150	…	40

Table 4. Effect of temperature on 1000h stress-rupture strengths of selected cast superalloys [6]

Alloy	Form	1000 h-Rupture strength at 760 °C (MPa)
HS-21	…	95
X-40 (HS-31)	…	140
MAR-M 509	…	225
FSX-414	…	85
WI-52	…	…
WI-52	…	…

These are the long-term mechanical performance data for selected Co-based superalloys, specifically focusing on the 1000-hour rupture strength. Table 3 provides the 1000-hour rupture strength at 760 °C for wrought alloys, while Table 4 presents the 1000-hour rupture strength at 815 °C for cast alloys.

3.5.2 Final selection

Based on the data collected in section 3.5.1, a table was created that includes the elastic yielding strength and 1000-hour rupture strength of the candidate alloys. While the temperatures at which these data were obtained do not exactly match the requirements, they provide a useful reference for evaluating the materials. The alloys listed in the table either meet or come very close to the set constraints.

Table 5. Mechanical properties summary table for superalloys

Name	Elastic yielding strength (MPa)	1000h rupture strength (MPa)
Haynes 188	290 MPa at 760 ℃	165 MPa at 760 ℃
L-605	260 MPa at 760 ℃	165 MPa at 760 ℃
X-40	275 MPa at 538 ℃	140 MPa at 815 ℃
MAR-M 509	400 MPa at 538 ℃	225 MPa at 815 ℃
WI-52	440 MPa at 538 ℃	195 MPa at 815 ℃

From Table 5, it is evident that MAR-M 509 and WI-52 exhibit both high 1000-hour rupture strength and elastic yielding strength. These two alloys are cast alloys, and their 1000-hour rupture strength remains significantly above the required constraints, even at temperatures higher than the minimum 650 °C. This suggests that both materials have excellent creep resistance, providing a large safety margin in this regard. However, the elastic yielding strength values provided are measured at 538 °C, and it is expected that these values will decrease as the temperature rises to 760 °C or higher. Unfortunately, additional data for their performance at higher temperatures is not available, making it difficult to determine which of the two would be superior under those conditions.

Among the wrought alloys, only Haynes 188 meets the standard for elastic yielding strength. However, its creep resistance is not as strong as MAR-M 509 and WI-52, making it less suitable for the extreme operating conditions required.

Therefore, the final selection narrows down to MAR-M 509 and WI-52, both of which offer exceptional long-term performance, especially in terms of creep resistance.

Table 6. Compositions of MAR-M 509 and WI-52

Element	MAR-M 509 (%)	WI-52 (%)
C	0.6	0.45
Cr	23.5	21
Co	54.5	63.5
W	7	11
Other	10% Ni, 0.2% Ti, 3.5% Ta, 0.5% Zr	2% Fe, 2% Nb+ Ta

Table 6 shows the composition elements and proportions of Co-based MAR-M 509 and WI-52.

4. Comparative Analysis of Ni-Based and Co-Based Superalloys

Now that Co-based superalloys have been identified as a potential alternative to Ni-based superalloys, the next section will focus on a detailed comparison between these two materials. This analysis will examine the strengths and weaknesses of Co-based superalloys relative to Ni-based superalloys, highlighting how the newly selected material compares to the leading alloys in the market. By evaluating key performance metrics such as mechanical properties, high-temperature resistance, and cost-effectiveness, this comparison aims to provide insights into the advantages and limitations of Co-based superalloys in turbine blade applications.

4.1. Problems Solved by Co-Based Superalloys

4.1.1 Higher temperature performance

Co-based superalloys exhibit superior performance at ultra-high temperatures compared to Ni-based alloys. This advantage is due to their ability to operate above 1200 °C, while Ni-based superalloys reach their performance limits around 1100 °C. Co-Re-based alloys have shown promise in gas turbine applications due to their ability to maintain mechanical integrity at these extreme temperatures [7].

4.1.2 Oxidation and corrosion resistance

Co-based alloys also outperform Ni-based superalloys in terms of oxidation and corrosion resistance at higher temperatures. With the addition of elements like chromium (Cr) and silicon (Si), Co-based alloys form more robust protective layers, making them more resilient in aggressive, high-temperature environments [7].

4.2. Problems Not Fully Solved by Co-Based Superalloys

4.2.1 Creep resistance

Co-based superalloys are designed to improve creep resistance at higher temperatures. However, Ni-based superalloys still maintain a competitive edge due to the γ' phase, which provides enhanced resistance to creep deformation at high temperatures. While Co-based alloys are promising, particularly with advanced alloying elements, their creep resistance, in many cases, is not as robust as the best Ni-based alloys [8].

4.2.2 Density and weight

Co-based superalloys generally have a higher density than Ni-based alloys. This higher weight is a disadvantage in applications where minimizing mass is crucial, such as in aerospace turbine blades. Ni-based superalloys maintain a balance between high performance and lower weight, making them preferable for weight-sensitive applications [9].

4.2.3 Mechanical strength

While Co-based superalloys offer excellent creep resistance, Ni-based alloys still outperform them in terms of overall mechanical strength, particularly at lower temperatures. Ni-based superalloys remain the benchmark for strength in extreme conditions due to their γ' phase structure [8].

4.2.4 Cost and manufacturing complexity

Co-based superalloys, especially those alloyed with expensive elements like rhenium (Re), present higher costs and more complex manufacturing processes compared to Ni-based alloys. This limits their widespread adoption despite their superior high-temperature performance [10].

5. Conclusion

In summary, the comparison between Ni-based and Co-based high-entropy alloys reveals their respective advantages and limitations in the application of turbine blades in the power industry. Ni-based high-entropy alloys continue to dominate due to their excellent mechanical strength, creep resistance, and oxidation resistance, especially at extreme temperatures. These characteristics, coupled with their relatively low cost and extensive research foundation, make Ni-based high-temperature alloys the preferred material for most turbine applications. Ni-based alloys showcase their widespread use and highlight the gaps in research on other alloy systems. This also indicates that there are still many areas worth studying in other alloy systems.

However, Co-based high-entropy alloys have significant advantages, especially in ultra-high temperature environments, where their excellent creep and oxidation resistance make them a viable alternative. Although Co-based alloys are often heavier and more expensive, their ability to maintain integrity at higher temperatures demonstrates their potential in specific high-performance applications. Despite these benefits, they still do not fully surpass Ni-based alloys in overall performance.

An important conclusion of this study is the significance of the material selection process itself. Even if the chosen alternatives, such as Co-based alloys, are inferior to Ni-based high-temperature alloys in all aspects, the selection method is crucial. This process is based on clear objectives, constraints, and free variables, ensuring a systematic evaluation of materials according to the specific requirements of turbine blades. This rigorous method not only highlights the superiority of Ni-based high-temperature alloys but also highlights opportunities for further development of alternative materials.

In summary, although Ni-based high-temperature alloys are still the industry standard, the exploration of alternatives, such as Co-based alloys, has opened up new avenues for material research. This process-driven approach emphasizes the importance of continuous material innovation to meet the constantly changing demands of turbine technology, ensuring that even substitutes with room for improvement can provide valuable insights for future alloy development.

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