A Review on Characterization, Classifications, and Applications of Super Alloys

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Abstract:

Over the past 50 years, the development of high-temperature engineering alloys had been a primary driver of increased operating temperatures for material used in gas turbine engines. This has resulted in dramatic improvements in both their power and efficiency. It has been reported that a 170 ℃ increase in the engine operating temperature improves an engine‘s thrust by 5 % and the efficiency by 1%. Materials used for turbine blades and vanes found in the hot sections of gas turbine engines must endure extremely hot engine gases, an oxidative and hot corrosive environment, large centrifugal loads,and high-velocity foreign object impacts. New blade/van materials must therefore possess a balance of high-temperature strength, toughness, oxidation, and corrosion resistance.

Superalloys are the major class of materials used for the high-temperature components in the fact that they are the only commercially available materials that retain their mechanical and corrosion / oxidation-resistant properties at high temperatures (up to 0.9 Tm). There are three main classes of superalloys: nickel-base superalloys, cobalt-base superalloys, and iron-base superalloys. Superalloys are currently used in many high-temperature fields from gas turbines used in aircraft, marine, and industrial applications, to space vehicles, nuclear reactors, steam power plants, and petrochemical equipment. The largest consumer of superalloys today the aircraft gas turbine engine industry. In this review, each group of superalloys has briefly presented its key characteristics and chemical compositions. Lastly, their manufacturing uses were illustrated.

Key words: Superalloys, Nickel-based superalloy, Cobalt base super alloy, Iron base superalloy, High temperature alloys, Main application of superalloy.

I.0.Introduction

High mechanical strength, high operative temperatures, creep, great fatigue resistance and generally high corrosion and oxidation resistance even at high tempers are the main developed features of the super alloys materials. These properties make super alloys suitable for using in ships, submarines, hot metals working dies, and reactors. Not all conditions are needed a high intensity of the temperature. Its high tolerance and resistance to corrosion have made it possible for biomedical joints and cryogenic implants to use some super alloy of high quality materials[1,2].

In general, these materials are categorized into 3 basic groups: Ni-based, Fe-based, and Co-based alloys (Figure 1). Due to the chemical structures and the metallurgical handling obtained during processing, the mechanical, physical, and machining activity of each category varies considerably. Super alloys are also known as wrought, powder metallurgy, and cast super alloy. The representative listing of compositions and super alloys, with a focus placed on alloys which were produced and used in the USA, are shown in the Figures 2 and 3. Super alloys can be turned into sheets/bars or otherwise developed in a number of shapes. The most easy way of working with raw materials is by using plates and bars stocks[3]. They are imported from material suppliers directly and are built to make sleeves, shafts, etc. Note that refractory metals do not have the same attractive properties as super-alloys and are not generally used, however, they have a higher melting point than super alloys. As main alloy elements, super alloys typically include Ni, Co, Cr, Fe and Mo. Others are W, Al, Ti, etc. The function of addition of these elements is to improve the super alloys characteristics of [4, 5]. Ni stabilizes the shape and features of alloys at the high values of the temperatures [6].

- Co, Mo, and W improve the strength at great temperatures.
- Cr, Al, Si increase oxidation resistance and the resistance of corrosion at high values ofthe temperatures.
- C improves the strength of the creep.

However, it should be noted that the properties of the these alloy are closely related to composition of the alloy and the processes of melting, casting techniques, working procedures, heat treatment after forging or casting. An integral part of super alloy production and implementation is the super alloys coating technology. Lack of a coating suggests less potential at high temperatures to use super alloys for longer periods. The limits of the temperature of these alloys have already been surpassed by some engineering applications. It is estimated that future jet engines can be work at 1500 °C. Super alloys in such applications are shielded by coatings which, in their operating environment, isolate them from gases[7,8].

2. Classification of Super alloys

Super alloys are categorized into 3 types based on the main metal existing in the alloy. They are [9] ;

- Ni-based super alloys
- Iron-based super alloys
- Co-based super alloys

2.1. Iron-based Super alloys

Irons-based super alloys have formed from austenitic stainless steels and are formed on the basis that FCC matrix is combined with both precipitate-forming and solid-solution hardening (in most cases). With at least 25 percent Ni required enhance the stabilization of FCC process, the austenitic matrix is formed by iron and nickel. Other elements for alloying, such as chromium, mainly partition to solid-solution hardening austenite [10]. There are three types of I-super alloys, which are cheaper than nickel or cobalt based super alloys: alloys that can be reinforced by a martensitic transformation type, austenitic alloys that are reinforced by a hot and cold working sequential processes (usually forging at 1094 to 1149℃ monitored by finishing process at 649 to 871℃), and finally the precipitation hardening that used for enhance the austenitic alloys [11, 12].

The last category is considered by some metallurgists only as super alloys, while others are listed as high-strength and high-temperature alloys. In fact, at temperatures below 538℃, the martensitic kinds are used in this working condition . The superalloy AISI 600 series consists of 6 iron-based alloy subclasses[9]:

- 601 through 604: Martensitic low-alloy steels.
- 610 through 613: Martensitic secondary hardening steels.
- 614 through 619: Martensitic chromium steels.
- 630 through 635: Martensitic precipitation-hardening and semi-austenitic stainless steels.
- 650 through 653: Hot/cold work strengthened Austenitic steels.
- 660 through 665: All grades of the Austenitic super alloys; except the alloy 661 that strengthened by precipitation processes of the second-phase.

Room-temperature and high temperature reliability, creep resistance, corrosion, wear, and oxidation are the main features of the iron-based super alloys. With increasing of the carbon content, resistance of the wear increases. The maximum value of the wear resistance is derived from alloys 613, 612, and 611, which can be used in aircraft bearing worked at high-temperature and sliding contact machinery components. Resistance to oxidation enhances as content of chromium increases. Martensitic chromium steels are preferable for blades of steam-turbine, in particular alloy 616. In all traditional mill types, super alloys are available; board, billet, forgings, bar, and special configurations are accessible for most types of alloys. In general, it is harder to machine austenitic alloys than martensitic forms, which machine better in the annealed state. In the solution-treated state, austenitic alloys are typically "gummy" and the machine better after being partly aged or completely hardened. By traditional means, sensitivity of crack makes much of the martensitic steels impossible to weld. Until welding, these types of alloys should be polished or tempered; post-heating and pre-heating are suggested even then. Alloys mechanical properties that rely on hot/cold work for strength are dramatically reduced by welding. All of the low-alloy martensitic steels are adequately machined and easily produced by cold working and hot working. The chromium alloys and martensitic secondary-hardening are all heat-treated by pre-heating process. Austenitic alloys forging is more complex than the grades of martensitic [13, 14].

2.2. Nickel-based Super alloys

Super alloys based on Ni are the utmost complicated, the most commonly used for the hottest sections, and several type of all super alloys [10]. Currently, they make up more than 50 percent of advanced parts of the aircraft engines. The properties of the alloy of the nickel base are the FCC Ni matrix phase solidity and the potential is to be strengthened by a combination of direct and indirect methods. In addition, by alloying with and/or chromium [11], the nickel surface stability is readily increased. The most prominent usage of the super alloys is in the gas turbines that used for the civil and military aviation and marine propulsion. Gas and oil devices, ships, space, military electric motors, nuclear reactors, submarines, processing vessels, chemical, and heat exchanger tubing industries are also manufactured from super alloys [15]. Various types of super alloys generations have been produced with better resistance for the temperature [16]. To attain the desired properties, the new iterations of super alloys contain costly alloying metals such as ruthenium and rhenium. The cost of modern super alloys may be five times more costly than high-quality turbine steel because of this. The goal is looking for a substantial increase to be used in these applications, especially as the sectors of aircraft and power generation. The high cost of some of the alloying metals used in super alloys along with nickel, however, can be a usage restriction. Actually (March 2013), for instance, markets $65 to 85 per ounce and rhenium at around $4200 per kilogram [17]. Commercial Ni-based superalloy compositions (wt. percent, bal. Ni) are listed in Table 1:

2.3. Co-based Super alloys

At extremely high temperatures, Ni-based super alloys have drawbacks, so parts are typically made of cobalt- based alloys in chambers for combustion, where the high temperature can reach higher than 1100 ° C. Super alloys based on cobalt (Table 3) are not as solid as super alloys based on nickel, but they maintain their performance at higher temperatures. Their strength is primarily derived from carbon and metal combinations such as W and Mo, that appear to accumulate at boundaries of grain (Fig. 4). This carbide network reinforces boundaries of the grain and almost up to the melting point, where the alloy becomes stable. Cobalt super alloys typically contain elevated Cr levels in addition to metal carbides and refractory metals to develop resistance to corrosion that usually happens in the vicinity of exhaust high temperature gases [18]. To produce a Cr_2O_3 shielding layer protects the alloy from destructive gases, the atoms of Cr interact with atoms of oxygen. Cobalt super alloys are not as sensitive as Ni-based super alloys and are not as prone to cracking under thermal shocks as other available super alloys [19]. Therefore, Co-based super alloys are more appropriate for parts which need to be welded or worked as noticed in the combustion chamber's complex structures. The Chemical components of the several Co-based superalloys are presented in Table 2.

3.0. Super alloys Application

Uses of the super alloys at the high temperature are comprehensive and extensive [20, 21]. In addition, super- alloys, are greatly used in the heat exchanger tubing, nuclear reactors, and commercial gas turbines that commonly used in the aerospace and marine industries. The F119 engine, is presented in figure 2. Temperatures of gas in these engines can rise to levels above 2000°F (1093°C) in the hot parts (rear engine areas). Cooling methods decrease the individual metal part temperatures to lower values, and the main components of the hot parts of such engines are super alloys that can work at these temperatures[22].

In today's trade, the importance of super alloys is characterized by the claim that, although just about 10 percent of the overall gas turbine weight used for an aircraft engine was made of super alloys in 1950, this amount had grown to about 50 percent by 1985. However, it will be remembered that not all systems need potential for

elevated-temperature power. Their high strength combined with resistance of corrosion has introduced super alloys adequate materials for biomedical application. In cryogenic applications, super alloys also considered as typical materials [23].

Superalloy uses are classified below; the majority of the tonnage in gas turbines is used [24]:

- Gas turbines for aircraft: combustion chambers, disks, casting, bolts, cases, shafts, exhaustsystems, burner cans, afterburners, vanes, blades, thrust reversers.
- Steam turbine: blades, bolts, re-heater stack gas
- Reciprocating motors: exhaust valves, turbochargers, hot plugs, seat adapters for valves
- Metal processing: casting dies: hot-work instruments and dies
- Health applications: prosthetic appliances: dentistry applications
- Space vehicles: rocket engine components: skins that are aerodynamically heated
- Equipment for heat-treating: conveyor belts, fixtures, trays, baskets, mufflers of furnace, fans,
- Nuclear power systems: structures for the control rod drive, ducting, valve stems, and springs.
- Industries in the petrochemical and chemical sector: spikes, fans, tubes, reaction vessels, piping, pumps
- Equipment for emission control: Scrubbers
- Mining mills for metals: afterburners, ovens, and exhaust fans
- Systems for coal liquefaction and gasification: re-heaters, heat exchangers, and piping.

3.1 Aero and turbines for land

Cobalt super alloys are quite well to non-rotating applications that require high fatigue resistance and high temperature resistance where stress levels are smaller than for rotating parts. Vanes of turbine and other static parts are therefore often produced in Co alloys. A much lower value of coefficient of thermal expansion and improved thermal conductivity than the Ni based super alloys makes the Co alloys good choices for technologies where a key design challenge is thermal fatigue. Land-based casting standards are increasingly getting more strict due to prolonged service life specifications [25].

3.2 Implants for surgery

The alloy has been known since the '30s of the last century under the patented name Vitallium. Still, orthopedic implants, most commonly knees and artificial hips, use this alloy. Generally, the alloy is mentioned by its ASTM number F-75 and comprises 6% Mo and 29% Cr. While the ASTM standard restricts carbon to 0.35%, designers of implants have chosen for lower carbon standards and an intentional nitrogen alloy. Co-Cr-Mo alloy attains higher strength with high value of ductility without surrendering resistance of corrosion and bio-compatibility. Via forging, casting or the technology of the powder metallurgy, Co-Cr-Mo implants can be made [26].

3.3 Gas Turbines Engines

Parts of these engines are prone to high value of the temperatures and need high resistance to creep, as well as oxidation and corrosion resistance, super alloys are widely used in gas turbine engines in which blades will face temperatures reaching if not exceeding their melting temperature[27,28]. Because of higher operating temperatures, modern jet engines are more powerful, demanding components of higher-performing. The use of super alloys will make it possible to raise the working temperature from 649 ℃ to 704 ℃. Higher temperatures result in decreased emissions, in addition to increasing performance and power output, since the combustion cycle is more complete [29,30]. Fig. 5 displays the places inside a jet engine where the hottest, highest pressure zones are manufactured from nickel-based super alloys.

3.4 Oil and Gas industry

In the oil and gas field, Ni-based super alloys are rapidly used in several applications. The conditions faced in the processing of natural gas and oil are often corrosive and difficult. There are also large concentrations of carbon dioxide, hydrogen sulfide, chlorine, and free sulfur. High temperatures and pressure up to 232°C can be faced in some of these conditions. Special materials are needed to extract natural gas and oil under these environmental conditions. 718, 725, and 925 nickel-based alloys are widely used in the processing of natural gas and oil. Molybdenum and Chrome and are found in these alloys that help prevent corrosion. Initially designed to apply in gas and aerospace turbines, Alloy 718 has been the chosen material for the wellhead parts manufacture, down-hole and auxiliary equipment, and safety valves sub-surface[31].

4.0 Conclusion

1- A superalloy is a metallic alloy engineered to bear most high temperatures values commonly up - to70% of the absolute melting point in several circumstances. All of these alloys have outstanding

resistance to cracking, oxidation, corrosion, as well as good fatigue life and surface stability[32].

2- The major alloying materials that can be established in the group of VIII of the elements in the periodic system, are copper, cobalt or nickel-iron. Most of them are used in the nuclear industries and aerospace, such as turbines. The expansion of these alloys allows turbines running at high temperatures to be best exploited via precipitation hardening and solid-solution and, Ni-super alloys can be improved [33].

3- Ni-based super alloys can be used at higher melting temperatures and are thus more favorable at working temperatures near the melting temperature of the components than I-N and Co-based and super alloys [34].

Conflicts of Interest

The author declares that they have no conflicts of interest.

5.0 References

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Table 1: Compositions of commercial Ni-based superalloys (wt. %, bal. Ni).

Alloy	Cr	Co	Mo	W	Ta	Re	Nb	Al	Ti	Hf	C	B	Y	Zr	Other
Conventionally Cast Alloys															
Mar-M246	8.3	10.0	0.7	10.0	3.0	—	—	5.5	1.0	1.50	0.14	0.02	—	0.05	—
Rene' 80	14.0	9.5	4.0	4.0	—	—	—	3.0	5.0	—	0.17	0.02	—	0.03	—
IN-713LC	12.0	—	4.5	—	—	—	2.0	5.9	0.6	—	0.05	0.01	—	0.10	—
C1023	15.5	10.0	8.5	—	—	—	—	4.2	3.6	—	0.16	0.01	—	—	—
Directionally Solidified Alloys															
IN792	12.6	9.0	1.9	4.3	4.3	—	—	3.4	4.0	1.00	0.09	0.02	—	0.06	—
GTD111	14.0	9.5	1.5	3.8	2.8	—	—	3.0	4.9	—	0.10	0.01	—	—	—
First-Generation Single-Crystal Alloys															
PWA 1480	10.0	5.0	—	4.0	12.0	—	—	5.0	1.5	—	—	—	—	—	—
Rene' N4	9.8	7.5	1.5	6.0	4.8	—	0.5	4.2	3.5	0.15	0.05	0.00	—	—	—
CMSX-3	8.0	5.0	0.6	8.0	6.0	—	—	5.6	1.0	0.10	—	—	—	—	—
Second-Generation Single-Crystal Alloys															
PWA 1484	5.0	10.0	2.0	6.0	9.0	3.0	—	5.6	—	0.10	—	—	—	—	—
Rene' N5	7.0	7.5	1.5	5.0	6.5	3.0	—	6.2	—	0.15	0.05	0.00	0.01	—	—
CMSX-4	6.5	9.0	0.6	6.0	6.5	3.0	—	5.6	1.0	0.10	—	—	—	—	—
Third-Generation Single-Crystal Alloys															
Rene' N6	4.2	12.5	1.4	6.0	7.2	5.4	—	5.8	—	0.15	0.05	0.00	0.01	—	—
CMSX-10	2.0	3.0	0.4	5.0	8.0	6.0	0.1	5.7	0.2	0.03	—	—	—	—	—
Wrought Superalloys															
IN 718	19.0	—	3.0	—	—	—	5.1	0.5	0.9	—	—	0.02	—	—	18.5Fe
Rene' 41	19.0	11.0	10.0	—	—	—	—	1.5	3.1	—	0.09	0.005	—	—	—
Nimonic 80A	19.5	—	—	—	—	—	—	1.4	2.4	—	0.06	0.003	—	0.06	—
Waspaloy	19.5	13.5	4.3	—	—	—	—	1.3	3.0	—	0.08	0.006	—	—	—
Udimet 720	17.9	14.7	3.0	1.3	—	—	—	2.5	5.0	—	0.03	0.03	—	0.03	—
Powder-Processed Superalloys															
Rene' 95	13.0	8.0	3.5	3.5	—	—	3.5	3.5	2.5	—	0.065	0.013	—	0.05	—
Rene' 88 DT	16.0	13.0	4.0	4.0	—	—	0.7	2.1	3.7	—	0.03	0.015	—	—	—
N18	11.2	15.6	6.5	—	—	—	—	4.4	4.4	0.5	0.02	0.015	—	0.03	—
IN100	12.4	18.4	3.2	—	—	—	—	4.9	4.3	—	0.07	0.02		0.07	

Table 2: Chemical Composition of Some Cobalt-Based Superalloys.

Alloy	C	Mn	Si	Cr	Ni	Mo	W	Fe	Co
X-45	0.25	.5	0.9	25	10	-	7.5	<2	Bal.
X-40	0.5	.5	0.9	25	10	-	7.5	<2	Bal.
FSX-414	0.35	.5	0.9	29.5	10	-	7.5	<2	Bal.
WI-52	0.45	.4	0.4	21	-	-	11	2	Bal.
Haynes -25	0.1	1.2	0.8	20	10	-	15	<3	Bal.
F-75	0.25	.5	0.8	28	<1	6	<.2	<0.75	Bal.
Haynes Ultimet	0.06	.8	0.3	25	9	5	2	3	Bal.
Co 6	1.1		0.8	29	<3	<1.5	5.5	<3	Bal.

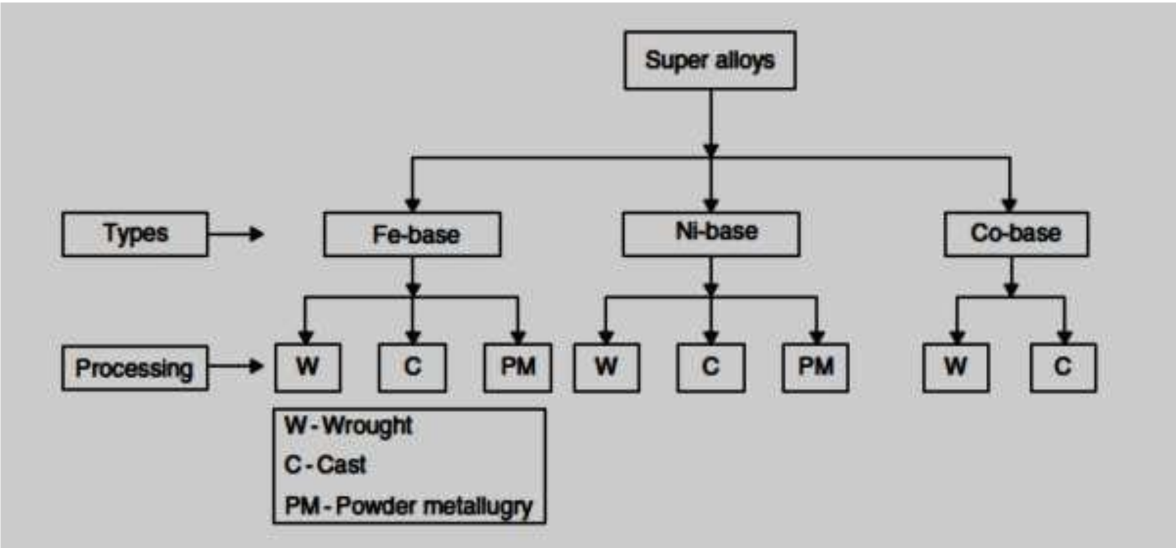

Figure 1 Classification of super alloys

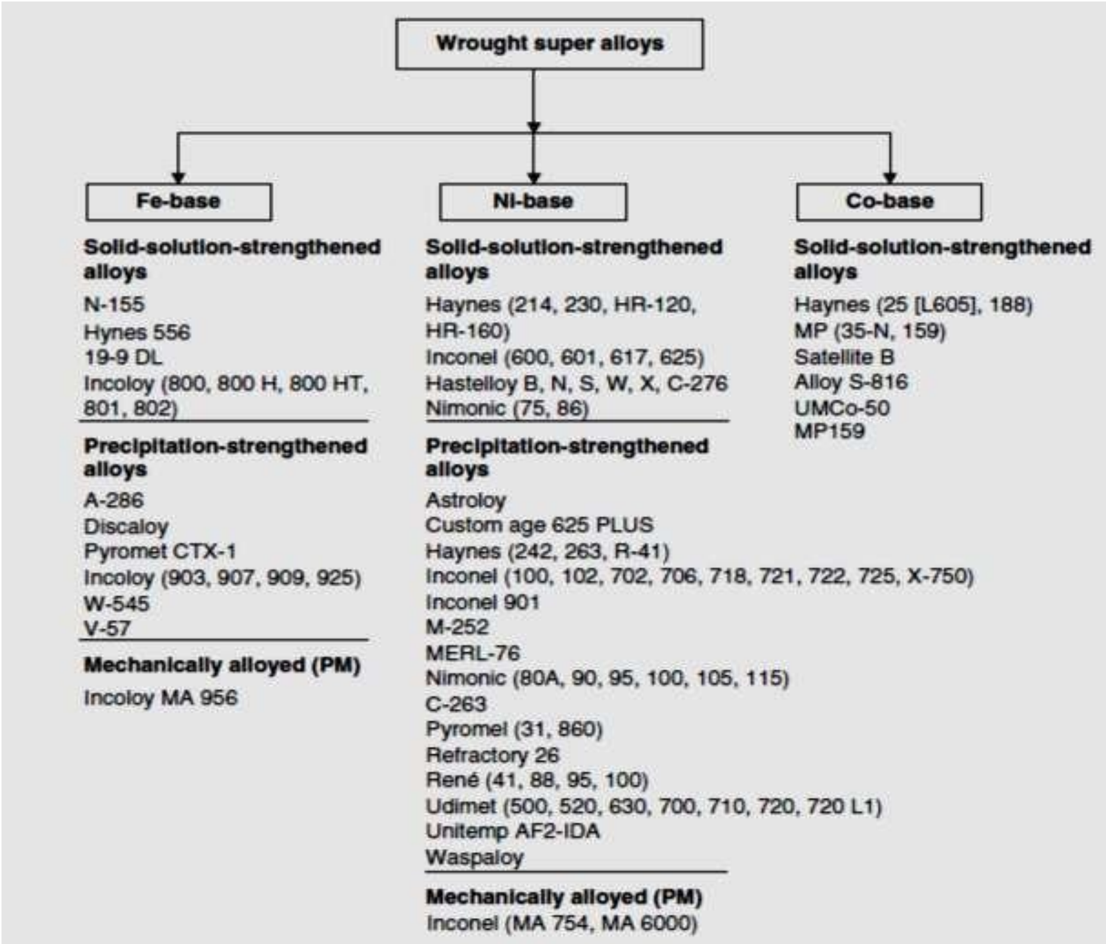

Figure 2 Commonly used wrought super alloys, as specified in their trade names.

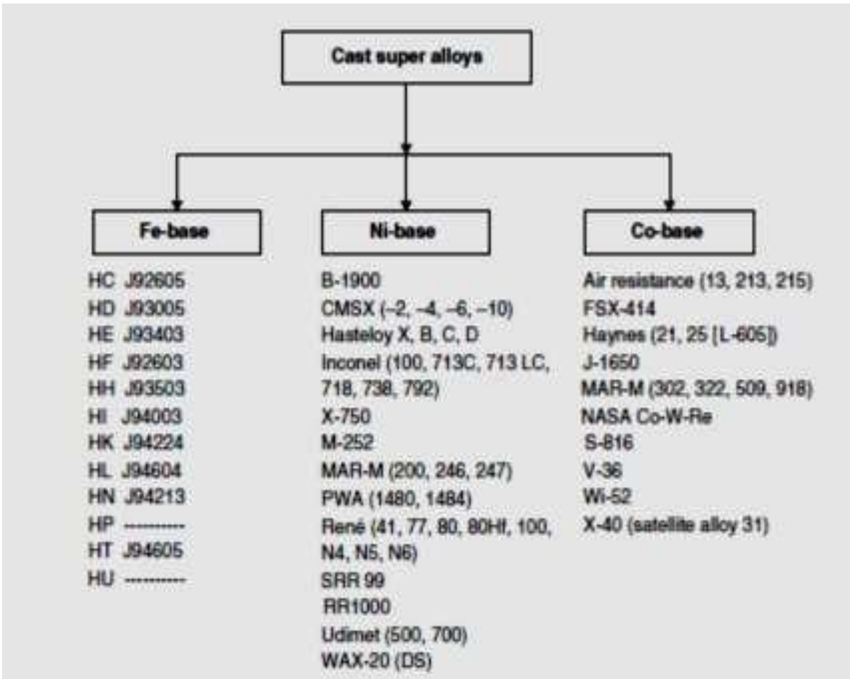

Figure 3 Commonly used cast super alloys, as specified in their trade names.

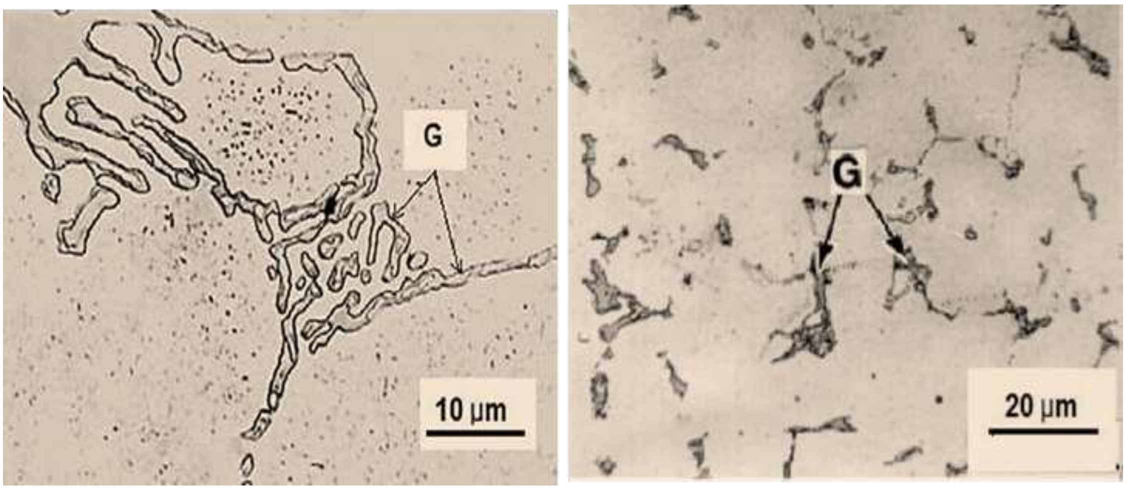

Figure 4: Optical micrograph of Haynes-25. G-mainly M6C carbides.

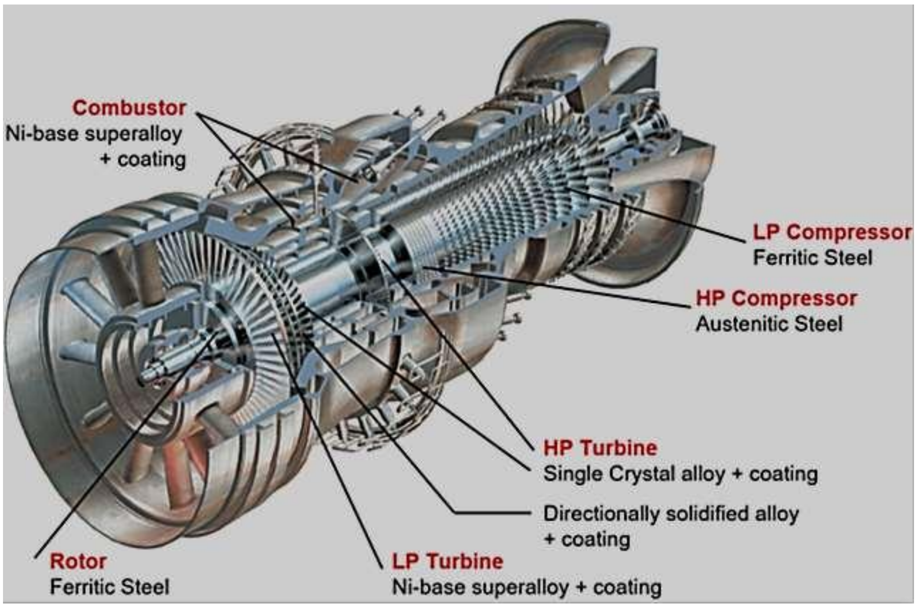

Figure 5: Material types used in different sections in an Alstom gas turbine engine.

مراجعة توصيف وتصنيفات وتطبيقات السبائك الفائقة

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الخلاصة

على مدار الخمسين عامًا الماضية، كان تطوير السبائك الهندسية عالية الحرارة هو المحرك الأساسي لزيادة درجات حرارة التشغيل للمواد المستخدمة في محركات التوربينات الغازية. وقد أدى ذلك إلى تحسينات كبيرة في كل من قوتها وكفاءتها. تم التوصل الى أن زيادة درجة حرارة تشغيل المحرك بمقدار 170 درجة مئوية تعمل على تحسين قوة دفع المحرك بنسبة 5٪ والكفاءة بنسبة 1٪. يجب أن تتحمل المواد المستخدمة في ريش التوربينات الموجودة في الاجزاء الساخنة لمحركات التوربينات الغازية غازات المحرك شديدة الحرارة، وبيئة مؤكسدة ومعرضة للتآكل، وأحمال طرد مركزي كبيرة، وتأثيرات أجسام غريبة عالية السرعة. لذلك يجب أن تمتلك مواد الريش التوربينية توازنًا بين مقاومة درجات الحرارة العالية والمتانة والأكسدة ومقاومة التآكل.

السبائك الفائقة هي الفئة الرئيسية من المواد المستخدمة للمكونات ذات درجة الحرارة المرتفعة في حقيقة أنها المواد المتاحة تجاريًا الوحيدة التي تحتفظ بخصائصها الميكانيكية ومقاومة التآكل / الأكسدة في درجات حرارة عالية (تصل إلى 0.9 من درجة الانصهار للمعدن الاساس) هناك ثلاثة اصناف رئيسية من السبائك الفائقة وهي: السبائك الفائقة ذات اساس نيكل، والسبائك الفائقة ذات اساس الكوبالت، والسبائك الفائقة ذات اساس حديد. تُستخدم السبائك الفائقة حاليًا في العديد من المجالات ذات درجات الحرارة المرتفعة من التوربينات الغازية المستخدمة في الطائرات والتطبيقات البحرية والصناعية إلى المركبات الفضائية والمفاعلات النووية ومحطات الطاقة البخارية والمعدات البتروكيماوية. أكبر مستهلك للسبائك الفائقة اليوم هو صناعة محركات التوربينات الغازية للطائرات. في هذا التقرير، قدمت كل مجموعة من السبائك الفائقة بإيجاز حول خصائصها الرئيسية والمكونات الكيميائية. أخيرًا، تم توضيح استخدامات التصنيع الخاصة بهم.

الكلمات الدالة: السبائك الفائقة، السبائك الفائقة ذات اساس النيكل، السبائك الفائقة ذات اساس لكوبلت، السبائك الفائقة ذات اساس حديد، السبائك عالية الحرارة، التطبيقات الرئيسية للسبائك الفائقة.