

# **INCONEL Alloy 706**

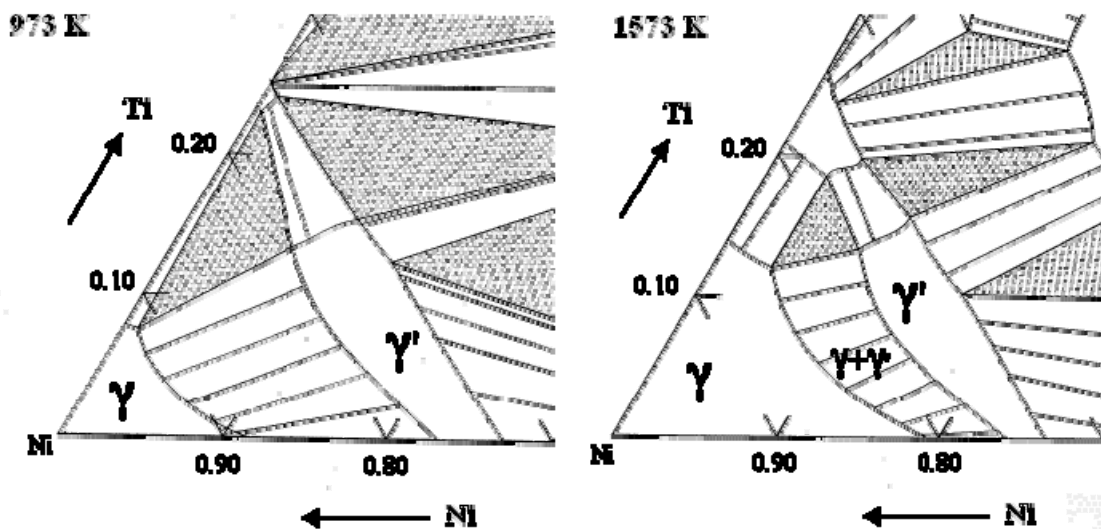
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The INCONEL 706 superalloy is derived from the INCONEL 718 superalloy composition in order to improve the producibility of large forgings for gas turbines. It is a precipitation-hardenable alloy with its primary constituents consisting of niobium and titanium. With a balanced content of nickel, chromium and aluminum, alloy 706 provides good hardenability and resistance against oxidation and corrosion. It displays excellent mechanical strength in combination with good fabricability, and is easier fabrication than 718, particularly by machining. In addition, there is a delayed hardening response during exposure to precipitation temperatures, which gives the alloy excellent resistance to postweld strain-age cracking. This alloy is used for applications requiring high strength and ease of fabrication, such as turbine discs, shafts, diffuser cases, compressor discs and shafts, engine mounts, and fasteners, which are related to the Aerospace field as well as turbine discs in industrial gas turbines (1).

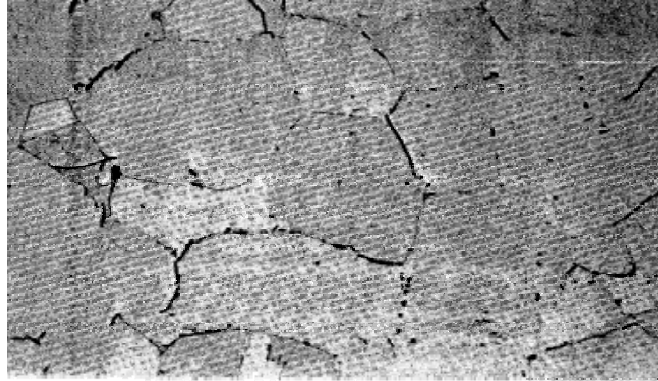
### Microstructure of IN 706

A superalloy is a metallic alloy primarily used for high temperatures applications in which creep and oxidation resistance are the main design criteria. Aluminum and Titanium are the vital solutes in nickel-based superalloys. They make up a total concentration of typically less than ten atomic percent, and generate a two-phase equilibrium microstructure, consisting of gamma ( $\gamma$ ) and gamma-prime ( $\gamma'$ ). The  $\gamma'$  phase contributes to the material's astonishing resistance to creep deformation and elevated temperature strength, and is dependent on the chemical composition and temperature as shown in Figure 1 (2).



**Figure 1-** Ni-Al-Ti Ternary Phase Diagram

The nickel-iron base superalloy 706 has commendable high temperature strength due to precipitation hardening by coherent intermetallic particles of  $\gamma'$  and  $\gamma''$  phases (3). Figure 2 shows the typical microstructure of the commercial 706 Alloy (4).



**Figure 2-** Typical Optical Microstructure of Alloy 706

This sample was heat treated using the suggested commercial heat treatment consisting of the following process (4, 5):

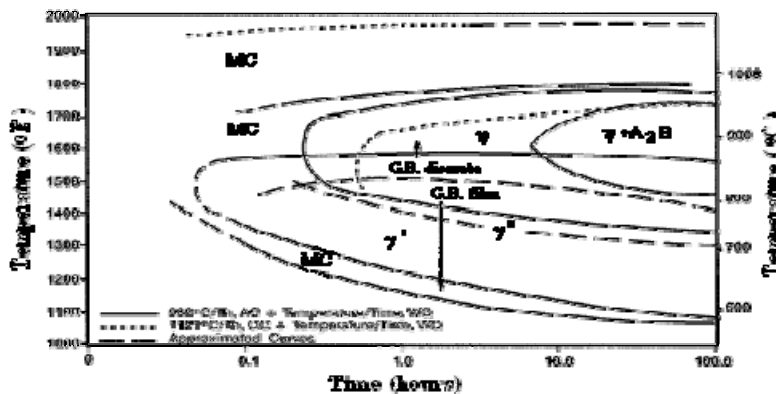
1. Solution Treatment- 1800°F (980°C)/ 1 hr/ air cool
2. Stabilization Age- 1550°F (845°C)/ 3 hrs/ air cool
3. Final Age- 1325°F (720°C)/ 8 hrs/ cool 100°F (55°C)/hr to 1150°F (620°C)/ 8 hrs/ air cool.

Table 1 displays the major phases and typical morphologies found in Alloy 706 (6).

**Table 1-** Major Precipitating Phases found in Alloy 706

Precipitating Phase	Composition	Structure	Morphology
$\gamma'$	$Ni_3(Al, Ti)$	Ordered FCC	Spheres
$\gamma''$	$Ni_3Nb$	Ordered BCT	Disks
Laves	$(Fe, Ni)_2Nb$	HCP	Globular
$\eta$	$Ni_3Ti$	HCP	Platelets/ Cellular

The microstructure reveals relatively coarse austenite grains ( $\gamma$  phases),  $\gamma'$  phases,  $\gamma''$  phases, a few MC type carbides, Laves,  $\eta$  phases, and some unresolved grain boundary constituents (4, 5, 6). Figure 3 reveals the TTT diagram for Alloy 706 (7).



**Figure 3-** Time-Temperature-Transformation Diagram for Alloy 706

The principal age hardening phase,  $\gamma'$ , forms by heat treating at or below  $\sim 1300^{\circ}\text{F}$  ( $705^{\circ}\text{C}$ ) and has a spherical shape with an ordered FCC  $L1_2$  crystal structure. This phase can transform into a more stable  $\eta$  phase, in the form of coarse platelets, either in cellular colonies growing from grain boundaries or as an intergranular Widmanstatten structure by receiving extended exposure to temperatures above  $\sim 1200^{\circ}\text{F}$  ( $650^{\circ}\text{C}$ ) (6).

The primary strengthening phase was identified to be the  $\gamma''$  phase, which precipitates by heat treating between  $\sim 1300^{\circ}\text{F}$  ( $705^{\circ}\text{C}$ ) and  $\sim 1400^{\circ}\text{F}$  ( $760^{\circ}\text{C}$ ), and has a disc shape with an ordered BCT  $\text{DO}_{22}$  crystal structure. This phase is in conjunction with the onset of titanium-rich  $\eta$  phase precipitation and seems to transform into the  $\eta$  phase along with the presence of  $\gamma'$  particles (6).

Electron metallographic studies showed that the stabilization treatments for the commercial 706 Alloy resulted in extensive precipitation of cellular and needle-like constituents. These constituents were identified as orthorhombic  $\text{Ni}_3\text{Cb}$  and hexagonal  $\text{Ni}_3(\text{Ti}, \text{Nb})$  ( $\eta$ ) phases. Although Alloys 706 and 718 are similar, the presence of the  $\eta$  phase has not been found in Alloy 718. However, these  $\eta$  phases are known to precipitate in many other Fe-Ni-base superalloys, such as Alloy 901 (4, 5).

Other phases formed by Alloy 706 are the Laves phases and the niobium and titanium rich MC carbides. The Laves phases are hexagonal  $\text{Fe}_2\text{Nb}$  C36 crystal structures which usually look microstructurally like coarse grain boundary  $\eta$  particles. These phases occur after extended exposure to temperatures of  $\sim 1600^{\circ}\text{F}$  ( $870^{\circ}\text{C}$ ) to  $\sim 1700^{\circ}\text{F}$  ( $925^{\circ}\text{C}$ ). The niobium and titanium rich (FCC) MC carbides form as very fine precipitates mainly on grain boundaries during processing and aging heat treatments. It has been reported that small amounts of  $\text{M}_{23}\text{C}_6$ ,  $\text{M}_3\text{C}$ ,  $\text{NbN}$ , or  $\text{Nb}(\text{C}, \text{N})$  type phases may also be present (6).

Ideal strength is achieved when a fine dispersion of  $\gamma''/\gamma'$  is formed in the alloy and finally stabilized. The final age treatment provides exceptional strength properties in less time with less probability of overaging to intragranular  $\eta$  phases than if a longer isothermal heat treatment were used. A third step treatment of  $1550^{\circ}\text{F}$  ( $845^{\circ}\text{C}$ ) / 3 hrs is inserted between the anneal and the first aging step when maximum stress rupture strength is needed. This step precipitates discontinuous grain boundary  $\eta$  phases that improve notch ductility near the  $\gamma''/\gamma'$  solvus (6).

### **Alloy Chemistry**

INCONEL Alloy 706 was developed in the late 1960's in order to satisfy metallurgical requirements for large forged gas turbine components (6, 7). This alloy, along with Alloys 718 and 625, evolved from studies performed at the International Nickel Company (INCO) in an attempt to investigate the strengthening effects of various common alloy elements, such as Cr, Mo, Nb, Al, and Ti, from the base metal Alloy 600. Table 2 shows the nominal compositions of these alloys (8).

**Table 2-** Nominal Compositions of Related Alloys

<b>Alloy</b>	<b>Al</b>	<b>C</b>	<b>Cr</b>	<b>Fe</b>	<b>Mn</b>	<b>Mo</b>	<b>Nb+Ta</b>	<b>Ni</b>	<b>Si</b>	<b>Ti</b>
600	-	0.08	15.5	8.0	0.5	-	-	76.0	0.2	-
625	0.2	0.05	21.5	2.5	0.2	3.0	3.6	61.0	0.2	0.2
718	0.5	0.04	19.0	18.5	0.2	9.0	5.1	52.5	0.2	0.9
706	0.2	0.03	16.0	40.0	0.2	-	2.9	41.5	0.2	1.8

### **Melting/ Casting Methods**

In order to prevent the formation of melt-related defects, significant enhancements to the historical melting technology were made for the development of large, high quality Alloy 706 ingots. Based on previous work done on Alloy 718, a triple melt process consisting of vacuum induction melting (VIM), electroslag remelting (ESR), and vacuum arc remelting (VAR) was utilized. The VIM process produces a clean starting material with a well-controlled chemistry. The ESR process supplies some refining of the metal and a sound electrode which remelts in the VAR furnace with minor potential for melting anomalies. For the final melting operation, the VAR process was selected because the shallow melt pools produced by this process make it the least likely to cause segregation-related defects (8).

### **Forging Methods**

It requires several steps to succeed in the forging of turbine disks. These steps involve the performance of multiple upset and draw operations of the ingot in order to break up the initial large as-cast grain size. Maintaining the working of all forging areas and avoiding die lock involves the use of special handling and lubrication. This is a significant step due to the excess large as-cast structures that may not get refined during the final forging operation. Tests have revealed that fatigue crack growth rates in large grains can be as much as three times higher in comparison to the surrounding fine grained matrix (8).

### **Heat Treatments**

Alloy 706 is mainly used in a solution treated and aged condition (8). The heat treatments are designed to produce either high tensile properties for room and moderate temperature applications or high stress-rupture properties for applications up to 1300°F (705°C). The typical commercial heat treatment given to the alloy for optimum creep and rupture properties is as follows (1):

#### **Heat Treatment A**

1. Solution Treatment- 1700-1850°F (925-1010°C) for a time commensurate with section size, air cool
2. Stabilizing Treatment- 1550°F (845°C)/ 3 hr, air cool
3. Precipitation Treatment- 1325°F (720°C)/ 8 hr, furnace cool at 100°F (55°C)/hr to 1150°F (620°C)/ 8 hr, air cool

The typical commercial heat treatment for tensile-limited applications is (1):

### Heat Treatment B

1. Solution Treatment- 1700-1850°F (925-1010°C) for a time commensurate with section size, air cool
2. Precipitation Treatment- 1350°F (730°C)/ 8 hr, furnace cool at 100°F (55°C)/hr to 1150°F (620°C)/ 8 hr, air cool

These heat treatments are based on metal temperatures and are derived from batch rather than continuous furnace operations (1).

### Chemical, Physical, Thermal, and Mechanical Properties

The characteristics of Alloy 706 are achieved by the limiting chemical composition listed in Table 3. The considerably large amounts of nickel and chromium contribute to oxidation and corrosion resistance. Niobium and titanium provide the dominant precipitation-hardening properties, in addition to aluminum (1).

**Table 3-** Chemical Composition of INCONEL Alloy 706

Element	Composition (%)
Aluminum	0.40 max
Boron	0.006 max
Carbon	0.06 max
Chromium	14.5-17.5
Cobalt	1.00 max
Copper	0.30 max
Iron	Balance
Manganese	0.35 max
Nickel (plus Cobalt)	39.0-44.0
Niobium (plus Titanium)	2.50-3.30
Phosphorous	0.020 max
Silicon	0.35 max
Sulfur	0.015 max
Titanium	1.50-2.00

Table 4 and Table 5 contain a list of physical, thermal, and electrical properties of the Alloy 706 that were determined for a precipitation-hardened material (1).

**Table 4-** Physical Constants of INCONEL Alloy 706

<b>Density</b>	
Annealed, lb/in <sup>3</sup>	0.291
Mg/m <sup>3</sup>	8.05
Precipitation-Hardened, lb/in <sup>3</sup>	0.292
Mg/m <sup>3</sup>	8.08
<b>Melting Range, °F</b>	
	2434-2499
°C	
	1334-1371
<b>Specific Heat, 70°F, Btu/lb*°F</b>	
	0.106
21°C, J/kg*°C	
	444
<b>Permeability at 200 oersted (15.9kA/m)</b>	
Annealed	
74°F (23°C)	1.011
-109°F (-78°C)	1.020
-320°F (-196°C)	Magnetic
Precipitation-Hardened	
74°F (23°C)	1.010
-109°F (-78°C)	1.040
-320°F (-196°C)	Magnetic
<b>Curie Temperature, °F</b>	
	<-109
°C	
	<-78

**Table 5-** Thermal Properties of INCONEL Alloy 706

Temperature	Specific Heat	Electrical Resistivity	Thermal Conductivity	Coefficient of Expansion
°F	Btu/lb*°F	Ohm*circ mil/ft	Btu*in/ft <sup>2</sup> *hr*°F	10 <sup>-6</sup> in/in/°F
-320	-	527	55	-
70	0.106	592	87	-
200	0.110	610	96	7.40
300	0.113	622	103	7.83
400	0.117	635	110	8.07
500	0.120	647	117	8.25
600	0.124	659	124	8.42
700	0.127	671	130	8.50
800	0.131	683	136	8.57
900	0.134	695	141	8.64
1000	0.138	707	147	8.73
1100	0.141	717	152	8.84
1200	0.145	-	-	8.97
1300	0.148	-	-	9.11

The precipitation-hardened Alloy 706 maintains its high strength at temperatures of up to 1300°F (705°C). Heat treatments A and B contribute to the optimal mechanical properties for the designated service temperature. Table 6 contains a list of the modulus of elasticities and Poisson's ratios at different temperatures (1).

**Table 6-** Modulus of Elasticity and Poisson's Ratio

Temperature	Tensile Modulus	Shear Modulus	Poisson's Ratio
°F	10 <sup>3</sup> ksi	10 <sup>3</sup> ksi	-
-320	31.6	11.6	0.362
70	30.4	11.0	0.382
200	29.9	10.8	0.387
400	29.0	10.4	0.393
600	27.9	10.0	0.395
800	27.0	9.6	0.405
1000	25.9	9.3	0.395
1200	24.7	8.8	0.403
1300	24.0	8.5	0.417

A list of forged disc tensile properties is given in Table 7. Each specimen from the three different heat treatments was tested at room temperature and 1200°F (650°C) (1).

**Table 7-** Forged Discs Yield Strength and Tensile Properties

Temperature		Heat Treatment	Tensile Strength		Yield Strength (0.2% Offset)		Elongation	Reduction of Area
°F	°C		ksi	Mpa	ksi	Mpa		
		-						
70	20	Solution Treated	108.0	745	41.7	288	50	55
70	20	A	180.5	1245	142.0	979	17	19
1200	650	A	143.5	989	119.5	824	21	27
70	20	B	183.0	1262	157.4	1085	22	43

### **Stress Accelerated Grain Boundary Oxidation (SAGBO)**

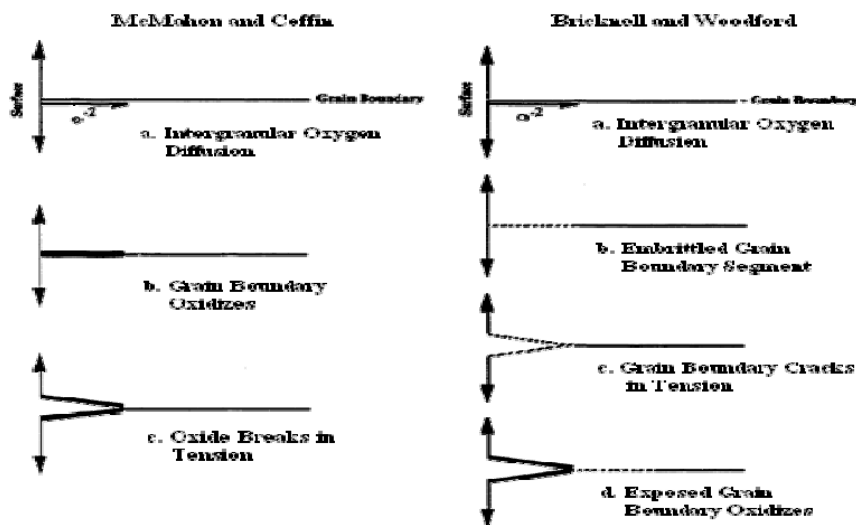
When exposed to oxygen, nickel-iron based superalloys are susceptible to embrittlement. This usually occurs at a temperature range of one-third or one-half their melting temperatures. These alloys frequently experience high stresses and fatigue loadings when put into service, therefore, causing combined effects of residual (plastic) stress or imposed stress, high temperature, and the presence of oxygen (9). These effects can lead to environmentally induced intergranular cracking, which belongs to a class known as stress accelerated grain boundary oxidation (SAGBO) (10).

SAGBO is a subclass of stress corrosion cracking (SCC). SCC occurs when there is a cumulation of a susceptible material, high tensile stress, a corrosive environment, and is usually path specific. Highly stressed components such as pressure vessels and turbines have all detected some form of SCC. Service along with part production, including welding, can be factors contributing to the stresses that cause SCC. However, SCC occurrence is limited to certain conditions. These conditions require a pairing of materials and environments above a certain tensile stress level. In industry, the main concerns with SCC include the structural components in long-time service made of stainless steels and superalloys. In an environment with high temperature and the presence of oxygen, the SCC in the stainless steel components increases along with the superalloy components which get endangered by hydrogen embrittlement (9, 10).

SAGBO involves the embrittlement along the grain boundaries due to oxygen diffusion which causes cracking (9). Its main limitation is in the use and fabrication of low coefficient of thermal expansion nickel-iron base superalloys. Typical characteristics of SAGBO are preferential oxide formations along grain boundaries, decreased stress rupture life in the 550-800°C temperature range in air, and intergranular cracking of notched sections in stress rupture specimens or in bend sections of U-bend samples. Varying depths of internal oxidation along with preferential oxidation of grain boundaries within the internally oxidized region are produced by high temperature (>900°C) air exposure to unstressed low coefficient of thermal expansion nickel-iron base superalloys (10).

### SAGBO Mechanisms

There have been two proposed mechanisms by McMahon and Coffin (11) and Bricknell and Woodford (12). McMahon and Coffin proposed the mechanism that suggests the oxidation of grain boundaries precedes crack growth, as oppose to Bricknell and Woodford, whose mechanism suggested that oxygen embrittlement of grain boundaries precedes crack growth (11, 12). Figure 4 shows a comparison of the two mechanisms (9).



**Figure 4-** Schematic Comparison of Proposed SAGBO Mechanisms

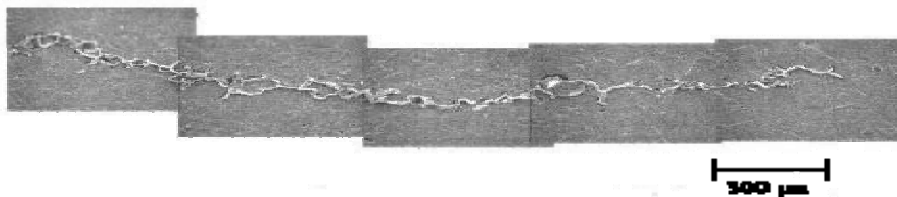
### **Remedial Actions for SAGBO**

There are several remedies for the SAGBO phenomenon which can be categorized into two main groups. One group deals with the residual tensile stress during the production of the conduits, and the other group addresses the oxygen issue. These remedies include reduction of applied tensile stress, reduction of oxygen content, modification of chemical composition, modification of microstructure, thermomechanical processing, and oxidation resistant coatings (9).

### **SAGBO in INCONEL Alloys 718 and 706**

It has been reported that SAGBO is responsible for much of the intergranular cracking occurring in INCONEL alloys 718 and 706 at elevated temperatures (13, 14). After a two step heat treatment involving solution annealing at 990°C for 10 hours followed by oil quenching, and then precipitation hardening at 730°C for 16 hours followed by furnace cooling to 620°C for 16 hours followed by air cooling, indications of a drop in ductility under constant slow strain rate tests revealed SAGBO effects in the INCONEL Alloy 706 at a temperature range of 650-700°C (14).

Figure 5 shows evidence of SAGBO-induced creep crack growth in Alloy 718, which occurred in several tests performed on single edge-notched tension specimens (13).



**Figure 5-** SAGBO-Induced Creep Crack Growth in Alloy 718

In conclusion, INCONEL Alloy 706 is a precipitation-hardenable alloy with excellent mechanical strength, good fabricability and resistance against oxidation and corrosion. Stress Accelerated Grain Boundary Oxidation (SAGBO) in Alloy 706 has been reported as the cause of cracking in the gas turbine discs.

## References

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