A review on processing and effect of thermal treatment on machinability of nickel-based superalloy

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Abstract: **Super alloys are advanced high-temperature functional materials, which maintain higher strength at elevated temperatures, microstructural stability and high resistance to oxidation under corrosive environment. This paper presents a general review on classification, characteristic properties, and development of microstructural stabilities of Super alloys at high temperature. This paper also explains the influence of processing techniques; strengthen mechanism on mechanical properties together with machinability characteristics.**

Keywords: **Nickel-based alloys; processing techniques; Mechanical Properties; Machinability characteristics**

1. INTRODUCTION

Materials played vital role in way of living life. With the advancement of technology, development and utilization of new materials augmented in different energy sectors. High temperature performing materials in power generation industries, turbo super chargers and aircraft turbine engines needed evolution of new materials[1]. Materials used for high temperature applications require good thermal, mechanical properties, high adequate corrosive resistance and fatigue resistance[2]–[5].Gas turbine engine consists of compressor, combustion chamber and turbine. Components used in gas turbine engine are exposed to extreme conditions i.e. high temperature, corrosive environment of gasses, vibrations and high mechanical loads[6]. Turbine blades are exposed to high temperature around 800^{o}C as well as corrosive environment due to combustion of gasses[7]–[9] The compressor blades and vanes are subjected to centrifugal force and fluctuating loads. Rotating discs must have high load bearing capacity to hold the blades against centrifugal force[10]. Structural deformation occurs due to thermal energy along with loads. Microstructural stability at ambient atmosphere is highly essential. The Amount, size, shape, distribution of phases influences on characteristics properties of materials. Presence of Cr_2O_3, Al_2O_3 forms thin and continuous oxide layer. It is impermeable to oxygen and enhances oxidation resistance. The stability of oxide layer is also influenced by the addition of other alloying elements like boron, yttrium, silicon etc. Addition of these alloying elements promotes the formation of adhesive protective layer.

1.1 Nickel based super alloys:

These are categorized as advanced engineering materials, since they are used for high temperature applications like aircraft, gas turbines, rocket engines, chemical and petroleum industries[11]. Ni based super alloys have emerged as choice for high temperature applications as compared to Fe and Co based super alloys[12]. Addition of alloying elements like Cr, Co, Fe, Mo, W, Ti, Al, Nb to Ni help the material to control properties for high temperature applications. These materials can be strengthened by solid solution strengthening and precipitation hardening methods.

Cobalt based super alloys are having superior hot corrosion resistance, thermal fatigue resistance; good weldable over Nickel based super alloys. However Co based super alloys having its own demerits[13]. The stress rupture strength of Co based super alloys is low and flatter up to 930 ^{0}C due to unstable micro structure. This makes unsuitable to use in hot chambers of turbine engine. Ni based super alloys are emerged as choice of high temperature applications. Nickel based super alloys consists of austenitic matrix phase(ϒ FCC)and other elements Co,Cr,Mo,W,Fe are ϒ forming elements, partition to the matrix of ϒ. Al,Nb,Ti,Ta,Hf forms ϒ' and other elements Cr, Mo,W,Nb,Ta,Ti forms carbides.

Table.1 Show some important Ni based super alloys, chemical composition, properties and applications.[13]–[15]

S. No.	Alloy	chemical composition	Properties	Applications
1	Inconel 600	76Ni-15Cr-8Fe	Elastic modulus160 GPa and YS 421 MPa at 760^{0}C,Creep strength - 234 Mpa ,Stress rupture strength σ =96Mpa at 816 ^{o}c	Construction for nuclear reactors, chemical industry for heaters, condensers, heaters

2	Nimonic alloy 75	Ni-Cr-Ta	Elastic modulus 206Gpa,T.S 750Mpa, YS 275 MPa	Gas turbine engines, heat treatment equipments
3	Nimonic alloy 90	54Ni,Cr18-20%Co-15-20%Ti2-3%, Al 1-2%	At 1000 ^{0}C, T.S 76Mpa, Y.S 48Mpa.	Turbine blades, discs, forgings, hot working tools
4	Rene N6	4Cr-12Co-1Mo-W6-Ta7-Al5.8-Hf0.2-Re5-Balance Ni	Creep rupture life 1100 Hrs at 1000 ^{0}C	Jet engines, low pressure and high pressure turbine blades
5	WASP alloy	60Ni-19Cr-4Mo-3Ti-1.3Al	At 1000 ^{0}C, Elastic modulus146GPa, YS-982MPa	Jet engines, gas turbine blades
6	TMS-162	Co-5.8,Cr-2.9,W-3.9,Al-5.3,Ta-5.8	At 1100 ^{o}C 137Mpa, creep rupture life 957Hr.	Turbine blades

Nimonic alloy is having high temperature strength and corrosion resistance than Inconel. These materials are used for military and commercial application in the form of single crystalline, poly crystalline or columnar structure. Addition of Co to Nimonic 80A increases creep resistance by 50 ^{o}C. Rhenium and Hafnium and Ruthenium obtain excellent creep resistance, but use of this alloy is limited due to more density and higher cost. Small increase in weight increases overall system weight i.e. shaft, disc, and blades. It reduces the fuel efficiency. Rene alloy, and TMS-173 alloys are precipitation hardened alloys used for special applications. Solid solution strengthening effect further enhanced by addition of Mo, Ti, Al. Wasp alloy is generally used for gas turbine engine parts, compressors and rotor discs, shafts, fasteners and other miscellaneous engine, spacers, seals, rings and casings, hardware, airframe assemblies and missile systems[16]. It has high resistance to corrosion at high temperature (950^{o}C-1083 ^{o}C) and be able to withstand frequent thermal cycling. Solution treated WASP alloy offers best oxidation resistance. Performance of Ni based super alloys are not only a function of composition but also function of method of melting, hot working conditions and optimization of heat treatment processes[17].

2. PROCESSING TECHNIQUES

Improvement in solidification processing techniques from equiaxed grains –directional solidification - single crystalline materials, leads to withstanding high temperature. Processing of single crystalline casting eliminate weaker grains and grain boundaries. In addition to that addition of grain boundary strengtheners like C, B, Si, Zr are eliminated in this process. It raises melting point and homogenization of solutionizing temperature of single crystalline blades.

The vacuum induction melting process (VIM) is the primary melting process, which reduces interstitial gases i.e. oxygen and nitrogen to low levels in the melt. Ultimately slag and dross formation is less in VIM process than air melting. During VIM process segregation and chemical in homogeneity and slag inclusions are higher. Secondary melting processes are Vacuum arc remelting process (VAR)and electro slag arc remelting processes (ESR).These are generally used for eliminate segregation and chemical inhomogeneity. Presence of non metallic inclusions reduces the fatigue properties. In ESR process, sulfur and oxides are reacting with molten metal droplets passing from electrode to weld pool eliminate the impurities present in the electrode.

3. STRENGTHENING METHODS OF SUPER ALLOYS

Super alloys are strengthened by a) Solid solution strengthening b) Precipitation hardening.

3.1 Solid solution strengthening:

Solute atom replaces the solvent atom, which produces elastic strain field surround the solute atom causes lattice distortion. Distorted lattice structure resist the movement of dislocations and hence increase in strength. Two mechanisms are involved a) Dislocation locking i.e interaction of stationary dislocations with solute b) dislocation friction i.e. interaction of gliding dislocation with solute. Dislocation locking depends on a) size of the solute atom b) concentration of solute atoms c) shear modulus and valance of solute atom. Lattice distortion (Ɛa) increases with increase in size difference. Ɛa=$\frac{\Delta a}{a\Delta c}$, Ɛa, Δa,Δc are the lattice distortion, difference in size, change concentration of solute and solvent atoms respectively.

As the solute concentration increases;

i. Change in binding energy between solute and adjacent solvent atoms causes the localized change in shear modulus (ε_G).The interaction of dislocations with solute atoms enhances the shear modulus. $\varepsilon_G=\frac{\Delta G}{G\Delta c}$ where G is shear modulus of material.
ii. The stacking fault energy decreases and separation of partial dislocations increase due to segregation of solute atoms at preferential sites of HCP. There is a frictional force exist between solute atom and dislocations due to pinning of dislocations. The yield strength of the materials increases with the number of obstacles interacts with dislocations. $\Delta\tau = Gb\,\varepsilon^{3/2}\sqrt{C}$ b is the magnitudeof the burgers vector. $\Delta\tau$ Isthe change in shear stress, C is the concentration of the solute.

Dislocation friction; during gliding of dislocations, there is a frictional force existing between solute atoms and dislocations. As the solute concentration increase number of obstacles increase Frictional force increase with increase in concentration i.e. solute concentration

3.2 Precipitation hardening:

Precipitation hardening is the process of a) Solutionizing b) quenching c) ageing. Ni based super alloy is heated to above the solvus line to dissolve alloying elements Al,Ti,Nb,Ta,Hf in the matrix of ϒ. Quenching of this alloy, produce super saturated solid solution. During ageing, thermal decomposition of the alloy occurs at elevated temperature. It produces coherent Ni_3 (Al,Ti) precipitate at the grain and grain boundary interface regions. Precipitation of these particles impede the movement of dislocations enhances the strength of the material. Amount, size, shape and distribution of second phase particles influence on mechanical property of material. Precipitation is nucleation and growth process. Heterogeneous nucleation occurs in a super alloy due to presence of carbides at high energy grain boundaries than grains.

Super alloys are difficult to machining due to presence of intermetallic compounds and high work hardening rate[4]. Not only that, it reduces the production efficiency owing to limited cutting speed. PCBN tools can be used up to cutting speed 90-120 m/min. The reason attributed that the chemical reactivity of CBN with other alloying additions Fe, Co, Ni, increases the tool wear rate. High Cutting forces generate more heat at the tool tip reduces the cutting speed. Low thermal conductivity of these alloys also restricts the amount of heat transfer at the tool tip results increase in temperature, which increases tool wear rate. Machinability of a material is also affected by the method of manufacturing and heat treatment process[18][19].

The properties of Ni-based alloys contributing to poor machinability may be summarized as follows:

(i) A major part of their strength is maintained during machining due to their high temperature properties.
(ii) Work hardening occurs rapidly during machining, which is a major factor contributing to notch wear at the tool nose and: or depth of cut line.
(iii) Cutting tools suffer from high abrasive wear owing to the presence of hard abrasive carbides in the super alloy
(iv) Chemical reaction occurs at high cutting temperatures when machining with commercially available cutting tool materials, leading to at high diffusion wear rate [20]
(v) Welding: adhesion of nickel alloys onto the cutting tool frequently occur during machining, causing severe notching as well as spalling on the tool rake face due to consequent pull-out of the tool materials[21]
(vi) Production of a tough and continuous chip, which is difficult to control during machining, thereby contributing to the degradation of the cutting tool by seizure and cratering.
(vii) The poor thermal diffusivity of nickel-based alloys often generates high temperature at the tool tip as well as high thermal gradients in the cutting tool of factors impairing the machinability of nickel based alloys, short tool life and severe surface abuse of machined workpiece are the most important consideration[22].

Aging is the heat treatment process in which precipitation of second phase particles resist the movement of dislocations and improves the high temperature properties[22].The size, morphology and distribution of coherent or semi coherent precipitate influence on machining characteristic[23].The machining operation of super alloy after solutionized treatment, produce rough surface. The reason behind that, all insoluble carbides may dissolve in matrix, produces soft and gummy structure. Instead of cutting it will push the tool bit and it cause overheating. The work hardening capacity of solutionized state of super alloy is higher than the aged condition. This reduces the machinability and produces the rough surface[24]. Age hardened material alters the microstructure. Precipitation of sub microscopic particles, morphological change of precipitate, grain size and improvement in hardness increase the machinability.

IV.CONCLUSION

1) Nickel based super alloys are chosen as advanced high temperature resisting material than cobalt based super alloys. Addition of other alloying elements increases creep resistance and oxidation resistance.

2) Wasp alloy is age hardenable alloy, precipitation of Ni_3Al at grain boundaries retains high strength and corrosion resistance at high temperature as compared to other group of nickel based alloys.

3) Even though nickel based super alloys are exceptionally hard, machinability is poor due to high work hardening rate. Age hardened material alters the microstructure. Precipitation of sub microscopic particles, morphological change of precipitate, grain size and improvement in hardness increase the machinability.

REFERENCES

[1] G. Srinivas, K. Raghunandana, and B. Satish Shenoy, “Recent developments in turbomachinery component materials and manufacturing challenges for aero engine applications,” *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 314, no. 1, 2018.

[2] M. A. Ezugwu EO, Wanga ZM, “The machinability of nickel-based alloys: a review,” *J Mater Process Technol ojy*, vol. ;86(1–3):, pp. 1–16, 1998.

[3] E.-B. M. Chouldhury IA, “Machinability assessment of nickel based alloys: tool life in turning Inconel 718.,” *Mach.*

Assess. nickel based Alloy. tool life Turn. Inconel 718. InProceedings sixth Cario Univ. Int. MDP Conf. Cario, Egypt;, vol. p. 233–40, pp. p. 233–40.

[4] J Deepu1, P. Kuppan1*, SBalan1 A S, and Oyyaravelu R., "' Investigations on the machinability of Waspaloy under dry environment ,'" *IOP Conf. Ser. Mater. Sci. Eng. Pap.*, 2016.

[5] N. R. Muktinutalapati, "Materials for Gas Turbines – An Overview," *Adv. Gas Turbine Technol.*, pp. 293–314, 2011.

[6] K. Singh, "Advanced Materials for Land Based Gas Turbines," *Trans. Indian Inst. Met.*, vol. 67, no. 5, pp. 601–615, 2014.

[7] K. and J. B. W. Harris, "New Superalloy Concepts for Single Crystal Turbine Vanes and Blades', Parsons 2000 Advanced materials for 21st century turbines and power plant:," in *Proc. 5th International Charles Parsons Turbine Conference, Churchill College, UK, (July 2000)*, 2000.

[8] N. S. Cheruvu, "Development of a Corrosion Resistant Directionally Solidified Material for Land Based Turbine Blades', Trans. of ASME, Vol 120, (Oct 1998), pp.744-750No Title," *Trans. of ASME*, vol. Vol 120, pp. pp.744–750.

[9] McColvin, G.M., J. Sutton, M. Withemurst, D.G. Fleck, T.A. Van Vrancken, K. Harris, G.L. Erickson and J.B. Wahl, "'Application of Second Generation DS Superalloy CM186LC to First Stage Turbine Blading in EGT Industrial Gas Turbines', Advances in Turbine Materials," *Des. Manuf. Proc. 5th Intl Charles Parsons Turbine Conf. Newcastle,UK*, pp. pp.339–358.

[10] I. bobic milant T.Jovanovic, Borislav, Lukic, Zoran miskovic, "Processing and some applications of nickel,cobalt and titanium based alloys," *J. Metall.*, pp. 91–106, 2012.

[11] E. Akca and A. Gürsel, "A Review on Superalloys and IN718 Nickel-Based INCONEL Superalloy," *Period. Eng. Nat. Sci.*, vol. 3, no. 1, 2015.

[12] J. Betteridge, W., Heslop, *"The Nimonic Alloys, and Other Nickel-Base High-TempratureAlloys"*. New York, 1974., 1974.

[13] Z. G. Yang, D. M. Paxton, K. S. Weil, J. W. Stevenson, and P. Singh, *Materials Properties Database for Selection of High-Temperature Alloys and Concepts of Alloy Design for SOFC Applications*, no. November. 2002.

[14] E. O. Ezugwu, Z. M. Wang, and A. R. Machado, "The machinability of nickel-based alloys : a review," vol. 86, pp. 1–16, 1999.

[15] W. S. Walston, K. S. O'Hara, E. W. Ross, T. M. Pollock, and W. H. Murphy, "Rene' N6: Third Generation Single Crystal Superalloy," *Superalloys 1996 (Eighth Int. Symp.*, pp. 27–34, 1996.

[16] A. S. Sb. and R. O. 1School J Deepu1, P Kuppan1*, "' Investigations on the machinability of Waspaloy under dry environment ,'" *IOP Conf. Mater. Sci.*, vol. doi:10.108, 2016.

[17] D. N. N and S. Kumar, "A Case Study on Ni based Super Alloys Ageing for Improvement of its Properties," *Iarjset*, vol. 2, no. 8, pp. 51–53, 2015.

[18] A. Mitchell, "Influence of process parameters during secondary melting of nickel based superalloys," *Mater. Sci. Technol.*, vol. Volume 25, 2009.

[19] R. Reed, "Secondary Melting Processes for Superalloys," vol. 17, no. February, 2007.

[20] C.H. White, *Nickel Base Alloys, Wiggin Alloy.* Springer, 1981.

[21] N. Richards and D. Aspinwall, "Use of ceramic tools for machiningnickel-based alloys," *Int. J. Mach. Tools Manuf.*, vol. 29, no. (4), pp. 575–588.

[22] C.T. Sims, W.C. Hagel, *The Superalloys, Wiley, New York,*. .

[23] S. S. Handa, "Precipitation of Carbides in a Ni-based Superalloy."

[24] S. A. Sajjadi, H. R. Elahifar, and H. Farhangi, "Effects of cooling rate on the microstructure and mechanical properties of the Ni-base superalloy UDIMET 500," vol. 455, pp. 215–220, 2008.