Mechanical properties and machinability of waspaloy for aerospace applications – review

G Veerappan 1 M Ravichandran 2* and S Marichamy 3

1Department of Mechanical Engineering, Vikram College of Engineering, Tamil Nadu, India.
2Department of Mechanical Engineering, Chennai Institute of Technology, Chennai, Tamil Nadu, India.
3Department of Mechanical Engineering, CMR Institute of Technology, Hyderabad, Telangana, India.

*Corresponding author: smravichandran@hotmail.com

Abstract. Waspaloy has distinctive properties which has extensive applications in aerospace field. Nickel base super alloy, Waspaloy are known for its high hardness, high strength retaining capacity at higher temperature and good corrosion resistant which makes suitable choice for jet engine technology. This paper reviews the research activities done over the last two decades which impacted the wide use of Waspaloy in industry. This work also elucidates on review of the material properties and characteristics. The machinability of the material is discussed.

Keywords: Waspaloy, hardness, yield strength, grain size, machinability, properties

1. Introduction

Today there is need of material which has much improved properties at elevated temperature. This is fulfilled by Super Alloy category, WaspAloy, which have excellent creep resistance, corrosion and oxidation resistance. The base metal is usually nickel, cobalt or nickel iron. Waspaloy is nickel based age hardenable alloy is widely used in some parts of the aircraft gas turbines namely combustion chamber, disks, blades, vanes, casings, shaft exhaust system. These alloys are used in stack gas reheaters, steam power plant bolts and casting dies [1]. These super alloys also have an extraordinary combination of toughness, high temperature strength, creep resistance, excellent thermal fatigue and resistance to degradation in oxidizing or corrosive environment [2, 3]. Waspaloy is superior for its strength retaining capacity at elevated temperature due to the precipitation hardening in which formation of nano sized precipitate phase was observed in the nickel rich matrix phase. The face centered cubic structure, gamma matrix which is a nickel base austenitic phase have high percentage of chromium, cobalt, molybdenum
and tungsten. The dislocation is hindered when the amount of the precipitates increases. This tends to increase in the hardness of the alloy [4]. Waspaloy retains excellent mechanical properties at elevated temperature say 650°C [5].

The objective of this review is to present the mechanical property behaviour, strengthening mechanism, fatigue behaviour under various conditions. The study also targets to examine the factors influencing tensile strength, hardness, creep and ductility. This work also reveals the various types of tools employed to machine the Waspaloy.

2. Literature Review

2.1 Mechanical Properties

The understanding of mechanical properties such as ultimate strength, yield strength, hardness, stress rupture properties of Waspaloy is utmost important related any application. Rehrer et.al investigated the effect of solution treating temperature and both the Al and Ti content on the, hardness, tensile strength and microstructure. The specimen with the highest Al and Ti contents exhibited the highest hardness values. There was a significant increase in 0.2% yield strength with increasing hardener content for 1865°F. The 0.2% yield strength for 1965°F solution treating also increases with increasing hardener content but to a lesser degree than that for 1865°F treating. Ultimate tensile strengths for both 1865°F and 1965°F treating also increase somewhat with Al, Ti and Al+Ti [5].

Chang et.al investigated the effect of Al-Ti content on the tensile properties of the alloys at room temperature and 649°C. It was observed that room temperature yield strength and ultimate tensile strength increases with the increase in proportion of Al and Ti content. The ductility behavior was found to reduce as the percentage of elongation is reduced with the addition of Al Ti content. The ductility behavior was found to reduce as the percentage of elongation is reduced with the addition of Al Ti content. From the Figure 1, the room temperature yield strength (1225Mpa) approximately was higher than the high temperature yield strength (1200Mpa). The effect of solution temperature has not much significant effect on the tensile properties. Due to precipitation, the ductility was decreased and stress rupture life is increased. The ductility of the alloy with 6% Al Ti content was the highest [6].

![Figure 1. Effect of Al+Ti content on the tensile properties of Waspaloy at both room temperature and 650°C](image)

Kamran Amair et.al did the experiment in which high density Waspaloy specimen was produced using selective laser melting of Waspaloy powder. The specimen was fabricated by selecting the control parameters such as pulse width, repetition rate, pulse energy and scan speed. The fabricated specimen was
material characterized in which it was noticed that it was above 95 percentage dense [7]. The majority of the component subjected to dynamic loading. The life of the components, subjected to cyclic loading, is tested for creep and fatigue at elevated temperature [8]. J.T.Yeom et.al investigated the Waspaloy under low-cycle fatigue condition to predict the reliable life of the component by two approaches namely strain range partitioning (SRP) method and damage law of fatigue and creep rupture method. The Chaboche model represented the hysteresis loops from strain controlled low cycle fatigue tests fairly well. It was found that predicted cycles of failures was in good agreement with the measured cycles to failure. It was also noticed that the damage law of creep and fatigue rupture was the most powerful approach which covered a wide range of low cycle fatigue loading condition [9].

Wilshire et.al conducted the experiments to find the creep behavior and tensile strength. The primary creep rate decreases with time due to the difficulty in dislocation movement. But the primary creep characteristics differ at stresses above and below about 700 MPa. The primary creep strain at 873K was first noticed only above 800MPa, but some appreciable creep strain at 1023K was noticed early at 600MPa. Then secondary creep starts. The tensile strength of the alloy decreases with increase in temperature. Tensile strength of the Waspaloy was found to be reduced substantially when the creep temperature increased from 873 to 1023K. Tensile strength decreases with increase in temperature which is evident from the observation. The tensile values of the Waspaloy are 1154 MPa, 1120 MPa, 975 MPa and 825MPa at 873K, 923K, 973K and 1023K respectively. While 0.2% proof stress decreases with lesser amount towards about 700MPa, but there is a sudden drop above 1023K [10].

J. Andersson et.al did the experimental work to find out the effect of different solution heat treatments on the hot ductility of super alloys. A maximum of between 80 and 90% RA was observed at 1050–1100°C for all conditions in the on-heating tests. Above 1100°C, % RA values falls which indicates ductile to brittle transition phenomena takes place. At 1200°C, % RA value was just 5% approximately. At 1250°, the Waspaloy becomes brittle in nature which has too low % RA value. Ductility recovery, as measured in the on-cooling tests from 1240°C, was very limited with less than 30% RA for all conditions and test temperatures except for the 1080uC/4 h treatment, which exhibited 60%RA at 980°C. The secondary phase decides the ductility. The distribution of secondary phases has a great influence and also affects the ductility. Both gamma and M23C6 at the grain boundaries will enhance the resistance to creep and stress rupture. In grain boundaries, spherical γ precipitates are visible and found to be evenly distributed in the grains at the two lower solution temperatures which is shown in Figure 2. [11].

The grain size plays major role in mechanical property. Stefan et.al investigated the influence of hardness and grain size. It was observed that bigger grain size has more hardness than smaller grain size. Large grains solutioned has grain size of ASTM 3 has 230HV. Small grain solutioned has grain size of ASTM 7 has 270HV [12].

Toh et.al investigated the fatigue and tensile behavior of Waspaloy. It was found that tensile strength and 0.2% proof stress of Waspaloy was 1359MPa and 998Mpa respectively. From Figure 3, Slip bands were clearly visible on the fatigue surface in micrograph study. Coarse grains showed more wide spread slip on multiple system when compared to fine grains. Slip bands, boundary of grain growth and annealing twins are the phenomena observed in crack initiation sites. Slip band nucleation happens in coarse grains [13].
L. M. Pike studied the effect of γ' on Hardness, ductility, tensile properties, creep rupture, low cycle fatigue, yield strength at elevated temperature, Percentage elongation at elevated temperature. The materials namely Waspaloy, 282 Alloy, R-41 alloy and 263 alloy was done. These alloys were solution annealed and heated up to temperature of 1010°C(1850°F) for 2 hours followed by air cooling and again heated up to temperature of 788°C(1450°F) for 2 hours followed by air cooling. The value of hardness for R-41 alloy, Waspaloy, 282 alloy and 263 alloy were 64Ra, 58Ra, 57Ra and 55Ra respectively. The maximum hardness values were obtained in samples aged at 816°C. At 816°C temperature, the two alloys namely R 41 alloy and Waspaloy with higher γ” content hardens quickly. Waspaloy has lower percentage elongation (9%) when compared to 263 alloy (34%) and 282 alloy (25%). It is evident that, due to less percentage elongation, Waspaloy is more susceptible to cracking [14].

R. L. Whelchel et.al investigated the mechanical and electrical characterization in age hardened Waspaloy microstructures. Four Waspaloy bars were solution treated at 1145°C for 4 hrs in an inert Argon atmosphere. Then solution treated bar was quenched in 5% Sodium Chloride and water which was heated up to 50°C. These bars were subsequently aged at temperatures of 600, 725, 800 and 875°C for times ranging from two minutes to seven sixty three hrs following intermediate quenching and reheating steps. The γ’ precipitates were observed in SEM images and also noticed that growth of γ’ precipitate size increased when temperature was increased. Waspaloy bar aged at 800°C exhibit high Vickers microhardness of 350HV than bars aged at 600,725 and 825°C. The conductivity and hardness was high at same aging times [15].

Figure 2. Microstructure of Waspaloy at different temperature
Sarwan Manna et al. evaluated the tensile properties and Impact strength of Waspaloy, 718 alloy, 706 alloy and 909 alloy at room temperature and 704°C. The two types of tensile test was carried out. In the first case, the specimen was first exposed to 704°C and that was subjected to tensile test at room temperature. The second case, the specimen was first exposed to 704°C and that was subjected to tensile test at 704°C. In the first case, it was observed that room temperature yield strength of the material which was exposed to 704°C was higher than the high temperature (704°C) yield strength of the material which was also exposed to 704°C. When compared with other three alloys, Waspaloy retains room temperature yield strength at exposed hours from 2000 to 5000. Waspaloy was the best among the other three alloys with respect strength retaining capacity at more exposed hours [16].

3. Machinability

This section presents a review of machinability assessment under various conditions. The merits and demerits of various tool materials used for machining the Waspaloy are reported. Nickel-base super alloys work harden rapidly during machining which is responsible for its poor mach inability. Built up edge hinders the ease of machining. During machining, Cutting zone shows high temperature 1273K and stress of 3450 MPa tends to accelerated notch and crater, flank wear, depending on the tool material and cutting conditions used [17].

Hongtao Ding et al. investigated the effect of temperature and cutting conditions on tool wear and surface finish during machining of Waspaloy via laser assisted. The result shows that, there was 20%
increase in specific cutting energy, tremendous improvement in surface finish (50 -75%) and 50% increase in tool life of ceramic tool [18].

U.Karaguzel et.al investigated the tool life of two different machining. The difficult to cut materials was machined by unconventional turning operations, namely turn-milling and rotary turning processes. From the experimental results, it was concluded that both rotary turning processes and turn-milling ensure longer tool life compared to conventional turning. The selection of operating condition for increasing the tool life was also done by considering the effect of cutting and cooling condition on tool life [19].

The presence of $\gamma$ phase of the type Ni3 (Ti, Al), the titanium and aluminium accounts for hardening. The tool wear increases with increase in titanium and aluminium [20].

3.1 Cutting tool Material
Waspaloy have poor machinability than Alloy 718 which result in more tool wear. Contrary, in some research, the machinability of Alloy 718 is higher than Waspaloy in which less tool wear is noticed [21]. The low wear tool possesses high hardness, excellent toughness, high hardness and dimensional stability and fracture toughness which influences the tool performance [22].

3.2 Cemented Carbide
The carbide was incredibly tough and four times as dense as titanium. Industry quickly employed the metallic compound in its manufacturing processes. Tungsten carbide is an inorganic compound that contains tungsten and carbide in equal proportions. Tungsten based carbides was suitable for high feed rate cutting and severe interrupted cutting but it cannot be used at high speed because of their poor thermochemical instability [23-24]. The foremost failure types are flank and notch wear when machining using cemented carbide tools at the depth of cut [25-26].

3.3 AlTiN and TiAlCrN hard coated on the cemented carbide
Al-rich and TiAlN family of coatings have proved reliable tool life under various conditions. Titanium carbide tools prevent the cratering. The more titanium carbide was added in the base material of tool, the tool became more brittle and weak. To avoid this titanium nitride was coated to the surface of the tool. This coating is applied by a chemical vapor deposition (CVD) process. It helps to prevent built up edge. With this set of characteristics, the AlTiN coating prevents the surface from physical erosion under severe rubbing condition which is suitable for machining of hard to cut aerospace alloys [27].

3.4 Ceramic tool
The two basic ceramic materials such as Aluminium oxide (Al2O3) and Silicon nitride (Si3N4) that are used as cutting tools. Normally ceramic tools are also produced by a sintering process. The addition of oxides of magnesium, titanium and chromium with this ceramic enhances properties which retain their hardness up to 1400 °C. High cutting speed was achieved by selection [24].

3.5 Chemical Vapor Deposition coated carbide insert
A CVD carbide insert was used during the turning process. Internal cooling system is attached in the tool holder which has a cooling fluid. This coolant inside the tool holder circulates and removes heat away from the tool which prevent the red hardness. In the case of dry machining, good surface finish was achieved and the tool life was increased by twelve percentages [28].

3.6 PVD nano-crystalline tungsten carbide inserts
The cutting tool was AlTiN coated tungsten carbide inserts (KCU25). This advanced PVD nano-crystalline coating with high Al content has high wear resistance due to the very thin layer of protective surface. The nomenclature of the tool used was, tool diameter was 0.2mm, the angle of the clearance and rake were 50° and -50° respectively.[29].

4. Conclusion

Nickel based alloy, Waspaloy, are still far from wide use due to the limit of poor machinability due to their hardness. The work attempts to review the experimental results of the mechanical properties, such as hardness, tensile strength and elevated temperature behavior, obtained over the years by various researchers in the field of Waspaloy. This paper also presents the broader view about the cutting tools used to machine the Waspaloy. The cutting tools used over the previous decades to machine the Waspaloy were also reviewed, with particular emphasis on machinability.

5. Reference

[1] Choudhury I A, El Baradie M A 1998 Machinability of nickel-base super alloys: a general review, J. Mater. Process. Technol. 77, 278-284.
[2] Pollock Tresa M and Sammy Tin 2006 Nickel-Based Superalloys for Advanced Turbine Engines: Chemistry, Microstructure and Properties, J. Propul. Power. 22, 361-374.
[3] Hung-Sung Liu, Biing-Hwa Yan, Fuang-Yuan Huang and Kuan-Her Qiu 2005 A study on the characterization of high nickel alloy micro-holes using micro-EDM and their applications, J. Mater. Process. Technol. 169, 418-426.
[4] Schaffer JP, Saxena A, Antolovich S D, Sanders T H and Warner S B 1999 The science and design of engineering materials (New York: McGraw-Hill)
[5] Rehrer WP, Muzyka D R and Heydt G B 1970 Solution Treatment and Al+Ti Effects on the Structure and Tensile Properties of Waspaloy JOM 22, 32-38
[6] Keh-Minn Chang and Xingbo Liu 2001 Effect of γ′ content on the mechanical behavior of the WASPALOY alloy system, J. Mater. Sci. Eng. A. 308, 1-8.
[7] Kamran Aamir Mumtaz, Poonjolai Erasenthiran and Neil Hopkinson 2008 High density selective laser melting of Waspaloy, J. Mater. Process. Technol. 195, 77-87.
[8] Dowling NE 1983 Fatigue Life Prediction for Complex Load versus Time Histories J. Eng. Mater. Technol. 105, 206-214.
[9] Yeom JT, Williams SJ and Park NK 2002 Low-cycle fatigue life prediction for Waspaloy, J. Mater. High Temp. 19, 153-161.
[10] Wilshire B and Scharning PJ 2008 Theoretical and practical approaches to creep of Waspaloy, J. Mater. Sci. Technol. 25 (2), 242-248.
[11] Andersson J, Sjoberg GP, Viskari L and Chaturvedi M 2013 Effects of different solution heat treatments on the hot ductility of superalloys, J. Mater. Sci. Technol. 29, 43-53.
[12] Stefan Olovsjo, Anders Wretland and Goran Sjoberg 2010 The effect of grain size and hardness of Waspaloy on the wear of cemented carbide tools, Int. J. Adv. Manuf. Technol. 50, 907-915.
[13] Toh SF and Rainforth WM Mater 1996 Fatigue of a nickel base superalloy with bimodal grain size, Sci. Technol. 12 1007-1014.
[14] Pike L M 2008 TMS (Hoboken,NJ: John Wiley &Sons)
[15] Whelcher R L, Kelekanjeri VSKG and Gerhardt RA 2009 Mechanical and electrical characterisation in age hardened Waspaloy microstructures International Heat Treatment and Surface Engineering. 3, 35-39.
[16] Sarwan Mannan, Shailesh Patel, and John deBarbadillo 2000 Superalloy TMS. 449-458.
[17] Ezugwu, EA, Machado AR, Pashby IR and Wallbank J 1991 The effect of high pressure coolant supply when machining a heat resistant nickel based superalloy, J. Soc. Tribologists Lub. Engs. 47 (9), 751-757.
[18] Hongtao Ding and Yung Shin C 2013 Improvement of machinability of Waspaloy via laser-assisted machining, Int. J. Adv. Manuf. Tech. 64, 475-486.
[19] Karaguzel U, Olgun U, Uysal E, Budak E and Bakkal M 2015 Increasing tool life in machining of difficult-to-cut materials using nonconventional turning processes, Int. J. Adv. Manuf. Tech. 77, 1993-2004.
[20] Richards N and Aspinwall D 1989 Use of ceramic tools for machining nickel based alloys, Int. J. Adv. Manuf. Tech. 29, 575-588.
[21] Olovsjo S, Wretland A, Sjoberg G 2010 The effect of grain size and hardness of Waspaloy on the wear of cemented carbide tools, Int. J. Adv. Manuf. Tech. 50, 907-915.
[22] Szeszulski K J, Thangaraj A R and Weinmann K J 1990 Fundamental Issues Machining ASME (USA: ASME).
[23] Takatsu S 1990 High Temp. Mat. Proc. 9, 175-193.
[24] Brandt G, Gerendas A and Mikus M 1990 Wear mechanisms of ceramic cutting tools when machining ferrous and non-ferrous alloys, J. Euro. Ceram. Soc. 6, 273-2910.
[25] Ezugwu EO and Machado AR 1988 Proc. Ist Int. Conf. on the Behaviour of Mats. in Mach., ( England: Stratford-Upon-Avon )
[26] Lenz E, Katz Z and Ber A 1976 Investigation of the Flank Wear of Cemented Carbide Tools, J. Eng. Ind. 98, 246-250.
[27] PalDey S, Deevi S C 2003 Single layer and multilayer wear resistant coatings of (Ti, Al) N: a review, J. Mater. Sci. Eng. A, 342, 58-79.
[28] Yahya Isik 2016 Using internally cooled cutting tools in the machining of difficult-to-cut materials based on Waspaloy, Adv. Mech. Eng. 8, 1-8.
[29] Vararaprasad, Srinivasa Rao and Vinay 2014 Effect of machining parameters on tool wear in hard turning of AISI D3 steel, Procedia Engineering. 97, 338-345.