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Effect of various parameters affecting the performance of nickel-based super alloy

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ABSTRACT

The nickel-based superalloy 720Li is employed in the gas turbine due to its mechanical performance at elevated temperatures. A comprehensive assessment of the behavior of the material under representative service conditions is reported to address the drive for ever-increasing temperatures and more arduous environmental exposure. Fatigue experiments have been performed in an air and air/SOx environment at 700 ∘ C containing a mixed salt as a contaminant. There is an intimate relationship between local salt level (flux), stress level, and stress state, i.e. static or cyclic. The interaction with these variables with the work-hardened layer present on the surface of all tested specimens as a result of the shot peening process directly affects the crack initiation process. If specific conditions of environment and stress are achieved, a significant reduction in fatigue life is observed.

Keywords: nickel-based superalloys, welding processes, microstructure, heat treatments

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INTRODUCTION

Superalloys are heat-resistant alloys, today used in high temperature and corrosion-resistant applications in a variety of industries. The development of gas turbines has been the main driving force for the existence of superalloys. Superalloys are heat-resistant alloys of nickel, nickel-iron, or cobalt that exhibit a combination of mechanical strength and resistance to surface degradation generally unmatched by other metallic compounds. The primary uses of these alloys are in Aircraft gas turbines, disks, combustion chambers, bolts, castings, shaft exhaust systems, blades, vanes, etc. Steam turbine power plants, bolts, blades, stack gas re-heaters, Reciprocating engines, turbocharger, exhaust valves, hot plugs,

Metal processing, hot work tool and dies, casting dies, Medical applications, e.g. dentistry uses, prosthetic devices., Space vehicles, Heat-treating equipment, Nuclear power systems, Chemical and petrochemical industries, Pollution control equipment, and Coal gasification and liquefaction systems. Superalloys are divided into three classes: nickel-based, cobalt-based and iron-nickel-based alloys. The nickel-based superalloys are the superalloys most frequently used in gas turbine components. These superalloys (Ni, FeNi, and Co-based) are further sub-divided into wrought, cast, and powder metallurgy alloys. Nickel-base alloys contain at least 50% nickel, whereas, in the nickel-iron base alloy, nickel is the major solute component.

Nickel-based superalloys offer high strength, corrosion resistance, thermal stability, and superb thermal fatigue properties. However, they have been one of the most difficult materials to machine due to these properties. Although we are witnessing improved machining strategies with the developing machining, tooling, and inspection technologies, machining of nickel-based superalloys is still a challenging task due to in-process strains and post-process part quality demands.

Selecting optimum machining parameters for quality, productivity and profitability are of paramount importance. Many studies have been conducted on various aspects of machinability of nickel-based superalloys including defining the optimum cutting parameters, to develop a better understanding of machining them. The recent studies suggest new findings and discuss previously reported results, related to the concerns of superalloy machining. This review presents the influences of the most significant cutting parameters on various machinability characteristics concerning the recent studies as well as the previous ones. The reviewed machinability characteristics may be listed as: tool wear, cutting forces, and surface integrity.

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The term "Superalloy" was first used shortly after World war II to describe a group of alloys developed for use in turbo-superchargers and aircraft turbine engines that required high performance at elevated temperatures. The range of applications for which superalloys are used has expanded to many other areas and now includes aircraft, gas turbines, rocket engines, chemical, and petroleum plants. They are particularly well suited for these demanding applications because of their ability to retain most of their strength even after long exposure times at temperatures above 650 °C. Their versatility stems from the fact that they combine this high-temperature strength with good low-temperature ductility (and/or formability) and excellent surface stability.

LITERATURE SURVEY

Spark Plasma Sintering of Metals and Metal Matrix Nanocomposites: A Review, Zafar Iqbal,1 Abdullah Khalil,1 Abbas Saeed Hakeem, Nasser A Aqeeli, Tahar Laoui, Amro Al-Qutub, and René Kirchner, 2012. Metal matrix nanocomposites (MMNCs) are those metal matrix composites where the reinforcement is of nanometer dimensions, typically less than 100 nm in size. Also, it is possible to have both the matrix and reinforcement phases of nanometer dimensions. The improvement in mechanical properties of MMNCs is attributed to the size and strength of the reinforcement as well as to the fine grain size of the matrix. Spark plasma sintering has been used extensively over the past years to consolidate a wide range of materials including nanocomposites and was shown to be an effective non-conventional sintering method for obtaining fully dense materials with preserved nanostructure features. The objective of this work is to briefly present the spark plasma sintering process and review published work on spark-plasma-sintered metals and metal matrix nanocomposites,

A study of silicon carbide reinforced W-Ni-Cu based heavy alloys sintered with different heat, A Raja Annamalai, Jitender Kumar Chaurasia, Muthe Srikanth, Dinesh K Agrawal, and Chun-Ping Jen, ing modes, 2020, The influence of silicon carbide (SiC) addition to W-Ni-Cu-based heavy alloys has been investigated in the present study. The powders of W-Ni-Cu with varying percentages of SiC were blended and sintered using conventional and Spark Plasma Sintering (SPS)techniques. The sintered samples were characterized to determine the density, microstructure, and mechanical properties. The alloy (W-7Ni-3Cu-0.5SiC) exhibits high ultimate tensile strength 430 MPa for conventional sintering and 831 MPa for spark plasma sintering, relative sintered density 71.84% and 88.25% of conventional sintered and spark plasma sintering, respectively. After the tensile test, the fracture surfaces show a mixed-mode fracture consisting of brittle W/W intergranular and ductile mode of fracture in the matrix.

Effect of Sintering Temperature on the Microstructure and Mechanical Properties of Fe30%Ni Alloys Produced by Spark Plasma Sintering, Mxolisi Brendon Shongwe, Saliou Diouf, Mondiu Olayinka Durowoju, Peter Apata Olubambi, 2015, Fe–30%Ni alloys were produced by sintering in the hybrid hot press spark plasma sintering system using iron and nickel as raw materials. The results indicate that the relative density, microhardness, and fracture morphology depend on the sintering temperature which also affects the microstructure. The densification and grain size of the alloys increased with increasing sintering temperature, facilitating the necking of grains. In the case of the sintering temperature at 1230°C, a relative density of 98.7% and a maximum grain size of around 200μm were obtained, and the maximum microhardness of 284Hv1.0, and the microhardness indentations revealed pincushioning indicating better sintering. Microhardness indentations at 1100°C and below were characterized by barreling, indicating poor densification and/or microhardness. The fracture type changing from intergranular fracture to transgranular fracture is an indication of improved consolidation of the Fe-30%Ni alloy with increasing sintering temperature.

METHODOLOGY

Most Ni-base superalloys, particularly high-γ′ (50% volume fraction) alloys that were designed for casting, are particularly susceptible to a host of various cracking modes due to the complex thermal histories imposed during the AM process. As stated previously, these thermal histories are most synonymous with welding processes and the observed cracking mechanisms show great parallels to those studied in welding. Some of the commonly encountered cracking mechanisms in AM Ni-base superalloys are solidification cracking, strain-age cracking, liquation cracking, and ductility-dip cracking; with solidification cracking being the most commonly observed amongst the studied alloys across many AM modalities. Despite the operation of these cracking mechanisms during AM processing, processing science has been leveraged to develop engineered scan strategies that can suppress detrimental thermal and stress states which give rise to cracking. These approaches are fruitful in the processing of the difficult to weld high- γ′ Ni-base superalloys Inconel 738 and MarM247; crack-free material has been obtained in both prismatic geometries and industrially relevant geometries such as airfoils. However, a strong relationship has been shown to exist between geometry, process parameters, and resultant microstructure in these highly engineered scan strategies.

Common to fusion AM processed Ni-base superalloys is the formation of columnar grains with a preferential alignment to the build direction of the material. Utilizing the same processing science of engineering scan strategies, the unique ability to control the local thermal gradients and solidification rates of the material have been demonstrated. Or in other words, AM processes can be leveraged to generate site-specific microstructure control within AM Ni-base superalloys. The basis of site-specific microstructure control resides in the classic theory of the columnar-to-equiaxed transition proposed by Hunt for castings. Furthermore, solidification texture may be controlled by the manipulation of thermal gradients. Utilizing this theory, research has shown SLM, EBM, and DED have the potential to manipulate both mesoscale morphology and texture. In their work on DED Inconel 625, showed the ability to control the degree of tilt of the [001] of the columnar grains by forming material with a zig-zag 45° and 60° orientations. Using localized thermal gradients and solidification rates, demonstrated the ability to switch between columnar and equiaxed textures to form the letters D, O, and E in texture as shown in the electron backscatter diffraction (EBSD) image. Further, researchers have shown the ability to fabricate single crystal Ni-base superalloys using the EBM process. As a result of these advanced process controls, the potential for site-specific microstructure control through AM has emerged to give rise to a new design paradigm to accompany the increasingly established ideas of topology optimization enabled through AM.

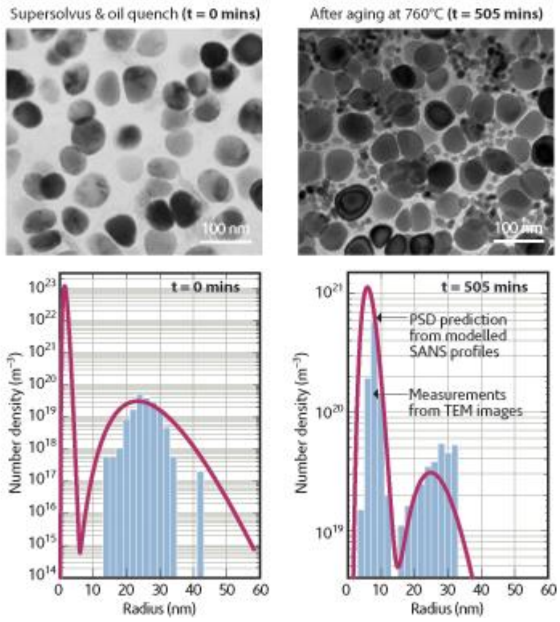

Fig 1: Aging is proposed to the supper-alloys

Existing System

Due to the highly engineered nature of Ni-base superalloy chemistry, the influence of the AM process on the expected chemical inhomogeneities and phases can vary greatly based on the AM modality used in processing. For Ni-base superalloys processed through fusion AM processes inhomogeneity arises as a result of the rapid and repeated thermal gyrations each material point undergoes. This can vary from spatially dependent microstructure gradients, non-equilibrium phase formation, and multi-length scale microstructure inhomogeneities. Whereas in binder-jet processing, which relies on sintering, carbon binders combined with powder particle size distribution have been observed to alter the eutectic temperature and equilibrium phases. In all instances, these observations are best understood for Inconel 718.

Proposed System

Based on the literature survey, it is clear to do some heat treatments on the material to improve its mechanical and physical properties. A special treatment called aging is proposed to be done on the supper-alloys. Natural aging meaning that the precipitates form at room temperature, in some applications, naturally aging alloys may be stored in a freezer to prevent hardening until after further operations-assembly of rivets, for example, maybe easier with a softer part. Artificial aging: when precipitates only form at elevated temperatures. Two types of heat treatment are usually recommended for bars, forgings, and flash welded rings of Nickel-base superalloys. These are solution heat-treatment (annealed); and (ii) precipitation heat treatment (aged). In the solution heat-treatment process, the specimen is heated to a temperature within the range 927℃ – 1010℃ (1700°F – 1859°F), holding at the selected temperature to within +14℃ (+25°F) for a time commensurate with the cross-sectional thickness and cooling at a rate equivalent to air cooling or faster. This leads to a hardness of Rc = 12–15. In the precipitation heat-treatment (aged) process, the specimen is heated to a temperature within the range 718℃ – 760℃ (1325 – 1400°F), holding at the selected temperature to within+ 8℃ (+15°F) for approximately 8 h, cooling at a rate of 55℃+8℃ (100°F+15°F) degrees per hour to a temperature within the range 621℃ – 649℃ (1150°F – 1200°F), holding at the selected temperature to within +8℃ (+15°F) for approximately 8 h and then air cooling instead of 55℃ (100°F) degrees per hour cooling rate to 621℃ – 649℃ (1150°F – 1200°F), the product may be furnace cooled at any rate provided that the Time at 621℃ – 649℃ (1150°F – 1200°F) is adjusted to give a total precipitation heat-treatment time of approximately 18 h. This usually leads to the hardness of superalloys.

In a search for promising metallic material systems for a temperature capability beyond 1200℃, some systems may be chosen. Niobium silicides and molybdenum borosilicides. The multi-phase system of molybdenum and niobium alloyed with silicon has demonstrated potential due to their high melting point of around 2000°C. Niobium silicides also have the advantage of lower density (~7 g/cm^3). However, their oxidation resistance is inadequate and no sufficiently effective protective coating systems are the problems that need to be solved. (2) γ′-strengthened cobalt-based superalloys. The report of a stable γ′-$L1_2$ phase in the ternary Co-Al-W system in 2006 by Sato has given rise to significant research on a new class of precipitation strengthened superalloys, analogous to nickel-based superalloys which are often utilized in high-temperature turbine engine components. However, significant challenges still exist for the commercial transition of these new alloys, including increasing the γ′-solvus, improving oxidation resistance, characterizing fatigue resistance, and establishing processing windows. Some new alloy system with higher γ′ solvus temperature and better microstructural stability becomes a development trend. Refractory high entropy alloys (RHEAs). RHEAs are generally considered as future materials for high-temperature structural applications beyond Ni-based superalloys. RHEAs were first introduced in 2010 and immediately attracted attention due to their ability to retain high strength up to 1600°C (Senkov *et al.*, 2018). The first two RHEAs were based on five refractory elements (molybdenum, niobium, tantalum, vanadium, and tungsten), but subsequent alloys have been drawn from a broader palette of nine elements in Group IV (titanium, zirconium, and hafnium), Group V (vanadium, niobium, and tantalum), and Group VI (chromium, molybdenum, and tungsten). Poor room temperature (RT) ductility, poor oxidation resistance, and high density limit the applications of many refractory alloys. Therefore, developing alloys that have both RT ductility and high-temperature strength is a grand goal.

Types Of Ni-Based Superalloys

- Gamma (γ): This phase composes the matrix of Ni-based superalloy. It is a solid solution fcc austenitic phase of the alloying elements. Alloying elements found in most commercial Ni-based alloys are C, Cr, Mo, W, Nb, Fe, Ti, Al, V, and Ta. During the formation of these materials, as the Ni-alloys are cooled from the melt, carbides begin to precipitate, at even lower temperatures γ' phase precipitates.
- Gamma prime (γ'): This phase constitutes the precipitate used to strengthen the alloy. It is an intermetallic phase based on Ni_3(Ti, Al) which has an ordered FCC $L1_2$ structure. The γ' phase is coherent with the matrix of the superalloy having a lattice parameter that varies by around 0.5%. Ni_3(Ti, Al) are ordered systems with Ni atoms at the cube faces and either Al or Ti atoms at the cube edges. As particles of γ' precipitate aggregate, they decrease their energy states by aligning along the <100> directions forming cuboidal structures. This phase has a window of instability between 600 °C and 850 °C, inside of which γ' will transform into the HCP η phase. For applications at temperatures below 650 °C, the γ" phase can be utilized for strengthening.

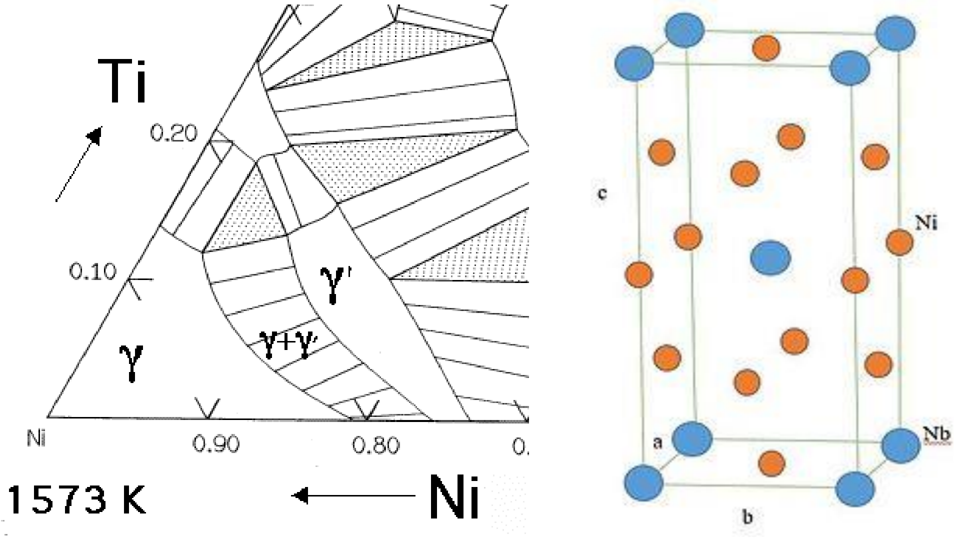

Fig 2: The crystal structure for γ" (Ni_3Nb) (Body-Centered Tetragonal)

- Gamma double prime (γ"): This phase typically possesses the composition of Ni_3Nb or Ni_3V and is used to strengthen Ni-based superalloys at lower temperatures (<650 °C) relative to γ'. The crystal structure of γ" is body-centered tetragonal (BCT), and the phase precipitates as 60 nm by 10 nm discs with the (001) planes in γ" parallel to the {001} family in γ. These anisotropic discs form as a result of lattice mismatch between the BCT precipitate and the FCC matrix. This lattice mismatch leads to high coherency strains which, together with order hardening, comprise the primary strengthening mechanisms. The γ" phase is unstable above approximately 650 °C.
- Carbide phases: Carbide formation is usually considered deleterious although Ni-based superalloys are used to stabilize the structure of the

material against deformation at high temperatures. Carbides form at the grain boundaries inhibiting grain boundary motion.

- Topologically close-packed (TCP) phases: The term "TCP phase" refers to any member of a family of phases (including the σ phase, the χ phase, the μ phase, and the Laves phase) which are not atomically close-packed but possess some close-packed planes with HCP stacking. TCP phases are characterized by their tendency to be highly brittle and deplete the γ matrix of strengthening, solid solution refractory elements (including Cr, Co, W, and Mo). These phases form as a result of kinetics after long periods (thousands of hours) at high temperatures (>750 °C).

Nickel-based superalloy MAR-M 247 had very good fatigue performance at temperatures of 800 and 900 °C.

Advantages

- Solid-solution strengthening: The requirements for a useful solid-solution strengthening addition are that firstly it should have a wide range of solid solutions in the matrix; secondly, it should have the largest possible dissimilarity in atomic size with the matrix atom and thirdly it should have a high melting point.
- At higher temperatures, where diffusion and dislocation cross-slip are important in determining the strength, then atoms which diffuse slowly such as molybdenum and tungsten would be useful solid-solution additions, as would elements that decrease the stacking fault energy between partial dislocations, such as cobalt.
- Precipitation hardening: A majority of nickel-base alloys, which are precipitation hardened, rely on the ' phase for strengthening. The ' compound is based on the formula Ni3(Ti, Al) and it can have a range of compositions depending on the titanium and aluminum contents of the alloy.

There is further flexibility in the composition since the nickel can be replaced to some extent by cobalt, molybdenum, chromium, and iron, and the aluminum + titanium can be replaced by niobium, tantalum, vanadium, molybdenum, chromium, and iron.

The important characteristic of ' in commercial alloys is that it forms as a fine homogeneous precipitate with spherical or cuboidal morphology.

The effectiveness in impeding dislocation movement depends on several factors. To get past a coherent precipitate particle a dislocation, moving on a slip plane can either cut through it loop round it by a mechanism known as Orowan looping. To a first approximation, it is the interparticle spacing that decides which by-pass mechanism operates. Dislocation movement occurs on the close-packed (111) crystallographic planes in the directions. When a dislocation enters an ordered phase it creates an anti-phase domain boundary on the slip plane which is a high energy area and which therefore strengthens the alloy. - phase has a□- phase. The transformation of ': ' is a metastable form of hexagonal crystal structure and is non-coherent with the matrix and generally exists as large phase confers little benefit−platelets which can extend right across grains. In this form, the transformation is undesirable. Mihalis and Decker to □on the alloy and therefore the reaction is accelerated by deformation of the alloy and this is to have shown that the presence of dislocations at the matrix/precipitate interface facilities the necessary relative (111) plane shifts.

Carbides; The carbon content of commercial nickel-base alloys ranges from 0.02 % upwards, and metallic carbides can form in these materials both at the grain boundaries and within the grains. Several types of carbides can form in nickel-base alloys. Mono-carbides of the general formula MC where M is Titanium, Tantalum, Niobium, or Tungsten are generally very stable and form during the melting of the material. They are difficult to dissolve in the solid phase and they play an important part in restricting grain growth during the solution treatment stage. More complex carbides which can be dissolved by a solution treatment in the range 1050 °C to 1200 °C have the general formula M23C6, M7C3, or M6C where M denotes the metallic constituent. In M23C6, M is usually chromium, but this element can be replaced by iron and to a lesser extent nickel, cobalt, and molybdenum, depending on the base composition of the alloy.

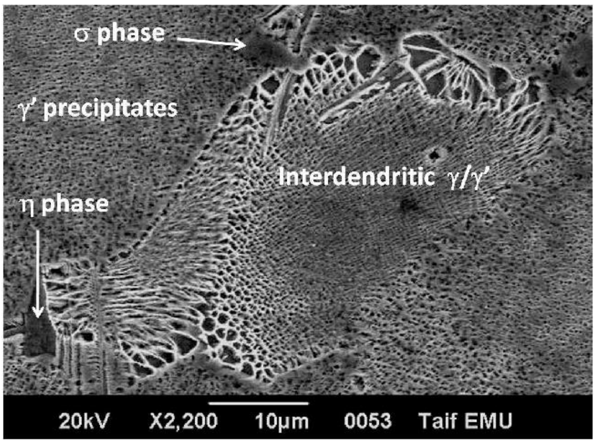

Fig 4: Microstructure Of Ni Based Superalloy

CONCLUSION

Nickel-based superalloys exhibit excellent creep,strength, oxidation resistance, corrosion resistance, and fracture toughness. This spectacular combination of properties did not come without effort – it required many decades of basic and applied research. However, with the increase of turbine inlet temperature in advanced aero-engine, the metal surface temperature at the hottest locations now approaches 1200°C which is the essential limit of nickel-based superalloys. Materials that can survive above this temperature limit are required. These materials should have a high melting point, low density, good oxidation resistance up to 1600°C, and exceptional high-temperature strength. To meet these demands, materials beyond the capabilities of Ni-base superalloys are being sought. In addition to higher strength, ductility, fracture toughness, impact resistance, reduced density, improved environmental resistance, and better coating compatibility are being emphasized. Manufacturability and lower cycle cost are also key requirements.

Future Work

This study aims to investigate the effects of powder particle size on the densification and microhardness properties of spark plasma sintered superalloy. Three particles size ranges of nickel were used in this study, namely, (3-44, 45-106, and 106-150 µm), and this is the matrix in the IN738LC superalloy composition (powder), used in the study. The effects of the particle size were examined at a specific applied temperature and pressure. The transitioning stages during the sintering process of the green powders to the formation of the sintered alloy were analyzed and given as the particle rearrangement stage, the localized deformation stage, and the neck formation/grain growth stage. There was the formation of γ, γ', and a solid solution within the microstructure of the sintered alloys. The effect of particle size was more pronounced on the grain sizes obtained, while the phases formed is the same for the three alloys. The results indicate that the nickel particle size (>60% of the total composition) has a significant influence on the densification, porosity, grain size, and hardness properties of the IN738LC sintered alloy. Finer nickel particle size resulted in a sintered product with smaller grain size (9 µm), reduced percentage porosity (3.9%), increased relative density (96.1%), and increased hardness properties (371 Hv)

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