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Effect of solution treatment on deep drawability of IN718 sheets: Experimental analysis and metallurgical characterization

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ABSTRACT

A promising approach to decrease deformation load and improve ductility during forming of Inconel-718 (IN718) is through the use of solution treated blanks. In the present work, IN718 sheets were separately solution treated to different temperatures in the domain of 970–1070 °C at an interval of 50 °C to dissolve the strengthening precipitates (γ' and γ''), and subsequently, were oil quenched to retain the microstructure. Due to significant difference in average grain size, the solution treated samples of 970 °C (HT970) and 1070 °C (HT1070) were selected for tensile characterization, deep drawing analysis, and micro-texture evolution. The tensile test response showed approximately 30% improvement in ductility and 27% reduction in load in case of HT1070 material with respect to that of HT970 material. The deep drawing process window was evaluated using flat bottom and hemispherical dome punch geometries, and it was found that the limiting draw ratio (LDR) improved marginally by 4.5% in case of HT1070 material. This improvement was due to the dominating presence of cube component in initial texture of HT1070 material. The high presence of cube and goss components in initial texture and the large difference in Taylor factor of individual grains at critical regions of deep drawn cups led to higher unsatisfactory surface roughness in the case of HT1070 material. Hence, it is suggested that the deep drawn components of HT970 material has better part performance in terms of surface roughness. Further, an attempt was made to correlate the fractographs with the fracture and formability behavior of sheet metal.

1. Introduction

Inconel-718 (IN718) alloy sheets find extensive applications in aerospace industry due to their high strength to weight ratio, excellent impact strength and fracture toughness, and ability to withstand extreme temperature conditions within the range of − 250 °C to 705 °C [1,2]. The present work is motivated by the challenges encountered while fabricating following critical space components using IN718 sheets namely: (a) outer casings of Ni-H_2 battery which are used to sustain high pressure while charging, so that, the battery can perform its function efficiently during the solar eclipse time for communication satellite service [3,4], and (b) high-pressure oxygen gas bottles used as life support systems for oxygen supply for astronauts in space mission [5]. In both these applications, two independent drawn cups were welded together to act as a single unit. Although the technology had been successfully achieved, the science related to deep drawing is still absent in the open literature. If the proper blank holding force (BHF) is not selected while manufacturing these components then the occurrence of deep drawing defects such as wrinkling and tearing is very high. Insufficient BHF leads to the flange and wall wrinkling, whereas high BHF results in excessive stretching which ultimately leads to fracture. Wrinkling is usually undesirable in final components for proper function and aesthetic appeal, and the occurrence of severe wrinkling can lead to blank destruction and tool damage in the manufacturing process [6]. These drawing defects and formability in terms of limiting draw ratio (LDR) can be changed with the use of different punch geometries [7]. However, the deep drawing process window at room temperature has not been evaluated for IN718, due to which manufacturing of components is currently ongoing with a large number of experimental trials. Hence, the deep drawing process window is highly essential for producing cost-effective IN718 sheet metal space components.

It is well known that IN718 is a polycrystalline low stacking fault energy (SFE) face-centered cubic (FCC) material whose mechanical behavior such as strength, the rate of work hardening and ductility etc. depend on the heat treatment process. In this context, several researchers [8–10] have studied the promising aspects of solution treatment on mechanical properties and microstructure of IN718, and have

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lucidly discussed that ductility of IN718 can be improved by heat treating at higher solutionizing temperature, which makes it suitable for cold forming operations with reduced deformation load. Ridha and Hutchinson [11] examined microstructures and textures of various samples of FCC material after cold rolling and solution treatments, and they observed that the change in the heat treatment sequence had altered the texture of material which ultimately led to change in the mechanical properties.

It is known that with increase in plastic deformation, the grains tend to rotate towards the more stable orientation of the lattice which leads to the development of a particular texture. A large number of experimental studies have shown that when metal is subjected to large plastic deformation, especially in the case of sheet metal forming, unconstrained metal surfaces tend to roughen [12,13]. In this context, some researchers correlated surface roughening with grain size and crystallographic texture of the material [14–16]. Becker [14] studied the effects of strain localization on the surface roughness of aluminum, and it was concluded that sheet surface behavior was accounted by crystallographic slip and rotation of the crystal lattice with deformation. Mahmudi and Mehdizadeh [15] examined surface roughening during plastic straining in uni-axial and bi-axial stretching of 70–30 brass sheets. Their studies substantiated that surface roughness evolved linearly with strain and it was dependent on the initial grain size. Lee et al. [16] investigated the influence of surface roughness in an aluminum 6022-T4 sheet for an automotive application using crystallographic analysis. In their studies, no close link was identified between surface roughness and the crystallographic orientation. In spite of numerous efforts, the evolution of texture and effect of individual texture components on the surface roughness in FCC materials during the deep drawing process are still unclear.

Previously, the authors have investigated the stretch forming behavior of 1.2 mm thick solution treated (at 970 °C) IN718 sheets [17–19]. The specimens were deformed along different strain paths using limiting dome height (LDH) test setup, and the stretch-formability in terms of LDH and strain distributions were successfully evaluated [19]. However, there was no open literature on the deep drawing behavior of different solution treated IN718 sheets. Also, based on the above discussion, it is necessary to comprehend the effect of different solution treatments on the deep drawability and its effect on surface roughness and microtexture for successful fabrication of critical space components. Hence, in the present work, the following targets are outlined: (a) to evaluate the deep drawing process window of solution treated materials with distinct microstructure using flat bottom and hemispherical dome punch geometries, (b) to characterize and quantify the quality and part performance of the fabricated deep drawn components in terms of surface roughness and crystallographic texture evolution, and (c) to comprehend the failure mechanism of differently deep drawn components.

2. Experimental procedure

2.1. Material selection and solution treatments

The chemical composition of the 1.0 mm thick cold rolled IN718 sheets is shown in Table 1. This Ni-based superalloy provides large solubility for many alloying elements including Fe, Cr, Nb, and Mo, and hence it enhances the strength by solid solution strengthening [20]. These cold-rolled sheets were subsequently heat treated as per the time-temperature schedule depicted in Fig. 1(a). It was reported that the strengthening precipitates (γ' and γ'') could be dissolved in the matrix by heating above the solvus temperature of 886°C [21]. Also, the dissolution of these strengthening precipitates will potentially help in reduction of forming load during deep drawing of space components. Hence, IN718 sheets were heated to different temperatures in the range of 920–1070 °C at an interval of 50 °C at a rate of 10 °C/min. The samples were soaked at the particular constant temperature for 1 hour in an inert gas atmosphere [22] and subsequently quenched. The sheets were observed to be distorted when water quenched, whereas the distortion level reduced significantly while using oil quenching as shown in the inset of Fig. 1(a). The use of mineral oil enhances the wetting of sheets during quenching which minimizes the formation of the undesirable thermal gradient, and hence oil quenching has been carried out for all the solution treated conditions.

The quenched samples solutionized at different temperatures were polished, and further electrochemically etched for detailed microstructure analysis. The average grain size was evaluated, and the variation in grain size with respect to different solutionizing temperature were depicted with error bars in Fig. 1(b). It was observed that the grain size increased with increase in solutionizing temperature. The grain size increased significantly from 17 μm to 82 μm when the solutionizing temperature changed from 970 °C to 1070 °C. The significant increase in the grain size with increase in solutionizing temperature is in agreement with the trend reported in the previous literature [23,24]. Henceforth, in this paper, these two solutionized conditions are referred as HT970 and HT1070 respectively and their microstructures are shown in Fig. 1(c) and (d). The microstructure reveals the annealing twins within the equiaxed grains, and these might have nucleated during the solution treatment [25]. The difference in grain size with the presence of annealing twin boundaries significantly affect mechanical properties and corrosion and fatigue resistance of the IN718 material [26]. Hence, two different solutionized HT970 and HT1070 samples were selected to study the microstructure, tensile properties and forming performance extensively.

2.2. Microstructure and tensile test

The detailed microstructure studies were carried out on both HT970 and HT1070 solutionized samples by scanning electron microscopy (Zeiss Merlin SEM) and transmission electron microscopy (Jeol JEM2100). Orientation imaging microscopy (OIM) scans were carried using Oxford HKL Channel 5 system attached to Zeiss Auriga Compact SEM. The detailed procedure for sample preparation is described elsewhere [19]. The OIM scans were acquired under the following conditions: an acceleration voltage of 25 kV, a specimen tilt of 70°, a scan step size of 0.5 μm. These scans (in .ctf file format) were then analyzed using TSL-OIM (version 7.2) software to obtain inverse pole figure (IPF), orientation distribution function (ODF), and Taylor factor maps following the standard procedures [27].

The tensile tests were conducted using 100 kN servo-hydraulic machine at a deformation speed of 2 mm/min in different directions with respect to the rolling direction (RD) of the sheet, i.e., 0° (RD), 45° (D) and 90° (TD). The tensile results in terms of true stress-strain were estimated from the load-displacement data obtained from the machine. In addition to the yield strength (YS), percentage elongation and ultimate tensile stress (UTS), the Lankford anisotropy coefficient (r-value) were also calculated. To determine the r-values, the tensile specimens along RD, DD, and TD were elongated to axial strain corresponding to 75–80% of UTS [28]. For easy evaluation of r-values, the circular grid

Table 1
Chemical composition of IN718 material evaluated by X-ray fluorescence technique.

Element	Cr	Fe	Nb	Mo	Ti	Al	C	Si	Co	S, Mn, Cu	Ni
Wt.(%)	17.85	19.42	5.20	3.16	1.08	0.56	0.02	0.05	0.02	0.03	Bal.