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Response of Microstructures of AISI4340 steel and Inconel 718 with heat treatment: A review

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Abstract—Hardened materials are used in many industries as these materials have distinguishable features which make them suitable for heavy industries. As in today's scenario no industry can work without the utilization of hardened materials, As the utilization of these materials increasing day by day so they should have desirable properties according to the need and application purpose like heavy-duty axles, shafts, heavy-duty gears, spindles, pins, studs, collets, bolts, couplings, sprockets, pinions, torsion bars, connecting rods, crow bars, conveyor parts etc., so for these application purpose they should withstand heavy loads , they should have high toughness, high strength, high wear resistance, should bear high temperature, should have high strain rates etc. So an effort has been made to know about the variation of properties of hardened materials with the variation in composition or with the help of different heat treatment processes how these materials reacts to these changes at microstructural level and also at the macro level i.e. how strength changes, or toughness varies with change in cooling conditions etc. For this study, AISI 4340 steel and Inconel 718 are chosen and amount of work is reviewed which already has been performed on these materials so that we will know about their response in different atmospheres i.e. in different conditions so as to make them more effective for a particular applications such that they will perform well in that conditions without any hindrance.

Keywords— *AISI 4340 steel, Inconel 718, Hardened materials, Heat treatment*

I. INTRODUCTION

Hardened materials are those materials whose hardness are more than 45HRC. As these hardened materials are produced by the heat treatment followed by quenching and then tempering. As heat treatment is the process of modifying the mechanical properties of the materials. The process of heat treatment involves the use of heating or cooling, usually to extreme temperatures to achieve the wanted result. It is very important manufacturing processes that can not only help manufacturing process but can also improve product, its performance, and its characteristics in many ways. AISI 4340 steel is an alloy of steel in which carbon, manganese silicon, nickel, chromium and molybdenum were added in suitable amount so as to impart desirable properties for particular application purpose. This material has a density of 7.85gm/cm^3 with a melting point of 1427°C. This material can be machined by conventional techniques and also machining can be done on annealed, tempered and normalized samples. This material is widely used in the military application purpose, in aircraft industry and in automobile industry because of its excellent behaviour in corrosion, wear, and fatigue high speed operating conditions and in high temperature conditions. Inconel 718 is basically a super alloy of nickel and chromium with some amount of aluminium, niobium, cobalt, titanium, manganese, silicon, phosphorus, sulphur, boron, copper and iron. As it contains so much of elements, which provide it a wide range of properties like wear resistance, oxidation resistance, high temperature operation, high tensile strength, ability to resist cracks due to which it has vast variety of applications in the area of jet engines, turbines, high temperature screws, cryogenic tanks, springs etc. It has a density of 8220kg/m^3. This alloy is very difficult to machine as it has high affinity for the tool materials, low thermal conductivity and also due to its tendency of work hardening. Also it causes abrasive wear of the tool material because of the carbide present in its microstructures, also it has affinity for many tool materials which causes rapid diffusive wear of the tool. To overcome these problems of Inconel 718 a reviewed study has been done. Both AISI 4340 steel and Inconel 718 are very difficult to machined because of their hardness, but by doing some compositional variation or by some heat treatment processes properties can be modified according to the requirement. Due to the large range of applications these two materials made a new place in the modern manufacturing industry. So for their effective use some studies are performed to know about their microstructural behaviour with change in different parameters like composition, heat treatment methods, coating of some other material etc.

II. LITERATURE SURVEY

K. Palaniradja etal.[1] conducted an induction hardening experiments on the specimen of AISI 4340 steel and found that there is moderate phase transformation occurs from austenite to martensite , which improves the hardness of the material to some extent.

Z. Samadi Shahreza1 etal.[2] Studied the different heat treatment cycles for achieving the optimum microstructures to improve the mechanical and magnetic properties of AISI 4340 steel. After experimentation they found out that the temperature and the time of austenizing and tempering transforms material in such a way such that it can bear long range of ultimate tensile stress, impact energy and forces these improvement in properties makes this material very useful with wide range of applications.

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Dr. S.S Sharma etal.[3] performed some experiments for studying the effect of quenching,austempering on AISI 4340 steel.After performing the tests they found out that austempering improves torsional, tensile and impact strength but it decreases hardness marginally as compared to quenching. Further it was observed that martensitic structures and lower bainitic were formed in quenched and austempered sample. There is increase in elastic limit of the specimen, toughness and also ductility of the sample increases when austempered samples were analysed as compared to quenched samples. There is conversion of microstructures to needle type bainitic structure and martensitic structure were revealed in quenched specimen.

Gurumurthy B.M etal.[4] investigated about the effects of quenching, normalizing on microstructures, hardness and toughness of AISI 4340 steel. After performing different tests on the specimen it was found that quenched sample has high hardness than the normalized samples. Microstructures of the normalized specimen are found to be of two phase pearlitic structures whereas quenched sample has needle like martensitic structure. Also it was found out that there is increase in impact resistance of normalized specimen as compared to quenched specimen.

Edwan Anderson ARIZA etal.[5] Studied mathematically about the residual stresses developed during quenching of AISI 4340 steel cylindrical bars. They used AC3 software to simulate microstructure evolution and FEM is used to analyse about the plastic , elastic , phase transformation stresses and strains.It was observed that microstructures of the bar has larger volume fraction of martensite at the surface than the centre. Tangential and axial residual stresses which are measured by X-ray diffraction are compressive in nature.

Gökçe Şen[6] experimentally studied about the fatique and the fracture behaviour of AISI 4340 steel. In his study he varies the composition of standard AISI 4340 steel and came to the conclusion that by varying the percentage of nickel, molybdenum and chromium the structure of the standard AISI 4340 steel is improved upto larger extent.He found out that there is improvement in the fracture toughness of the component upto 25percent and also there is increase in the 15 percent increase in the elongation, which further lead to increase other properties of material.

Charles P etal.[7] performed experiments to know about the cold working effect and aged treatment effect on AISI 4340 samples. It was found out that the aged samples have high strength, high ductility. The process of reprecipitation and resolution were the main causes for increase in strength.

Sule Yildiz Sirin etal.[8] Studied the effects of ion nitriding process parameters such as temperature and treatment time on the structural characteristic of quenched and tempered AISI 4340. It was found that ion nitriding increases the surface roughness. The time and temperature plays an important role for increasing the thickess of compound layer and diffusion layer.These ion nitridic samples have better performance because of high homogeneity as it consists of only one phase in it. Time and temperature also plays a significant role in increasing surface hardness but longer nitriding time effects adversely.

Shi Da Sun etal.[9] Analysed the micro hardness and microstructure properties of the deposited AISI 4340 clad layer on AISI 4340 substrate. It was observed that clad layer was 40-50% harder than the base substrate of AISI 4340.They reported that clad layer has austenitic dendrites and fine martensitic and bainitic structure.

Roberto O Richie etal. [10] experimentally found that austenizing treatment at 1200˚C instead of standard 870˚C increases the fracture toughness and decreases the charpy impact energy of AISI 4340 steel with the help of sharp crack fracture toughness test and the rounded notch impact energy test. They also conveyed that this kind of behaviour of material doesnot depend upon the shear lip energy and strain rate.

K Divya Bharathi etal.[11] studied about the ratcheting behaviour in annealed and normalised AISI 4340 steel samples by varying the stress ratios and came to the conclusion that by increasing the stress ratio ratcheting strain increased in both the samples because of the increased in the dislocation densities in the ratched samples.

Woei-Shyan Lee etal.[12] Investigated about the deformation behaviour of AISI 4340 steel under the impact of high strain rates at constant temperature, and came to the conclusion that with the increase in strain rate there is increase in the flow stress but on the other if temperature increases flow stress decreases. Also the strain hardening exponent decreases with both increase in strain rate and temperature. The fracture of the takes place with adiabatic shear failure mode. At microscopic level they found out that dislocations and precipitates formation depends upon the strain rate and temperature. They proposed a flow rule which incorporates all the changes related to material deformation.

Moukrane Dehmas etal.[13] experimentally with the help of by X ray diffraction and Transmission electron microscopy found that Inconel 718 retain strength even at high temperatures just because of the metastable γ'' Ni_3Nb precipitation associated with a smaller volume fraction of γ' Ni3Al precipitates. He found that long ageing time decomposes γ'' into stable Ni_3Nb. He further found out that δ phase may grow directly from the supersaturated γ matrix.

Nathan Allen Kistler [14] perform some experiments by additive manufacturing technique to know about the microstructural behaviour of Inconel 718. In his experiment he creates a square Inconel 718 test coupon with a side length of 2.4 cm and a height of 4 mm and divided these samples into six subsets in which half sets are given solution treatment and half are given age heat treatment. He found out that when there is a large temperature gradient occurs because of additive manufacturing bed then there is formation of vertical dendrite morphology parallel to the build direction of the sample. If perpendicular direction is seen then dendrites form along the edge of melt track. He further found out that γ'' phase is coherent with the matrix, thus increasing hardness by blocking dislocation motion.

Vidhi Acharya etal.[15] done investigation about the different microstructural features of Inconel 718 with the help of DC electrical resistivity measurements and correlate these results with the variation in hardness. In wrought condition Inconel 718 contains uneven distribution of δ , γ", γ' and carbides in an austenite matrix γ. They came to the conclusion that when precipitates reaches the critical size then only the effect of precipitation can be seen on the material because at this size effect on dislocation movement can be seen. After further investigation they found that at higher temperature and longer time of exposure resistivity increases with the formation of δ-phase.

S. Srinivas etal.[16] studied about the factors which are responsible for the wide variation in the notch rupture properties of wrought Inconel 718. By microscopic examination they found out that large amount of variations occurred because of the non-uniform distribution of the delta phase and also due to the reduced size of γ" phase.

CJD Hetherington etal.[17] studied about the microstructures of the machined Inconel 718 using transmission electron microscopy technique. In his study he took different parameters for studying microstructures i.e. samples are distinguished on the basis of different cutting speeds, feed rate, tool wear etc.He found out that there is the appearance of white layer on the machined surface which reduces the fatique life of the component. He studied that Inconel 718 has an fcc matrix with a grain size of 23µm and the this structure has high strength due to the dispersion of coherent γ'' Ni_3Nb precipitates. γ'' has body centred tetragonal structure. He further found out that when sample is taken with worn tool and with the use of coolant then the white layer and grain size increases. He finally came to a point that γ'' precipitates doesn't found in white layer but they retained in highly deformed zone.

Hung-Hua Sheu etal. [18] studied about the effects of addition of hafnium and heat treatment process on Inconel 718.In his study he found that new phase Ni_5Hf is formed during the post heat due to the fusion of MC phase with hf. He came to the conclusion that hardness of the samples decreases as the heat treatment process increases i.e. T3 post heat has higher hardness than T8 post heat treatment because of the formation of delta phase and Widmanstatten structure. He found that arm space decreases with the increase content of hafanium. He finally concluded that Ni_5Hf improves high temperature mechanical properties i.e. hardness increased by 20% yield strength increased by 5% and tensile strength increased by 4.3% with the addition of 1.5%Hf by wt.

Xavier Sauvage etal.[19] studied about the microstructure evolution of an Ultra-Fine Grained INCONEL 718 processed by Severe Plastic Deformation. The ultrafine grain structure has high density of γ''. They concluded that ultra-fine grain structure with low precipitate density is produced when high pressure torsion is applied on the coarse grain Inconel 718. Again when they apply multiple forging technique for the production of ultra-fine grain structures by the action of severe plastic deformation it was found out that grain size increases and have larger precipitate densities of delta phase which further increases the hardness. They further came to the conclusion that this variation is because of the γ'and γ''particles which are dissolved in high pressure torsion processed material because of the mechanical mixing in it. These γ'and γ''particles quickly transforms into the stable delta phase during multiple forging process because of the enhanced diffusion. Finally it can be stated that high pressure torsion technique has lower thermal stability because of the reprecipitation of δ, γ"and γ' precipitates.

Kishan E.V.R etal.[20] studied about mechanical properties of age hardened heat treated forged Inconel 718.They found that Inconel 718 is best suited for precipitation hardening heat treatment for improving the strength of forged components. Upto 20 hammer blows the strength of the component increases and if we go beyond this then the strength reduces because of the heating due to friction. At microstructural level they found that recrystallized fine grains and annealing twins are responsible for increase in strength and also precipitation hardnening increases the strength by 33.5%.

Miao Zhu-Jun etal.[21] studied about the effects of boron and phosphorus addition on the as cast microstructures and homogenization parameters of Inconel 718. After doing the analysis with differential scanning calorimeter and electron probe micro analysis characterization solidification sequence was found to be follow the trend as $L \rightarrow L+\gamma \rightarrow L+\gamma+ MC \rightarrow L+\gamma+MC+Laves \rightarrow \gamma+MC+Laves+B$-bearing phase. They came to the conclusion that both boron and phosphorus causes a solid effect on as-cast microstructure of Inconel 718 and form the blocky leaves phase.B bearing phase contains Mo, Nb and Cr. Also it was found that the homogenization temperature must be kept atleast 40 °C lower than that of standard Inconel 718.

S.K. Mukhtarov etal.[22] studied about the effect of severe plastic deformation and heat treatment on the microstructures of Inconel 718.They came to the conclusion that nanostructural grains of Inconel has more hardness, high tensile strength and lower ductility than that of the conventional microstructural grains. They concluded that after heat treatment nanostructured Inconel has more fatigue life, good plasticity at room temperature than conventional coarsed grains.

J. Krawczyk etal.[23] studied about the microstructural changes in Inconel 718 after hot forging. They came to the conclusion that microstructures obtained after forging was in solutionized condition with different levels of recrystallization. At low temperature some uncystallized grains were observed but when the temperature increases new grains formed at the grain boundaries, and also at high temperature more uniform microstructures were obtained and also there is uniform hardness was observed thought the recrystallized structure. Also it was observed that decrease in strain leads to the grain growth in recrystallized parts of the investigated forgings.

J. Belan[24] performed high frequency fatigue test of Inconel 718 to know about the microstructures and came to the conclusion that microstructures of Inconel consists of lenticular and needle like particles of stable δ (Ni3Nb) orthorhombic phase and light gray blocks of mostly primary carbides MC created by Ti and Nb, γ′′and γ′ were not observed because of the low temperature of the testing. Carbides so produced are not responsible for crack initiators. He also concluded with the help of fractography that at higher stress levels fatigue crack initiates from multiple sites and as the stress value decreases crack initiation sites were reduced into one controlled by crystallographic slip at surface grains or massively oxidized areas. After initiation, the crack is propagated by typical trans crystalline mechanism.

G. Appa Rao etal.[25] works for the improvement of properties of hot isostatically pressed Inconel 718 with the help of heat treatment processes. They also studied about the influence of solution treatment temperature on the structure and properties of Inconel 718. They found out that transgranular ductile mode of fracture takes place for unaged condition for all solution treatment temperatures. They revealed that Solution treatment of hot isostatically pressed Inconel 718 in temperature range of 850 – 1050˚C resulted in precipitation and coarsening followed by dissolution of δ, γ” and γ phases, but at higher temperatures dissolution of MC carbides, disruption of PPB networks, and considerable grain growth occurred. They finally came to the conclusion that on increasing the solution treatment temperature the Yield strength, Ultimate strength increases upto 1150 ˚C but after that they decreases slightly. But on the contrary ductility, stress rupture life and rupture ductility increases with increase in temperature, this is due to the increase in bonding between particles and increase in grain size at higher temperature.

Felipe Rocha Caliari etal.[26] studied about the secondary phases in Inconel 718 using thermodynamics modelling. They found that the gamma matrix is highly stabled in temperature range of 500 and 1000˚C and at some point between 1200 and 1250˚C. This is because of the presence of Niobium, Also presence of Cr in the form of FeCr, FeCrMo makes sigma phase brittle and also this phase losses its mechanical strength at elevated temperatures. Al is found in secondary phase gamma primeNi_3Al, and, it seems that gamma prime is well precipitated in the gamma matrix. This phase is associated with loss of mechanical resistance at elevated temperatures.

J.W. Brooks etal.[27] studied about the metallurgical stability of Inconel 718 and also studied about the effect of forging on microstructures and mechanical properties with the long term stability of Inconel 718.They used modern vacuum melting practice to know abot the time temperature transformation characteristics of material. After doing analysis they concluded that primary strengthening phase is body centred tetragonal, designated γ * Ni3Nb, Creep ductility of 718 is directly related to the amount of intergrannular delta precipitation, this gives rise to niobium depletion and hence softening the grain boundary. Also there is no loss of ductility occurs on thermal exposure at temperatures up to 650°C for times up to 10,000 hours.

Josiah J.M. etal.[28] studied about the effect of hydrogen diffusion coefficients through Inconel 718 in different metallurgical conditions.After performing hydrogen permeation through cold rolled , solutionized and precipitation hardened Inconel 718 they came to the conclusion that the value of effective hydrogen diffusion coefficient is higher for solutionized Inconel 718 than for either cold rolled or precipitation hardened specimens. The reduced hydrogen diffusion coefficient in cold rolled and precipitation hardened specimens occurs because of hydrogen trapping at dislocations and precipitates, respectively, which are present at much higher concentrations than in the solutionized specimens. In addition, differences between hydrogen transport during the first and subsequent permeation transients shows presence for irreversible hydrogen trapping in cold rolled and precipitation hardened Inconel 718.

Hwa-Teng Lee etal.[29] studied about the mechanism of forming grains and mechanical properties of Inconel 718. Traditionally grains are refined by aging treatment, and a high volume fraction of acicular δ phase precipitates before the structure forms, but in their study they used resolution heat treated at a temperature higher than the δ solvus temperature specimens of Inconel 718 to ensure thorough dissolution of the precipitated δ phase into the austenite matrix and produce a niobium oversaturated matrix. The specimens are then cold compressed to produce a dislocation saturated matrix and are finally recrystallized at 950°C to induce the precipitation of fine δ phase. They finally concluded that the volume fraction of δ phase precipitates increases significantly as the compression reduction ratio is increased to 50%. Therefore, the δ phase precipitates exert a strong grain-boundary pinning effect, and thus a fine grain structure is obtained despite the high recrystallization temperature. The proposed method results in an improved grain-boundary pinning effect, and yields a more refined and uniformly distributed grain structure, it also increases the ultimate tensile strength and also the ductility of the sample.

Nader El-Bagoury etal.[30] studied about the effect of addition of Rhenium in Inconel 718 alloy as well as effect of solution and aging treatments on microstructure and hardness property. They came to the conclusion that modified solution treatment alloys have higher levels of hardness for the Standard and Re-containing IN718 alloys. The standard structure has precipitates of δ phase with the morphology of needle shape Ni_2Nb phase but modified structure donot have any precipitation of δ phase and lower volume of Ni_2N phase. Aging time, temperature increases the hardness of modified Inconel 718. This is because of the precipitation of the hard phases such as γ', γ" and Re clusters.

III. CONCLUSION

From the above discussion it can be concluded that by increasing the austenizing, tempering, normalizing temperature and time improves the mechanical properties of AISI 4340 and Inconel upto a large extent. Also it can be concluded that in wrought condition Inconel 718 contains uneven distribution of δ, γ'', γ' and carbides in an austenite matrix γ, but after heat treatment it will be converted into stable delta phase, which improves properties.

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