Heat treatment and fine-blankin Inconel 718

Toplotna obdelava in precizno štancanje Inconela 718

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Abstract: Inconel 718 is a nickel based superalloy. Functional properties of Inconel 718 can be achieved by choosing proper heat treatment. The most important kind of hardening is precipitation hardening. The process consists of solution annealing, quenching and aging. The correct heat treatment is required to ensure proper rate between γ'' and δ phases. The effect of time and temperature on microstructure and mechanical properties was determined by microstructure changes, measurement of hardness, tensile strength and toughness. Furthermore, the influences of different heat treatment procedures on mechanical properties of Inconel 718 alloy that are reflected in the loading on the tool were investigated. A force that acts on the punch during fine-blanking of parts to be used in turbochargers for automotive diesel engines was measured. The measurements were made with a force transducer composed of strain gauges, connected in a full Weatstone bridge, placed directly on the punch. The sheet metal from which segments were produced was alloy Inconel 718. The aim was to define the time - dependence of the force.

Izvleček: Inconel 718 je superzlitina na osnovi niklja. Uporabne lastnosti Inconela 718 zagotovimo s pravilno izbiro toplotne obdelave. Glavni način utrjevanja je izločevalno utrjevanje. Postopek obsega raztopno žarenje, gašenje in staranje. Pravilna toplotna obdelava je potrebna, da zagotovimo ustrezno razmerje med fazama γ'' in δ. Vpliv časa in temperature na mikrostrukturo in mehanske lastnosti smo zasledovali s pomočjo mikrostrukturnih sprememb, meritev trdote, natezne trdnosti in udarne žilavosti. Prav tako smo zasledovali vpliv mikrostrukturnih in mehanskih lastnosti na obremenitev orodja pri preciznem štancanju Inconela 718. Vpliv smo zasledovali z meritvijo sile preciznega štancanja pri izdelovanju segmentov, ki se uporabljajo za turbopolnilnike dizelskega motorja. Silo smo merili z merilnimi lističi povezanimi v Weatstonov mostič, ki smo jih nalepili na nož orodja. Pločevina iz katere smo izdelovali segmente je bila zlitina Inconel 718. Cilj je bil določiti časovni potek sile.

Scientific paper

Key words: Inconel 718, heat treatment, microstructure, mechanical properties, fine-blanking, load on punch
Ključne besede: Inconel 718, toplotna obdelava, mikrostruktura, mehanske lastnosti, precizno štancanje, obremenitev orodja

Introduction

The sheet metal from which turbocharger segments were fine-blanked was a nickel base superalloy Inconel 718. Superalloy Inconel 718 is widely used for high temperature applications in aerospace, power and nuclear industry. Due to its good mechanical properties and microstructural stability at elevated temperature it has found its place also in automobile industry. It is used for parts in a turbocharger. The most important method of hardening alloy Inconel 718 is precipitation hardening. The process consists of solution annealing, quenching and aging. The temperature of solution annealing must be high enough to dissolve alloying elements in the metal matrix, which during aging forms precipitates that harden the nickel matrix. Two heat treatments are generally utilized for Inconel 718 [1,2].

A. Solution annealing at 925-1010 °C, then quenching in water, aged at 720 °C for 8 hours, then furnace cooled to 620 °C, held at 620 °C for a total aging time of 18 hours, finally air cooled.
B. Solution annealing at 1035-1065 °C, then quenching in water, aged at 760 °C for 10 hours, then furnace cooled to 650 °C, held at 650 °C for a total aging time of 20 hours, finally air cooled.

The material is machined, formed or welded in the solution annealed condition. After fabrication, it can be heat - treated as required by the foreseen application.

Before any detailed research was done, it was believed that materials requirements for fine-blanking should be similar to those of conventional stamping. The conditions present in stamping were also assumed to be at work in fine-blanking. This assumption was found to be false. Research revealed that the process involves both metal flow and shearing. If stresses in the material are considered, the fine-blanking process is closer to deep-drawing and cold forming than to stamping. For this reason, fine-blanking calls for soft, easily cold formed materials[3].

The purpose of this study was to determine the influence of microstructure and mechanical properties on the process of fine-blanking Inconel 718 by measuring the forces present in the process. In designing the tool it is very important to know as much as possible about the mechanical and microstructure properties and deformation abilities of the alloy that strongly depend on the chosen heat treatment.

Experimental

The starting samples were 3.2 mm thick sheet-metal pieces made of superalloy Inconel 718 with the chemical composition given in Table 1. The samples were used

Table 1. Chemical composition of the investigated alloy Inconel 718
Tabela 1. Kemična sestava preiskovane zlitine Inconel 718

Element	Ni	Cr	Nb	Mo	Ti	Al	Co	C
mas. %	53.4	18.4	4.97	3.05	1.0001	0.54	0.1972	0.053
Element	Mn	Si	P	S	B	Cu	Fe	
mas. %	0.2459	0.08	< 0.005	< 0.002	0.003	0.0173	In balance	

Table 2. Heat treatment procedure for Inconel 718
Tabela 2. Parametri toplotne obdelave Inconela 718

Samples	**Heat treatment procedures**	
	Solution annealing t = 1h	**Ageing**
A	960 °C → water	
B	1050 °C → water	
A1	960 °C → water →	720 °C/8h $\xrightarrow{2h}$ 620 °C/8h → air
A2	960 °C → water →	760 °C/10h $\xrightarrow{2h}$ 650 °C/8h → air
B1	1050 °C → water →	720 °C/8h $\xrightarrow{2h}$ 620 °C/8h → air
B2	1050 °C → water →	760 °C/10h $\xrightarrow{2h}$ 650 °C/8h → air

for analysis of microstructure, tensile test and for fine-blanking process itself. Samples were solution annealed at temperature 960 °C and 1050 °C, quenched in water and then age – hardened according to two different procedures. All of the investigated heat treatment procedures are given in Table 2.

After different heat treating procedures, the microstructure was determined using the method of electronic scanning microscopy, performed on the JEOL JSM – 5610 microscope, and the method of electronic transmission microscopy, performed on TEM JEM – 2010 F. Once the tensile tests and measurement of hardness had been performed, the mechanical properties were determined. The tensile test was performed on the ZWICK Z250 tensile machine in conformance with standard SIST EN 10002 – 1. The Charpy test of toughness was also performed complying with standard SIST EN 10045.

Finally, the force of fine-blanking was measured with a force transducer placed as a full Weastone bridge directly on the punch of the tool (Figure 1a). For fabricate the turbocharger parts (Figure 1c), straps (Figure 1b) made of solution annealed Inconel 718 sheet metal annealed at 960 °C

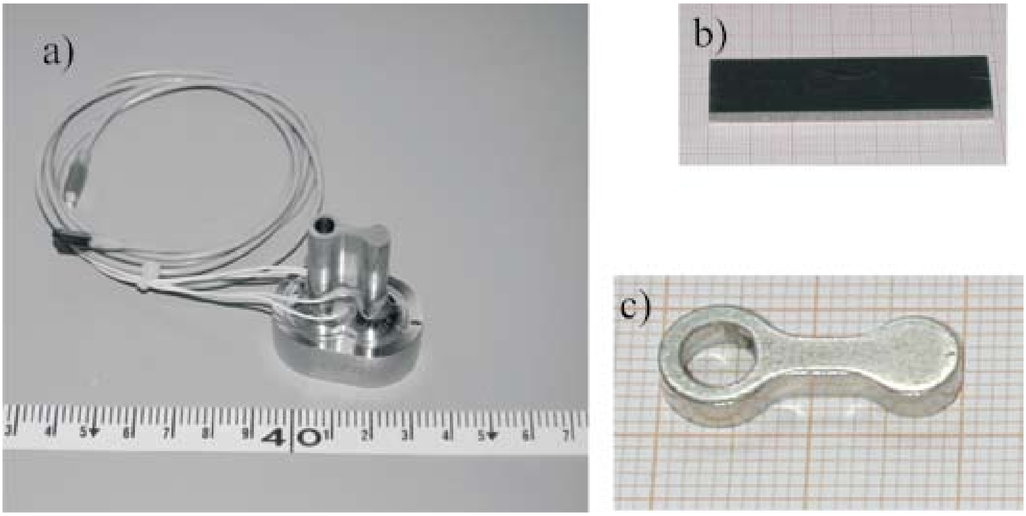

Figure 1. a) strain gauge placed on punch, b) input sample in a shape of strap, c) fine-blanked part for turbocharger
Slika 1. a) merilni lističi nalepljeni na nož, b) vhodni vzorec v obliki traku, c) precizno štancan segment turbopolnilnika

and 1050 °C and quenched in water were used. The different solution annealed straps were manually inserted into the press. During fine-blanking the force acting on the punch was being measured.

Results and discussion

Microstructure of alloy Inconel 718

The temperature of solution annealing affects the amount of intermetal solution Ni_3Nb, known as δ phase which is present in the nickel matrix. With higher temperature a higher amount of δ phases is dissolved. In the Inconel 718 microstructure, some titanium - niobium carbides - (Ti, Nb) C were observed (Figure 2). They can be seen in all other microstructures images.

After solution annealing at 960 °C, some amount of δ phase shown in Figure 3 (left), was still present in the nickel matrix. However, after solution annealing at 1050 °C, all of the δ phase has dissolved (Figure 4). This is only reasonable. As the temperature increased, the volume of δ phase decreased. Complete solution occurred at the δ solvus temperature at 1010 °C [4-8].

During solution annealing the growth of the grains occurs. After solution annealing at 960 °C the grains are 8.5 µm large, after solution annealing at 1050 °C the grains are 42 µm large. This agrees well with previous investigations[4,6]. The growth of crystal grains during annealing is hindered by precipitates on the crystal grain boundaries. Significant grain growth is observed only after complete dissolution of the δ phase.

The changes in microstructure after ageing can not be observed with electronic

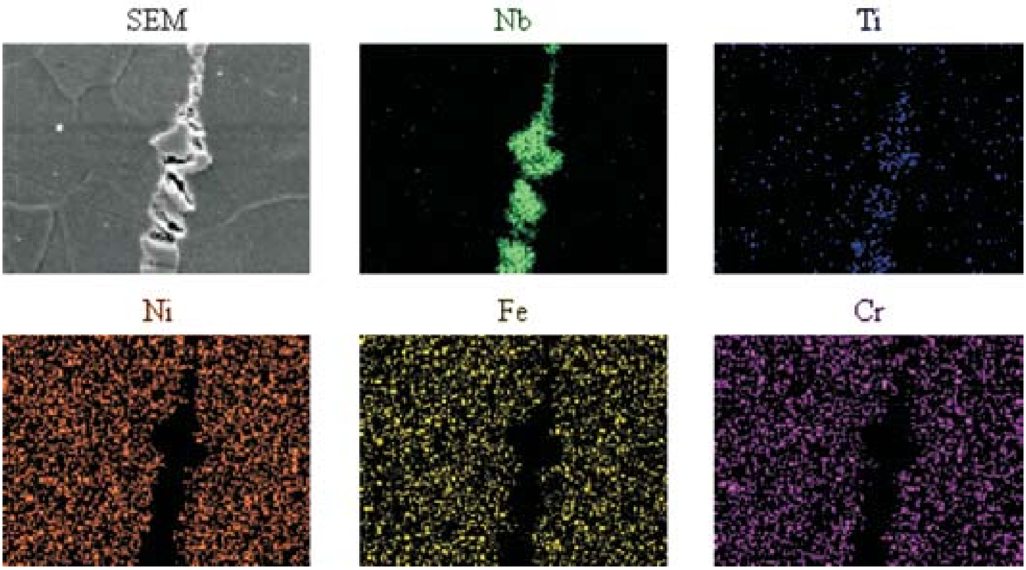

Figure 2. Mapping of carbide particle in metal matrix (SEM)
Slika 2. Kvalitativna ploskovna mikroanaliza karbidnega delca v kovinski osnovi (SEM)

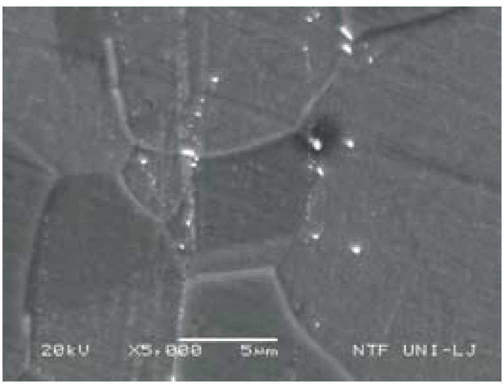

Figure 3. Microstructure obtained after solution annealing at 960 °C and quenching in water (SEM). In the microstructure are seen particles of δ phase in the nickel matrix.
Slika 3. Mikrostruktura po raztopnem žarjenju na 960 °C in gašenju v vodi (SEM). Vidni so delci δ faze v nikljevi osnovi.

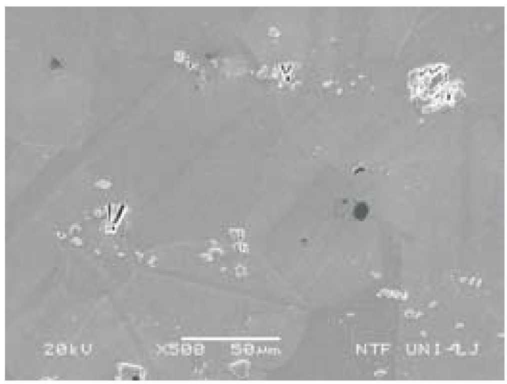

Figure 4. Microstructure after solution annealing at 1050 °C and quenching in water (SEM). In the microstructure are seen only carbide particles in the nickel matrix. All of δ phase has dissolved.
Slika 4. Mikrostruktura po raztopnem žarjenju na 1050 °C in gašenju v vodi (SEM). V nikljevi osnovi so vidni le karbidni delci. Vsa δ faza se je raztopila.

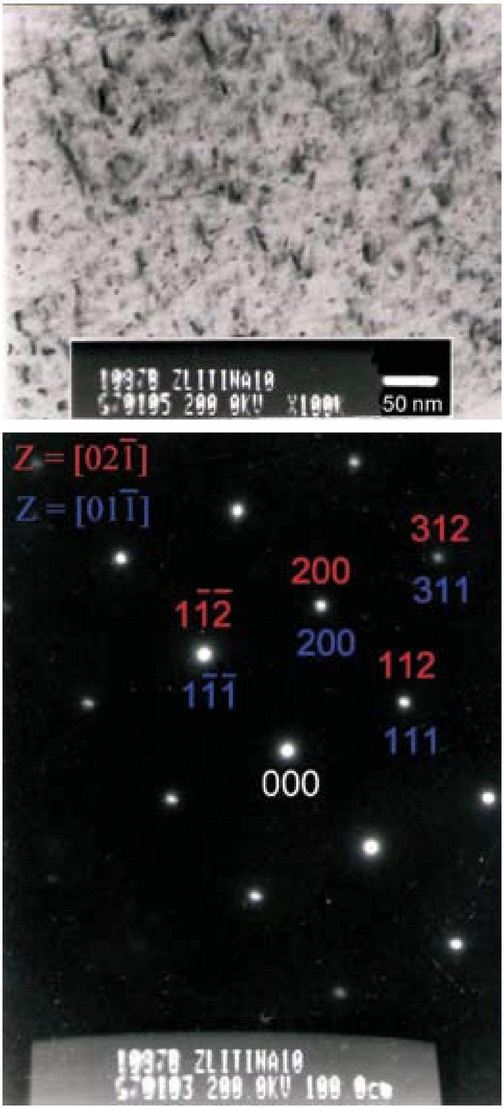

Figure 5. a) Microstructure after ageing (TEM). In the microstructure is seen *γ"* phase in the nickel matrix. b) Diffraction pattern of precipitate.

Slika 5. a) Mikrostruktura po staranju (TEM). Vidni so delci *γ"* v nikljevi osnovi. b) Uklonska slika precipitata.

scanning microscopy. The precipitations are only 10 nm large (Figure 5a), so the electronic transmission microscopy must be used. The diffraction pattern (Figure 5b) belongs to face centered cubic space lattice and/or tetragonal space lattice. The precipitations are *γ"* phase. To the equal results came also other researchers[4,5,9,10]. After ageing the *γ"* phase is main hardening phase.

Mechanical properties of alloy Inconel 718

The chosen heat treatment procedure affects also the mechanical properties of Inconel 718. The mechanical properties in terms of the chosen heat treatment are given in Table 3. The changes of mechanical properties are in correlation with changes of microstructure.

During solution annealing the *δ* phase is dissolving, a lower amount of *δ* phase means lower mechanical properties. With higher temperature of solution annealing, yield stress ($R_{p0,2}$), tensile stress (R_m) and hardness (HV) become lower, but elongation (A) and toughness (KV) become higher due to lower amount of *δ* phase and bigger grains.

Mechanical properties of alloy become higher after ageing due to precipitations of *γ"* phase. Yield stress ($R_{p0,2}$), tensile stress (R_m) and hardness (HV) become higher. On the other hand, elongation (A) and toughness (KV) become lower. The mechanical properties are in correlation with distribution of precipitations. For

Table 3. The influence of different heat treatment on mechanical properties of Inconel 718
Tabela 3. Vpliv različnih toplotnih obdelav na mehanske lastnosti Inconela 718

Type of heat treatment	Average values						
	$R_{p0,2}$ [MPa]	R_m [MPa]	A [%]	n [/]	C [MPa]	HV0,3	KV [J]
A	443	877	48	0.39	1816	220	117.3
B	293	757	59	0.46	1572	185	147.8
A1	1230	1431	21	0.130	2134	470	61.7
A2	774	1185	25	0.192	1983	470	56.5
B1	1076	1288	21	0.136	1943	478	80.6
B2	1029	1348	23	0.157	2113	446	61.2

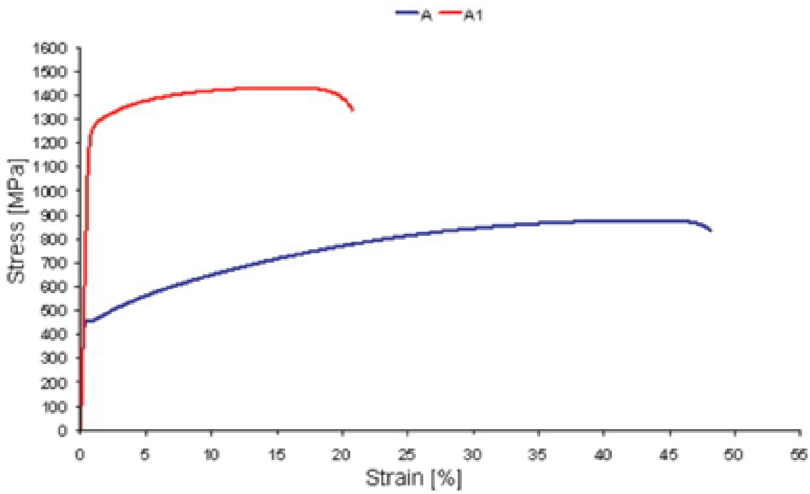

Figure 6. Stress - elongation curve for alloy Inconel 718 for different heat treatments; A – solution annealing at 960 °C, A1 – heat treating according to procedure A1
Slika 6. Inženirska krivulja napetost - raztezek različno toplotno obdelane zlitine Inconel 718; A – raztopno žarjenje na 960 °C, A1 – toplotna obdelava po postopku A1

exact understanding the role of precipitations distribution in hardening Inconel 718 a more extensive investigation is needed. The stress – strain curves for the solution annealed and aged alloy Inconel 718 are presented in Figure 6.

Force in fine-blanking

Mechanical and microstructure properties of sheet metal have an influence on the force in fine-blanking. A line graph of force versus time is presented in Figure 7. During fine-blanking of alloy A the punch is loaded with force of 255 kN. On the other hand, during fine-blanking of alloy B the punch is loaded with force of 235 kN. The reasons for this are lower mechanical properties and higher deformation abilities of alloy B, which was solution annealed at higher temperature.

The punch touches the sheet metal at the time t = 0, after that time the force starts increasing. The curve can be divided into two parts: the first with elastic deformation of sheet metal (part I.), and the second when the ability of elastic deformation is exceeded and plastic deformation of sheet metal begins (part II.). The plastic deformation continues until the punch cuts through the entire thickness of sheet metal.

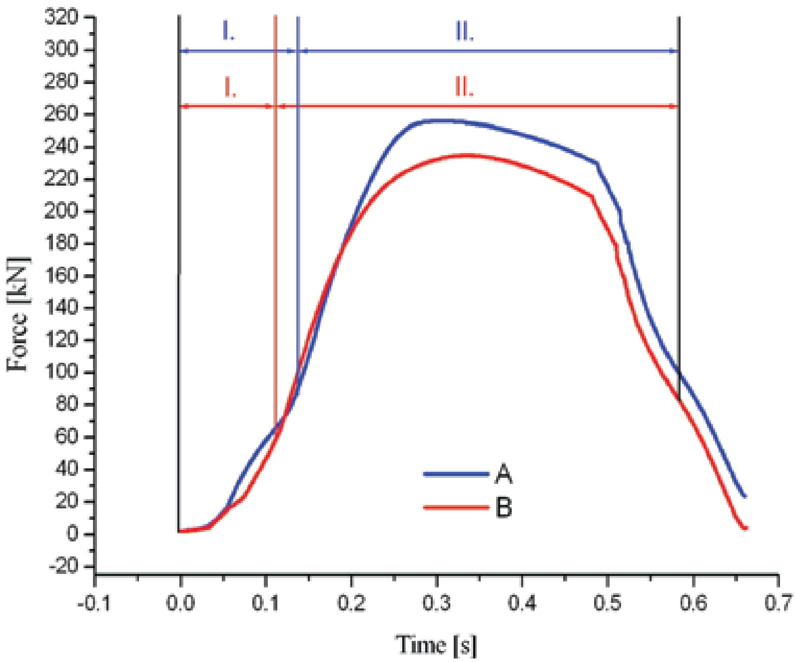

Figure 7. Curves for force versus time during the process of fine-blanking; A – solution annealed alloy Inconel 718 at temperature 960 °C, B – solution annealed alloy Inconel 718 at temperature 1050 °C

Slika 7. Časovni potek sile pri preciznem štancanju; A – raztopno žarjena zlitina Inconel 718 na temperaturi 960 °C, B – raztopno žarjena zlitina Inconel 718 °C na temperaturi 1050 °C

Conclusions

The purpose of our investigation was to determine the influence of heat treatment on microstructure and mechanical properties. The properties of the alloy were changed with different heat treatment procedures. Furthermore, the relationship between mechanical and microstructure properties of the alloy and the fine-blanking force was investigated. Action of the force that is applied on the punch during fine-blanking segments for the turbocharger from alloy Inconel 718 and the dependence of this force on time were also determined.

1. After solution annealing at 960 °C for 1 hour in the nickel matrix there is a presence of globular δ phase. After solution annealing at 1050 °C for 1 hour all of δ phase has dissolved.
2. During solution annealing at 1050 °C the growth of grains occurs. The grains grow up from 8.5 µm to 42 µm.
3. Precipitation of γ'' phase occurs during ageing.
4. Mechanical properties of alloy become higher after ageing due to precipitations of γ'' phase. Yield stress, tensile stress and hardness become higher, but elongation and toughness become lower.
5. Mechanical and microstructure properties of sheet metal have an influence on the force of fine-blanking. During fine-blanking of alloy A the punch is loaded with maximal force of 255 kN and during fine-blanking of alloy B with a maximal force of 235 kN. The Reasons for this are lower mechanical properties and higher deformation abilities of alloy B.

Povzetek

Toplotna obdelava in precizno štancanje Inconela 718

Inconel 718 je superzlitina na osnovi niklja in je zaradi svojih dobrih lastnosti široko uporabljen. Glavni način utrjevanja zlitine je izločevalno utrjevanje. Postopek obsega raztopno žarenje, gašenje in staranje. Proces preciznega štancanja zahteva duktilne materiale, ki se z lahkoto hladno preoblikujejo

Izhodni vzorec je bila 3,2 mm debela pločevina iz zlitine Inconel 718. Vzorce smo toplotno obdelali pri različnih temperaturah in časih. Nato smo določili vpliv različnih parametrov toplotne obdelave na mikrostrukturne in mehanske lastnosti zlitine. Iz zlitine smo izdelovali segmente turbopolnilnika dizelskega motorja in pri tem merili silo s katero zlitina obremenjuje nož orodja. Na ta način smo določili časovni potek sile in vpliv lastnosti zlitine na velikost sile.

Temperatura raztopnega žarjenja vpliva na delež faze δ. Po raztopnem žarjenju na temperaturi 960 °C so v nikljevi osnovi še delci faze δ. Med raztopnim žarjenjem na temperaturi 1050 °C se v nikljevi osnovi raztopijo vsi delci faze δ. Med staranjem se iz prenasičene trdne raztopine izloča utrjevalna faza γ''.

Mehanske lastnosti zlitine so odvisne od temperature raztopnega žarjenja. Zlitina ima po raztopnem žarjenju na 960 °C večje mehanske lastnosti od zlitine žarje-

ne na 1050 °C. Mehanske lastnosti zlitine pred staranjem so odvisne od precipitatov faze *δ*. Mehanske lastnosti zlitine po staranju se povečajo. Mehanske lastnosti zlitine po staranju so odvisne od porazdelitve in velikosti precipitatov faze *γ″*.

Višja temperatura raztopnega žarjenja zmanjša silo in potrebno delo preciznega štancanja surovca iz zlitine Inconel 718. Maksimalna sila preciznega štancanja surovca iz raztopno žarjene na temperaturi 960 °C in gašene zlitine znaša 255 kN. Maksimalna sila preciznega štancanja surovca iz raztopno žarjene na temperaturi 1050 °C in gašene zlitine pa znaša 235 kN.

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