Hladna predelava zlitine Nimonic 263 v trakove

Cold Working of Nimonic 263 Alloy into Strips

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Namen raziskave je bil ugotoviti sposobnost zlitine za vroče in hladno valjanje v trakove. Z metalografskimi preiskavami in meritvami trdot smo ugotavljali spremembe struktur in mehanskih lastnosti.

A. UVOD

Zlitina Nimonic 263 je značilna superzlitina za uporabo v delih reaktivnih motorjev, ki se segrevajo do okoli 850 °C. Razvita je bila posebej za tiste dele, ki se izdelujejo iz pločevin, na primer za zgorevalne komore, vendar jo rabijo tudi za druge toplotno obremenjene dele v plinskih turbinah. Sestava zlitine Nimonic 263 je osnovana na niklju, vendar vsebuje tudi 20 % kobalta, ki zelo izboljša predelavnost, predvsem glede nevarnosti nastajanja razpok med vročim valjanjem. Ima pa, kot vse superzlitine, veliko odpornost proti deformacijam pri visokih temperaturah. Leta 1987 smo na instrumentiranem valjalnem stroju ugotovili, da ima zlitina Nimonic 263 pri temperaturah med 1000 in 1100 °C za faktor 1,6 večjo predelovalno trdnost kot jeklo Prokron 11, ki sicer velja med jekli za zelo trdno pri visokih temperaturah. To in pa sorazmerno ozek temperaturni interval predelave (1150 do 950 °C) je glavni vzrok, da je zelo težko uporabiti za predelavo te zlitine iste predelovalne agregate kot za jekla.

B. EKSPERIMENTALNI DEL

1. Material za preizkuse

V Železarni Ravne so izdelali osnovno talino te zlitine (chg 432 920), ki je bila nato po delih pretaljena po postopku EPŽ (chg 08574/0). EPŽ-blok je bil nato kovan na kovaškem stroju.

***Tabela 1:** Sestava zlitine*

Element	Predpisana sestava % (ppm)	Sestava šarže 08574/0 % (ppm)
C	0,04—0,08	0,07
Si	maks.0,4	0,26
Mn	maks. 0,6	0,06
P	—	0,011
S	maks. 70 ppm	0,001
Cr	19,0—21,0	20,5

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The purpose of the investigation was to establish the alloy ability for hot and cold rolling into strips. By means of metallographic research and hardness measurements we established the occurrence of changes in structure and in mechanical properties.

A. INTRODUCTION

Nimonic 263 alloy is a typical superalloy being used in jet engine parts which are heated to around 850 °C. It was developed especially for parts which are made from sheets e. g. for combustion chambers, but it is also used for other heated parts in gas turbines. The composition of Nimonic 263 alloy is based on nickel, but it also contains 20 % cobalt which substantially improves its workability, especially with regard to heat checking during hot rolling. Like all superalloys, it proves to have a great resistance to deformation at elevated temperatures. In 1987, using a rolling mill equipped with instruments, we established that in a temperature range of 1000 to 1100 °C, Nimonic 263 alloy has a resistance to deformation which is 1,6 times greater than that of Prokron 11 steel which is considered a very strong steel at high temperatures. This fact and the relatively narrow interval of working temperatures (1150 to 950 °C) are the main reasons which make it very difficult to work such alloys on the same working machines as used for steels.

B. EXPERIMENTAL

1. Testing Material

The prime charge of that alloy was produced in Železarna Ravne (chg 432 920) and it was remelted per partes by electroşlag remelting process (chg 08574/0). EPŽ ingot was then forged on a forging machine.

*The chemical composition of this material is shown in **Table 1**, together with the prescribed composition.*

***Table 1**:Alloy composition*

Element	*Prescribed composition % (ppm)*	*Charge (08574/0) composition % (ppm)*
C	0,04—0,08	0,07
Si	max.0,4	0,26
Mn	max. 0,6	0,06
P	—	0,011
S	max. 70 ppm	0,001
Cr	19,0—21,0	20,5
Ni	Bal.	50,4
Co	18,5—21,0	19,3

Element	Predpisana sestava % (ppm)	Sestava šarže 08574/0 % (ppm)
Ni	ostalo	50,4
Co	18,5—21,0	19,3
Mo	5,6—6,1	6,05
Ti	1,9—2,4	2,2
Al	0,3—0,6	0,39
Ti + Al	2,4—2,8	2,59
Fe	maks. 0,7	0,7
Cu	maks. 0,2	0,01
B	maks. 50 ppm	11 ppm
Ag	maks. 5 ppm	0,3 ppm
Bi	maks. 1 ppm	pod 1,0 ppm
Pb	maks. 20 ppm	3,2 ppm

Kot je videti iz tabele, je sestava zlitine v skladu s predpisano, še posebej je dobro, da so škodljivi oligoelementi daleč pod največjo dovoljeno vrednostjo.

Za preizkuse valjanja smo imeli na razpolago dve gredici, debelin 25 in 45 mm, in več palic kvadratnega preseka 25 × 25 mm.

2. Vroče valjanje, trdote in strukture

Gredice in palice smo pred valjanjem segrevali na 1150 °C, in sicer 1 do 1,5 ure. Palice smo nato valjali v eni vročini do debelin 4 do 5 mm, gredice pa v 3 vročinah do istih končnih debelin. Končne temperature valjanja so bile od 870 °C do 960 °C.

Trdote vroče valjanih trakov so odvisne od končne temperature valjanja. Trak, ki smo ga valjali do 870 °C, je imel trdoto okoli 515 HV; trakovi, ki smo jih valjali do 915 °C, so imeli trdote okoli 450 HV, medtem ko so imeli trakovi, valjani do 950 °C, trdote okoli 365 HV.

Tako visokih trdot (515 HV) ne dosežemo niti pri izločevalnem utrjanju, niti pri zelo močnem hladnem valjanju. Očitno je visoka trdota po vročem valjanju do sorazmerno nizkih temperatur (870 °C) posledica seštevka utrditve zaradi valjanja pri temperaturah, pri katerih zlitina več ne rekristalizira, in izločevalne utrditve pri nizkih temperaturah valjanja in ohlajevanja po valjanju.

Dva primera struktur po vročem valjanju prikazujeta **sliki 1 in 2.** Sodimo, da med vročim valjanjem zlitina rekristalizira le do okoli 1050° C, pri nižjih temperaturah pa se deformacijsko in izločevalno utrjuje.

Element	*Prescribed composition % (ppm)*	*Charge (08574/0) composition % (ppm)*
Mo	5,6—6,1	6,05
Ti	1,9—2,4	2,2
Al	0,3—0,6	0,39
Ti + Al	2,4—2,8	2,59
Fe	max. 0,7	0,7
Cu	max. 0,2	0,01
B	max. 50 ppm	11 ppm
Ag	max. 5 ppm	0,3 ppm
Bi	max. 1 ppm	below 1,0 ppm
Pb	max. 20 ppm	3,2 ppm

As seen from the above Table the alloy composition is in compliance with the prescribed values, it is especially suitable that the harmful impurities are far below the highnest allowed value.

To carry out rolling experiments two billets were used 25 and 45 mm thick and several bars of square crossection 25 × 25 mm.

2. Hot Rolling, Hardness and Structures

Before the billets and the bars were rolled, they were heated to 1150 °C for 1 to 1,5 hour. Bars were then rolled to a thickness of 4 to 5 mm in one heat whereas the billets were rolled to the same final thickness in three heats. Finish rolling temperatures were kept between 870to 960 °C.

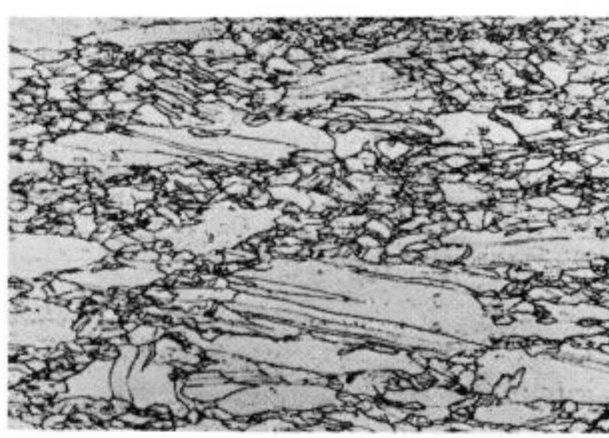
The hardness values of hot-rolled strips depend upon finish rolling temperatures. The strip which was rolled to a temperature of 870 °C had a hardness value of about 515 HV and the strips which were rolled to a temperature of 915 °C had a hardness value of about 450 HV whereas the ones rolled to a temperature of 950 °C had a hardness value about 365 HV.

Such high hardness values (515 HV)cannot be achieved either by precipitation hardening, or by very intensive cold-rolling. Obviously high hardness after hot-rolling to relatively low temperatures (870 °C) results from the combination of hardening due to rolling at temperatures at which the alloy no longer recrystallizes and of precipitation hardening at low rolling temperatures and during cooling after rolling.

*Two examples of structures after hot-rolling are shown in **Fig. 1 and 2.** We estimate that during hot-roll-*

Slika 1.
Struktura zlitine Nimonic 263, valjane do temperature 870 °C v eni vročini

Figure 1.
Structure of Nimonic 263 alloy, rolled to 870 °C in one heat

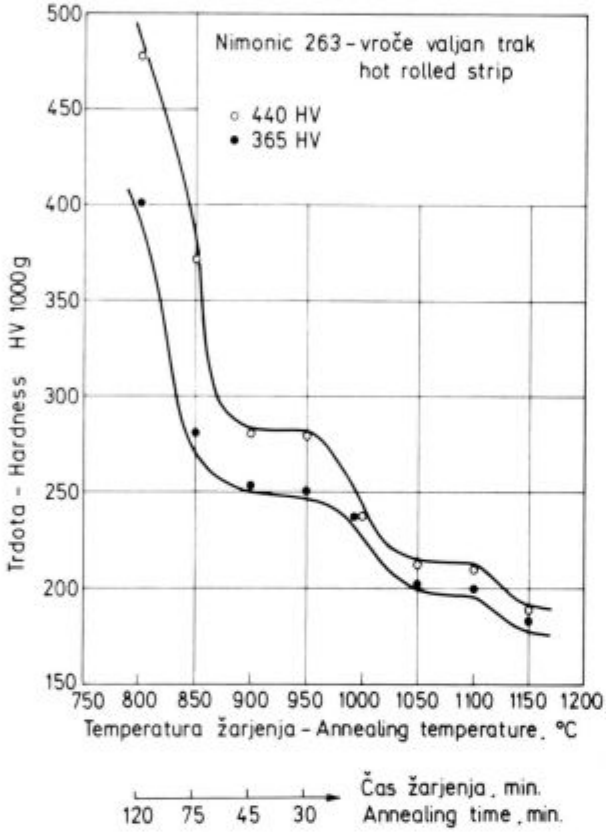


Slika 2.
Struktura zlitine Nimonic 263, valjane do temperature 960 °C v treh vročinah

Figure 2.
Structure of Nimonic 263 alloy, rolled to 960 °C in three heats

3. Žarjenje vroče valjanih trakov

Vzorce dveh trakov s trdotama 440 in 365 HV smo žarili pri temperaturah med 1150 in 800 °C. Trdote po teh žarjenjih so prikazane na **sliki 3.** Po žarjenju na 800 °C se trdota zaradi izločevalnega utrjanja celo poveča. Do 950 °C rekristalizira najbolj deformiran del strukture, do 1050° C pa še preostali del strukture. Obenem poteka tudi raztapljanje izločkov γ', ki sicer utrjujejo zlitino in preprečujejo rekristalizacijo. Najnižjo trdoto pa doseže zlitina šele po žarjenju na 1150 °C.



Slika 3.
Žarjenje vroče valjanih trakov: odvisnost trdote od temperature žarjenja

Figure 3.
Annealing of hot-rolled strips. Relationship between hardness and annealing temperature

4. Hladno valjanje trakov

Vroče valjane trakove smo najprej žarili v vakuumu na 1100 °C 1 uro, nato pa jih hladno valjali na debelino 3,6 mm, zato da smo izravnali debeline trakov po širini. Po vročem valjanju so bili namreč trakovi precej bombirani, na robi tanjši, na sredini pa debelejši. Nato smo trakove ponovno žarili v vakuumu na 1100 °C 1 uro.

En trak smo nato hladno valjali in vmes odrezovali vzorce za merjenje trdot, metalografijo in preiskave žarjenja. Končni cilj so bili trakovi, debeline 0,91 mm, ker take potrebuje določen uporabnik te zlitine. Pred hladnim valjanjem smo menili, da bo za hladno valjanje od 3,6 do 0,91 mm potrebno najmanj enkratno vmesno žarjenje, vendar je šlo brez tega, lahko bi rekli celo precej gladko, posebno glede na to, da naš valjalni stroj ni zelo močan. Debeline, deformacije in trdote so navedene v **tabeli 2.**

ing the alloy recrystallizes only down to approximately 1050° C, at lower temperatures it hardens due to deformation and precipitation.

3. Annealing of Hot-Rolled Strips

Samples of two strips with a hardness of 440 and 365 HV were annealed at temperatures between 115° and 800 °C. Hardness values after these annealings are shown in ***Fig. 3.*** *After annealing at 800 °C, hardness even increases due to precipitation hardening. The most deformed part of the structure recrystallizes up to 950 °C and the remaining part of the structure recrystallizes up to 1050° C.*

Simultaneously, the dissolution of γ' precipitates occurs, which otherwise would harden the alloy and prevent recrystallization.

The alloy achieves the lowest hardness only after annealing at 1150 °C.

4. Cold Rolling of Strips

Hot-rolled strips were first annealed in a vacuum at 1100 °C for 1 hour and then they were cold-rolled to a thickness of 3,6 mm in order to level their thickness across the width because the strips were rather bowed — thinner at the edges and thicker in the middle — after hot rolling. After that the strips were annealed again at 1100 °C for one hour in vacuum.

One strip was then cold-rolled and samples were cut off during the process to measure hardness, for metallographic research and to investigate annealing. The final aim was to produce 0,91 mm thick strips as required by the user of the alloy.

Before cold-rolling, it was believed that at least one intermediate annealing would be required for cold-rolling from 3,6 to 0,91 mm, but it succeded without this and it could even be said that it worked out rather successfully, especially with regard to the fact that the rolling mill which was used was not very powerful. Thicknesses, deformations and hardness values are shown in ***Table 2.***

Table 2: *Cold-rolling parameters and hardness*

Thickness mm	True strain $\varphi = (\ln d_o/d) \cdot 100$ %		Conventional strain $\varepsilon = [d_o - d)/d_o] \cdot 100$ %		Hardness HV 1000 g
	intermediate	cumulative	intermediate	cumulative	
3,6	—	—	—	—	214
3,17	12,72	12,72	11,94	11,94	324
2,9	8,9	21,62	8,52	19,4	360
2,6	10,92	32,54	10,34	27,8	395
2,3	12,26	44,8	11,54	36,1	414
1,97	15,49	60,3	14,35	45,3	449
1,63	18,95	79,23	17,26	54,7	460
1,38	16,65	95,88	15,34	61,7	476
1,12	20,88	116,76	18,84	69,0	490
1,03	8,38	125,14	8,03	71,4	495
0,91	12,39	137,52	11,65	74,7	510

REMARKS on the Table:

— intermediate deformation does not mean only one pass but more especially for smaller thicknesses.

— in true strains, each addition of intermediate values is equal to cumulative ones, whereas this is not true of conventional strains.

Hardness values which were measured after determined intermediate strains were set out in a diagram of hardness — deformation and a hardening curve was obtained as illustrated in ***Fig. 4.*** *The initial hardness of the alloy is 214 HV as before rolling it was annealed at*

Tabela 2: *Parametri hladnega valjanja in trdote*

Debelina mm	Logaritmična deformacija $\varphi = (\ln d_0/d) \cdot 100$ %		Tehnična deformacija $\varepsilon = [d_0-d)/d_0] \cdot 100$ %		Trdota HV 1000 g
	vmesna	kumulativna	vmesna	kumulativna	
3,6	—	—	—	—	214
3,17	12,72	12,72	11,94	11,94	324
2,9	8,9	21,62	8,52	19,4	360
2,6	10,92	32,54	10,34	27,8	395
2,3	12,26	44,8	11,54	36,1	414
1,97	15,49	60,3	14,35	45,3	449
1,63	18,95	79,23	17,26	54,7	460
1,38	16,65	95,88	15,34	61,7	476
1,12	20,88	116,76	18,84	69,0	490
1,03	8,38	125,14	8,03	71,4	495
0,91	12,39	137,52	11,65	74,7	510

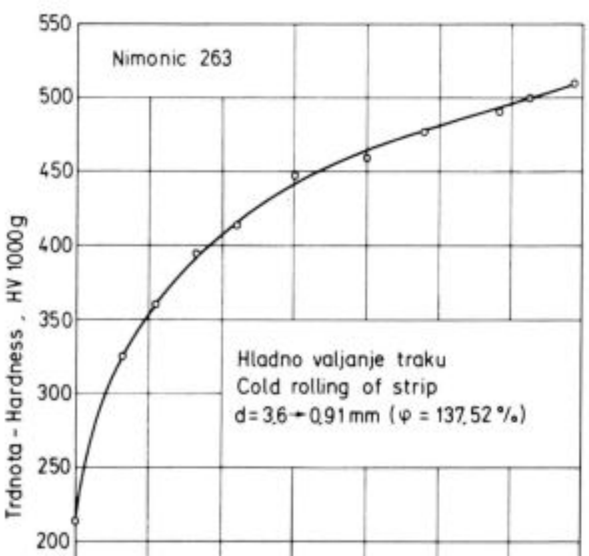
OPOMBE k tabeli:

— vmesna deformacija ne pomeni enega vtika, ampak več, posebno pri manjših debelinah,

— pri logaritmičnih deformacijah je vsak seštevek vmesnih deformacij enak kumulativni, pri tehničnih pa ne.

Izmerjene trdote po izbranih vmesnih deformacijah smo vnesli v diagram trdote/deformacije in dobili utrjevalno krivuljo, ki je prikazana na **sliki 4.** Začetna trdota je 214 HV, ker smo zlitino pred valjanjem žarili na 1100 °C in ne na 1150 °C, ki je prava temperatura za raztopno žarjenje. Iz podatkov v literaturi smo zvedeli, da je za rekristalizacijsko žarjenje zadostna temperatura 1100 °C, čeprav se na 1150 °C dobi še nekoliko nižja trdota.

Kot je razvidno iz tabele 2 in diagrama na sliki 4 smo zlitino hladno valjali do preko 500 HV (50 HRc, natezna



Slika 4.

Utrjevanje zlitine Nimonic 263 pri hladnem valjanju traku

Figure 4.

Hardening of Nimonic 263 alloy by cold-rolling of a strip

1100 °C and not at 1150 °C which is the appropriate temperature for the solution treatment. From reference data we learned that a temperature of 1100 °C is sufficient for recrystallization annealing although even a lower hardness is achieved at a temperature of 1150 °C.

*As shown in **Table 2** and diagram in **Fig. 4** the alloy was cold-rolled beyond 500 HV (50 HRc, tensile strength according to comparative tables around 1670 N/mm²). The alloy has therefore a really very great deformability.*

*To establish hardening properties a log-log plot of hardness vs. deformation was set out as shown in **Fig. 5**. The alloy is obviously behaving in accordance with the conventional hardening equation:*

$$HV = a \cdot \varphi^n,$$

*where **a** is a constant, φ is the true strain, and **n** is the hardening exponent.*

The straight line equation is given by logaritmic calculation:

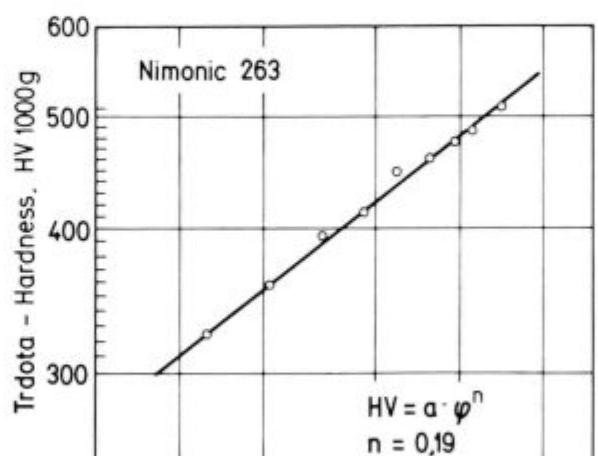
$$\lg HV = \lg a + n \cdot \lg \varphi$$

In other words, if deformation and hardness data are plotted into a diagram with logarithmic coordinates, the straight line shall be obtained. In this case, hardening (or hardening rate) is illustrated by the slope of the straight line — the steeper the slope, the more steel hardens.

*The calculation of the straight line in **Fig. 5** gives the value*

$$n = 0,19$$

For comparison, it could be mentioned that years ago a similar method was used to determine the hardening characteristics of soft steels JMP for cold bulk deformation. JMP 10 steel (soft steel with about 0,1 % C) had a hardening exponent n = 0,185 and JMP 15 steel (around 0,15 % C) had n = 0,165. From these data it results that hardening rate of Nimonic 263 alloy is not es-



Slika 5.

Utrjevanje zlitine Nimonic 263 pri hladnem valjanju traku (logaritmične koordinate)

Figure 5.

Hardening of Nimonic 263 alloy by cold-rolling of a strip (logarithmic coordinates) trdnost po primerjalnih tabelah okoli 1670 N/mm^2). Zlitina je torej zares zelo plastična.

Za določitev utrjevalne lastnosti smo iste podatke vrisali v logaritmični koordinati za trdoto in deformacijo. To je prikazano na **sliki 5.** Vidimo, da se zlitina dobro ravna po klasični utrjevalni enačbi:

$$HV = a \cdot \varphi^n,$$

v kateri je **a** konstanta, φ logaritmična deformacija, **n** pa eksponent utrjevanja.

Z logaritmiranjem dobimo enačbo premice:

$$\lg HV = \lg a + n \cdot \lg \varphi$$

Ali drugače, če podatke za deformacije in trdote vnesemo v diagram z logaritmičnimi koordinatami, moramo dobiti premico. Utrjevanje (ali hitrost utrjevanja) v tem primeru ponazarja naklon premice; čim večji je, bolj se jeklo utrjuje.

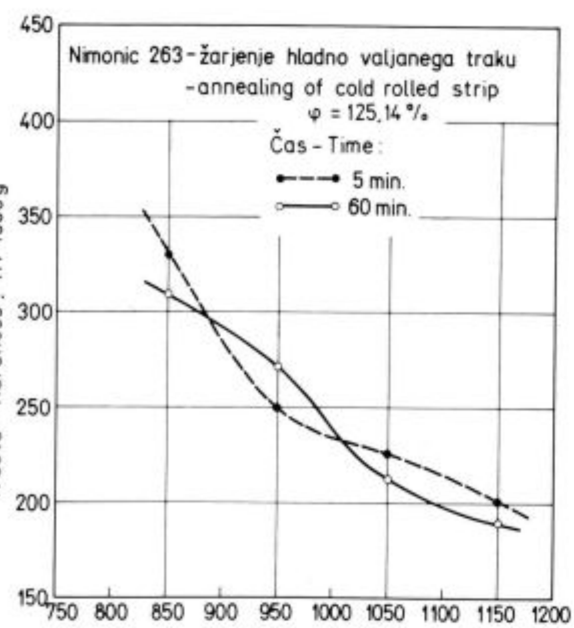
Račun za premico na **sliki 5** nam da vrednost:

$$n = 0{,}19$$

Za primerjavo lahko navedemo, da smo pred leti na podoben način ugotavljali utrjevalnost mehkih jekel za masivno preoblikovanje z oznakami JMP. Jeklo JMP 10 (mehko jeklo z okoli 0,1 % C) je imelo eksponent utrjevanja n = 0,185, jeklo JMP 15 (okoli 0,15 % C) pa n = 0,165. Iz teh podatkov torej vidimo, da utrjevalnost zlitine Nimonic 263 ni bistveno višja kot pri mehkem jeklu. Seveda pa utrjevalnosti ne smemo zamenjevati z absolutnimi vrednostmi trdote, ki jih v prej omenjeni enačbi ponazarja konstanta **a** (JMP 10 začne s trdoto okoli 90 HV in jo ima pri φ = 137 % okoli 210 HV).

5. Rekristalizacija hladno valjanih trakov

Vzorce s parcialnimi in končnimi deformacijami smo žarili na temperaturah 1150, 1050, 950 in 850 °C različne čase: 5, 10, 20 in 60 minut. Stopnjo omehčanja in rekristalizacije smo ugotavljali z meritvami trdote in metalografskimi pregledi.



Slika 6.
Rekristalizacijska žarjenja hladno valjanega traku

Figure 6.
Recrystallizing annealings of a cold-rolled strip

*sentially higher than that of soft steel. Of course, the hardening rate should not be confused with the absolute hardness values which are illustrated by the constant **a** in the previously mentioned equation (JMP 10 starts with a hardness of about 90 HV and achieves a hardness of about 210 HV when φ = 137 %).*

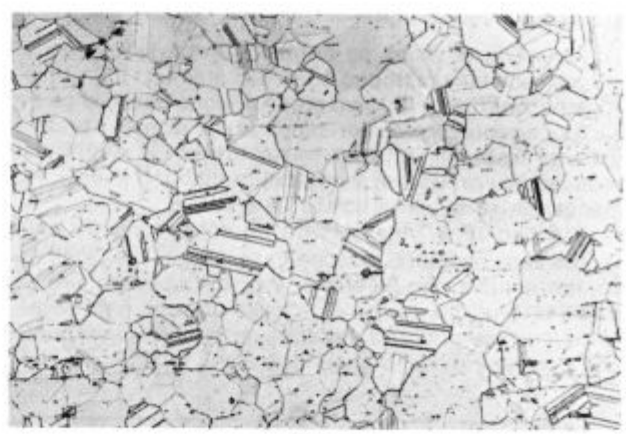
5. Recrystallization of Cold-Rolled Strips

Samples with partial and final deformations were annealed at 1150, 1050, 950 and 850 °C for 5, 10, 20 and 60 minutes respectively. The degree of softening and recrystallization was established by means of hardness measurements and metallographic investigation.

***Fig. 6** illustrates the dependence of hardness upon the annealing temperature for two annealing periods (5 and 60 minutes).*

The true strain of samples was 125,14 %. Above all, it can be established that the annealing time does not essentially affect the degree of recrystallization.

At the temperature of 1150 °C recrystallization is complete but structures are different according to annealing time and previous degree of deformation. At



Slika 7.
Rekristalizirana struktura po žarjenju 5 minut na 1150 °C. Predhodna hladna deformacija 125,14 %

Figure 7.
Recrystallized structure after 5 minutes annealing at 1150 °C. Preliminary cold deformation 125,14 %

Slika 8.
Rekristalizirana struktura po žarjenju 60 minut na 1150 °C. Predhodna hladna deformacija 12,7 %

Figure 8.
Recrystallized structure after 60 minutes annealing at 1150 °C. Preliminary cold deformation 12,7 %

Na **sliki 6** je prikazana odvisnost trdote od temperature žarjenja in dveh časov žarjenja (5 in 60 minut). Logaritmična deformacija vzorcev je bila 125,14 %. Predvsem lahko ugotovimo, da čas žarjenja ne vpliva bistveno na stopnjo rekristalizacije.

Pri 1150 °C je rekristalizacija popolna, vendar so strukture različne glede na čas žarjenja in predhodno stopnjo deformacije. Pri večji deformaciji (125,14 %) in kratkem času žarjenja (5 minut) so kristalna zrna sorazmerno drobna (**slika 7**), pri manjši deformaciji (12,7 %) in daljšem času žarjenja (60 minut) pa se pojavi rast zrn in terciarna rekristalizacija (**slika 8**).

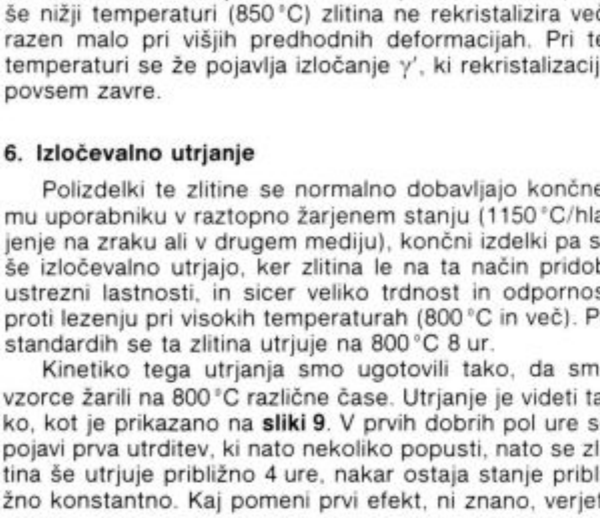
Tudi na 1050 °C je rekristalizacija v vseh primerih popolna. Bistveno drobnejša pa so kristalna zrna in terciarna rekristalizacija se več ne pojavlja. Zaradi manjših kristalnih zrn je trdota nekoliko višja (**slika 6**).

Pri 950 °C rekristalizacija še poteka, vendar nepopolno, kar se odraža v previsoki trdoti (250 do 275 HV). Pri še nižji temperaturi (850 °C) zlitina ne rekristalizira več, razen malo pri višjih predhodnih deformacijah. Pri tej temperaturi se že pojavlja izločanje γ', ki rekristalizacijo povsem zavre.

6. Izločevalno utrjanje

Polizdelki te zlitine se normalno dobavljajo končnemu uporabniku v raztopno žarjenem stanju (1150 °C/hlajenje na zraku ali v drugem mediju), končni izdelki pa se še izločevalno utrjajo, ker zlitina le na ta način pridobi ustrezni lastnosti, in sicer veliko trdnost in odpornost proti lezenju pri visokih temperaturah (800 °C in več). Po standardih se ta zlitina utrjuje na 800 °C 8 ur.

Kinetiko tega utrjanja smo ugotovili tako, da smo vzorce žarili na 800 °C različne čase. Utrjanje je videti tako, kot je prikazano na **sliki 9**. V prvih dobrih pol ure se pojavi prva utrditev, ki nato nekoliko popusti, nato se zlitina še utrjuje približno 4 ure, nakar ostaja stanje približno konstantno. Kaj pomeni prvi efekt, ni znano, verjet-



Slika 9.
Trdota zlitine Nimonic 263 v odvisnosti od časa žarjenja na 800 °C

Figure 9.
Relationship between hardness of Nimonic 263 alloy and annealing time at 800 °C

*greater deformation (125,14 %) and short annealing time (5 minutes) crystal grains are relatively small **(Fig. 7)** whereas at smaller deformation (12 %) and longer annealing time (60 minutes) grain growth and tercial recrystallization occur **(Fig. 8)**.*

*Also a temperature of 1050 °C, recrystallization is complete in all cases. However, crystal grains are essentially smaller and tercial recrystallization no longer occurs. Hardness is somewhat higher due to smaller crystal grains (**Fig. 6**).*

At a temperature of 950 °C recrystallization is still occuring but it is not complete, this is reflected in too high a hardness (250 to 275 HV). At still lower temperature (850 °C) the alloy no longer recrystallizes, with the exception of a very small scale of recrystallization owing to previous higher deformations. At this temperature, γ' precipitation occurs, completely preventing recrystallization.

6. Precipitation Hardening

Semi-finished products of this alloy are normally delivered to the end-user in a solution treated state (1150 °C/air cooling or other cooling media), whereas finished products are precipitation hardened since it is the only way to give the alloy the adequate properties i. e. high strength and resistance to creep at high temperatures (800 °C and more). According to standards, this alloy hardens at a temperature of 800 °C for 8 hours.

*The kinetics hardening was established in such a way that the sample were annealed at 800 °C for different periods. Hardening is illustrated in **Fig. 9**. The first hardening occurs a little over the first half hour, after that it regresses somewhat and the alloy hardens again for about 4 hours, from then on the state of the alloy remains nearly unchanged. The significance of the first effect is not known, it is probably a matter of unstable precipitates which are able to precipitate rapidly and to transform themselves into stable precipitates.*

The hardness of the precipitation hardened alloy is relatively low as it hardly reaches 290 HV (the standard required is at least 275 HV hardness). However, as it has already been stated, the main advantages of this alloy show up only when used at elevated temperatures.

C. CONCLUSIONS

1. Nimonic 263 alloy previously forged into a billet (or slab) can very well be hot-rolled into a strip. Without exception, even if rolling was carried out below 950 °C no larger tears occurred at the edges. After hot-rolling, the strip is very hard and it can even achieve a hardness of 500 HV when it is rolled below 950 °C.

2. Softening (recrystallization) of hot-rolled strips must be carried out at least at 1050 °C, at the best at 1150 °C, however for a very short time in order to avoid crystal grain growth. At this temperature the lowest hardness is also achieved (180 to 190 HV) which is a good state for further cold-rolling.

3. Cold-rolling established that the alloy is very deformable. Despite the use of a less powerful rolling mill the total deformation of $\varphi = 137{,}52$ % ($\varepsilon = 74{,}7$) was achieved without difficulty and without intermediate annealing. Of course, this process substantially hardens the alloy up to 500 HV and even more. The hardening exponent of this alloy is not essentially higher than that of ordinary steels, however its hardness level is very high and its resistance to deformation certainly requires adequately powerful rolling mills.

no gre za neke nestabilne izločke, sposobne hitrega izločanja, ki pa se nato transformirajo v stabilne izločke.

Trdota izločevalno utrjene zlitine je sorazmerno nizka, komaj dosega 290 HV (po standardu mora imeti najmanj 275 HV). Toda, kot smo že rekli, glavne prednosti te zlitine se pokažejo šele pri uporabi na visokih temperaturah.

C. ZAKLJUČKI

1. Zlitina Nimonic 263, predhodno kovana v gredico (ali slab), se zelo dobro vroče valja v trak. V nobenem primeru, tudi če smo valjali pod 950 °C, niso nastajale večje razpoke na robovih. Trak je po vročem valjanju zelo trd, trdota lahko doseže tudi 500 HV, če je valjanje potekalo pod 950 °.

2. Omehčanje (rekristalizacijo) vroče valjanih trakov je treba izvesti najmanj na 1050 °C, najbolje pa na 1150 °C, vendar zelo kratek čas, da ne narastejo kristalna zrna. Pri tej temperaturi dobimo tudi najnižjo trdoto (180 do 190 HV), kar je dobra osnova za kasnejše hladno valjanje.

3. Hladno valjanje je pokazalo, da je zlitina zelo plastična. Čeprav uporabljeni valjalni stroj ni močan, smo brez težav in brez vmesnih žarjenj dosegli skupno deformacijo $\varphi = 137{,}52$ % ($\varepsilon = 74{,}7$). Seveda pa se pri tem zlitina močno utrdi, do 500 in več HV. Eksponent utrjevanja te zlitine sicer ni dosti večji kot pri navadnih jeklih, vendar pa je nivo trdot precej visok in specifična preoblikovalna odpornost gotovo zahteva dovolj močne valjalne stroje.

4. Vmesna žarjenja med hladnim valjanjem (za rekristalizacijo) lahko izvajamo podobno, kot smo zapisali v točki 2, to je med 1050 in 1150 °C. Če žarilni agregat in skupna masa žarjenega materiala omogočata zelo kratkotrajno žarjenje (10 minut), je najbolje žariti na 1150 °C, sicer pa je temperatura lahko tudi nižja, vendar ne pod 1050 °C.

5. Zlitina se pri izločevalnem utrjanju (800 °C in več kot 4 ure) utrdi na okoli 290 HV.

4. Intermediate annealing during cold-rolling (for recrystallization) can be carried out similarly as described in point 2 i. e. between 1050 and 1150 °C. If the annealing furnace and the total quantity of annealed material allow a very short annealing period (10 minutes), then the best annealing is carried out at 1150 °C although the temperature may also be lower, but not below 1050 °C.

5. In precipitation hardening (800 °C, more than 4 hours) the alloy hardens to about 290 HV.

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