

## ACIKULARNI FERIT U METALU ŠAVA NISKOUGLJENIČNIH ČELIKA ACICULAR FERRITE IN WELD METAL OF LOW CARBON STEEL

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### Ključne reči

- Acikularni ferit
- Metal šava
- Mikrostruktura
- Niskougljenični čelik
- Uključci

### Izvod

Ustanovljeno je da u metalu šava mikrolegiranih čelika dominira struktura ferita, koja se javlja u različitim morfološkim oblicima. Koji će od njih biti najzastupljeniji u mikrostrukturi metala šava zavisi od velikog broja faktora. U ovom radu je opisan acikularni ferit kao morfološki oblik ferita, koji se javlja u metalu šava mikrolegiranih čelika i doprinosi čvrstoći i žilavosti metala šava.

### UVOD

Acikularni (igličasti) ferit se često koristi kao sinonim za pločice beinitnog ferita, koje formiraju beinitne snopove. Međutim, u najmanje dva slučaja ovaj naziv je upotrebljen da bi se opisale nestandardne morfologije. Prvi se odnosi na niskougljenične mikrolegirane čelike visoke čvrstoće, a drugi na strukturu koja se javlja u niskougljeničnim zavarenim spojevima. Kasnija ispitivanja su pokazala da se u prvom slučaju zapravo radi o klasičnim mikrolegiranim beinitnim snopovima, pa je predloženo da se ovaj naziv koristi za strukturu metala šava zavarenog spoja. Danas je u metalurgiji zavarivanja prihvaćeno da se morfologija, za koju su karakteristične ukrštene iglice/pločice, koje se prostiru u više pravaca i po pravilu su intragranularno (unutar zrna) nukleirane na uključcima, nazovu acikularni ferit. Kasnije je utvrđeno da se ovakva struktura može obrazovati i u niskougljeničnim mikrolegiranim čelicima kojima su dodati inokulanti, a pokazano je da se acikularni ferit može obrazovati i u srednjeugljeničnim mikrolegiranim čelicima /1,2/.

Acikularni ferit se javlja ispod temperature izdvajanja Vidmanštetenovog ferita i prepoznaje se po trodimenzionalnom obliku tanke ploče u vidu sočiva. Odnos širine i dužine svake ploče nije meren, ali je prosečno oko 10 μm dugačak i 2 μm širok /3,4/, uz odnos debljine i dužine od 1:3 do 1:10. Ove iglice se javljaju na temperaturama između 500 i 400 °C brzo /3/ i imaju veliku dezorijentaciju iznad 20°C (tj. ugao između iglica ferita), kao i veliku gustinu dislokacija. Eksperimentalno je dokazano da je acikularni ferit u stvari identičan beinitu, ali se morfološki razlikuju po

### Keywords

- Acicular ferrite
- Weld metal
- Microstructure
- Low carbon steel
- Inclusions

### Abstract

It has been established that in weld metal of microalloyed steel the ferritic structure dominates, occurring in different morphologic forms. The most dominating form in the weld metal depends on a significant number of factors. In this paper acicular ferrite as a morphologic form is described that occurs in weld metal of microalloyed steel and contributes to weld metal strength and toughness.

### INTRODUCTION

Acicular (needle-like) ferrite is often used as a synonym for plates of bainitic ferrite that are formed from bainitic bundles. However, in at least two cases, the term is applied in order to describe non-standard morphologies. The first refers to low carbon high strength microalloyed steels, and the second one to the structure that occurs in low carbon welded joints. Later tests have shown that in the first case classical microalloyed bainitic bundles are in question, so it is proposed to use this term for the structure of weld metal in the welded joint. Today, it is accepted in welding metallurgy that the morphology characterized by interwoven needles/plates, extending in several directions, that are generally nucleated intragranularly (inside grains) on inclusions, is termed as acicular ferrite. Later, it is established that such a structure can be formed also in low carbon microalloyed steels containing added inoculants, and it is demonstrated that acicular ferrite can be formed also in medium carbon microalloyed steel /1, 2/.

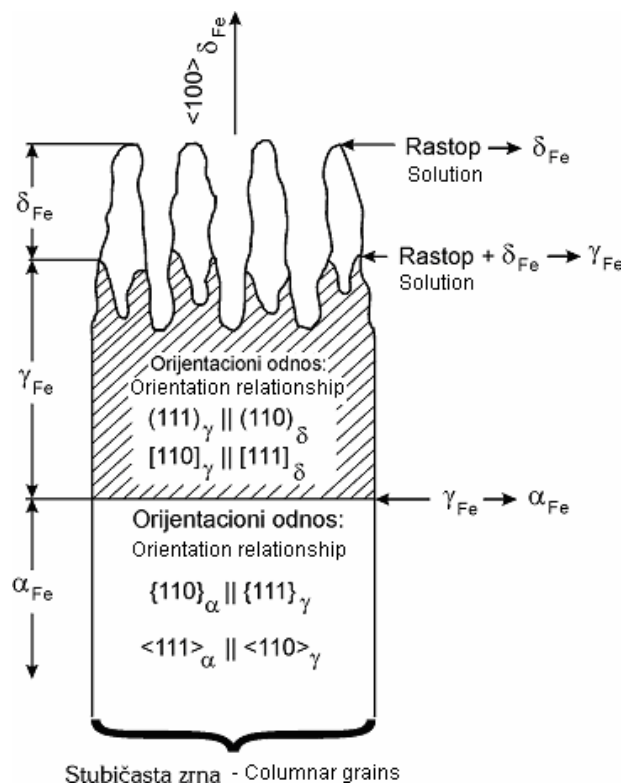
Acicular ferrite occurs below the precipitation temperature of Widmanstätten ferrite and is recognized by a three-dimensional shape of thin plate-like lens. The width to length ratio of each plate is not measured, but in average it is about 10 μm long and 2 μm wide /3,4/, with thickness to length ratio from 1:3 to 1:10. These needles occur rapidly at temperatures between 500 and 400 °C /3/ and are very disorientated above 20°C (i.e. angle between ferritic needles) with high dislocation density. Experiments have shown that in fact acicular ferrite is identical to bainite, but their mor-

tome što igličasti ferit nukleira intergranularno na uključcima unutar velikih  $\gamma$  zrna, dok bainit nukleira inicijalno na površini  $\gamma$ - $\gamma$  zrna i raste ponovljenim obrazovanjem subjedinica, dok se ne obrazuje morfologija u obliku snopa /5/.

#### MEHANIZAM NASTANKA I RASTA ACIKULARNOG FERITA

Transformacija acikularnog ferita predstavlja fenomen nepotpune reakcije, što je i karakteristika bainita, pa je ove dve strukture ponekad teško razlikovati. Step en reakcije teži nuli kako temperatura transformacije raste i na određenoj temperaturi transformacija prestaje. Rast acikularnog ferita je bezdifuzioni /6/.

Dokazano je da postoji veza između orijentacionog odnosa rasta ploča acikularnog ferita i sa austenitom i sa stubičastim zrnima primarnog  $\delta$ -ferita (u kojem austenit raste) /7/. Delta ferit nukleira na uključcima koji se nalaze u rastopu /6/. Posmatrani orijentacioni odnos leži unutar Bainovog orijentacionog regiona i može se opisati sa tri teksturne komponente, tj.  $\langle 100 \rangle$  komponentom i dve komplementarne  $\langle 111 \rangle$  komponente. Svaka od ovih teksturnih komponenti je orijentisana približno paralelno pravcu rasta prvobitne ćelije/dendrita /4/. Oblast stubičastog  $\delta$ -ferita karakteriše izražena  $\langle 100 \rangle$  tekstura očvršćavanja (sl. 1).



Slika 1. Šematski prikaz orijentacionog odnosa primarnog stubičastog  $\delta$ -ferita, austenita i acikularnog ferita, /7/  
Figure 1. Schematic presentation of directional ratio of primary columnar  $\delta$ -ferrite, austenite and acicular ferrite, /7/.

Pri kraju peritektičke reakcije, austenit usaglašava K-S (Kurdjumow-Sachs) tip orijentacionog odnosa sa  $\delta$ -feritom zbog minimiziranja energetske barijere za nukleaciju /7,8/. Austenit kasnije raste po periferiji primarne faze dok se ne dodirnu granice susednih zrna. Tokom  $\gamma$ - $\alpha$  transformacije "efekat memorije" dolazi do izražaja, pri čemu se formiraju

phologies differ in that acicular ferrite nucleates intergranularly on inclusions inside large  $\gamma$  grains, while bainite initially nucleates on  $\gamma$ - $\gamma$  grain surfaces and grows by repeated forming of subunits until bundled morphology is created /5/.

#### INITIATION AND GROWTH MECHANISM OF ACICULAR FERRITE

Transformation of acicular ferrite represents an incomplete reaction phenomenon which is also a characteristic of bainite, so it is sometimes difficult to differentiate these two structures. The reaction degree approaches zero with increasing temperature and at a certain temperature it stops. Acicular ferrite growth is non-diffusional /6/.

It has been shown that a link exists between the direction relationship of acicular ferrite growth and austenite and also of primary  $\delta$ -ferrite columnar grains (where austenite grows) /7/. Delta ferrite nucleates at inclusions contained in the solution /6/. The considered orientation relationship lies within the Bain orientation region and can be described with three textural components, i.e.  $\langle 100 \rangle$  and two complementary  $\langle 111 \rangle$  components. Each of these textural components is oriented approximately parallel to growth direction of primary cell/dendrite /4/. The region of columnar  $\delta$ -ferrite is characterized by clear  $\langle 100 \rangle$  solidification texture (Fig. 1).

ploče acikularnog ferita koje imaju  $\langle 100 \rangle$  pravac približno paralelan sa pravcem rasta prvobitne ćelije/dendrita. Prisustvo drugih teksturnih komponenta je rezultat dopunske rotacije kristala unutar iste orijentacione oblasti /7/.

Interesantno je da je opšta funkcija nukleacije acikularnog ferita na uključcima u suštini identična funkciji nukleacije bainita u običnim čelicima i u zavarenim spojevima. To potvrđuje da je acikularni ferit u stvari intragranularno nukleisani bainit. Nukleacija se odvija heterogeno, na nemetalnim uključcima prisutnim u čeliku. Odvijanje nukleacije zahteva klizanje dodirnih površina između nukleusa i matrice, (tj. kada dolazi do klizanja na površini uključak/austenit) i tako se razvije klica ferita. To je moguće, jer nagomilane dislokacije u austenitu u okolini uključaka (nastale verovatno usled različitog termičkog širenja austenita i uključaka) mogu da obezbede neophodne redoslede koji se razvijaju u odgovarajuće klice /9,10/.

Na formiranje acikularnog ferita (AF) u metalu šava mikrolegiranih čelika utiče veliki broj faktora kao što su: vrsta, veličina i broj nemetalnih uključaka, uneta količina toplote pri zavarivanju, prisustvo kiseonika, legirajući elementi, veličina austenitnih zrna.

#### ULOGA NEMETALNIH UKLJUČAKA

Mišljenja u pogledu mehanizma obrazovanja acikularnog ferita su različita. Prema jednom mišljenju, acikularni ferit je intragranularno nukleiran Vidmanštetenov ferit, a prema drugima to je intragranularno nukleirani bainit /1,2,11/.

Najnovija ispitivanja na C-Mn-Ni šavu su pokazala da se prva grupa iglica acikularnog ferita nukleisala na uključcima, što potvrđuje da nemetalni uključci predstavljaju prva nukleaciona jezgra za acikularni ferit. Na sl. 2 su šematski prikazani različiti tipovi nukleacije acikularnog ferita, kao i indukovane nukleacije /12/.

Sa sl. 2 se vidi da se uzajamni odnos između feritnih iglica i uključaka menja i zavisi od pravca rasta nukleisanih embriona. Nukleacija acikularnog ferita i uzdužni pravci rasta označeni su strelicama prikazani su na sl. 2a i 2b. Nukleacija i rast ovog tipa AF stvara dve morfologije, "zarobljenog" nukleacionog uključka, sl. 2a, ili dugačku feritnu iglicu koja dodiruje uključak na jednoj strani, sl. 2b. Prva morfologija je karakteristična za manje uključke, a druga za veće. Na sl. 2c i sl. 3 prikazana je "zvezdasta" nukleacija, gde se uključak nalazi u centru feritne zvezde, odnosno, feritne iglice zrakasto izlaze iz uključka. Ovaj tip nukleacije je takođe karakterističan za veće uključke /12, 13/. Formiranje iglica acikularnog ferita na uključku može dovesti do autokatalitičke reakcije, tako da se broj aktivnih uključaka ne slaže sa brojem acikularnih feritnih pločica, /6,12/.

U prethodnom tekstu opisana je nukleacija acikularnog ferita potpomognuta uključcima. Posle toga dolazi do takozvane indukovane nukleacije. Indukovane feritne iglice normalno nukleišu iz postojećeg igličastog ferita koji je nastao nukleacijom na uključcima. Ove indukovane feritne iglice rastu pod velikim uglom u odnosu na početne feritne iglice koje ih nukleiraju i manjih su dimenzija od njih (početnih feritnih iglica; sl. 2d i 3) /12,13/. Acikularni ferit može takođe indukovano da nukleiše iz granice zrna između pro-

formation of acicular ferrite plates of  $\langle 100 \rangle$  orientation that is almost parallel to primary cell/dendrite growth orientation. Presence of other textural components is the result of additional rotation of crystals within the same orientation region /7/.

It is interesting that the general function of acicular ferrite nucleation at inclusions is in fact identical to bainite nucleation function in ordinary steels and in welded joints. This confirms that acicular ferrite is in fact intragranularly nucleated bainite. Nucleation develops heterogeneously at nonmetallic inclusions existing in steel. Development of nucleation requires sliding of contact surfaces between the nucleus and matrix (i.e. when sliding occurs on the inclusion/austenite interface) thus forming the ferritic nucleus. It is possible since dislocation pile-up in austenite in the vicinity of inclusion (probably formed due to different thermal expansion of austenite and inclusions) assures required sequences that develop the corresponding nuclei /9,10/.

Significant number of factors affect acicular ferrite (AF) formation in weld metal of microalloyed steels, such as: type, size and number of nonmetallic inclusions, welding heat input, oxygen presence, alloying elements, austenitic grain size.

#### THE ROLE OF NONMETALLIC INCLUSIONS

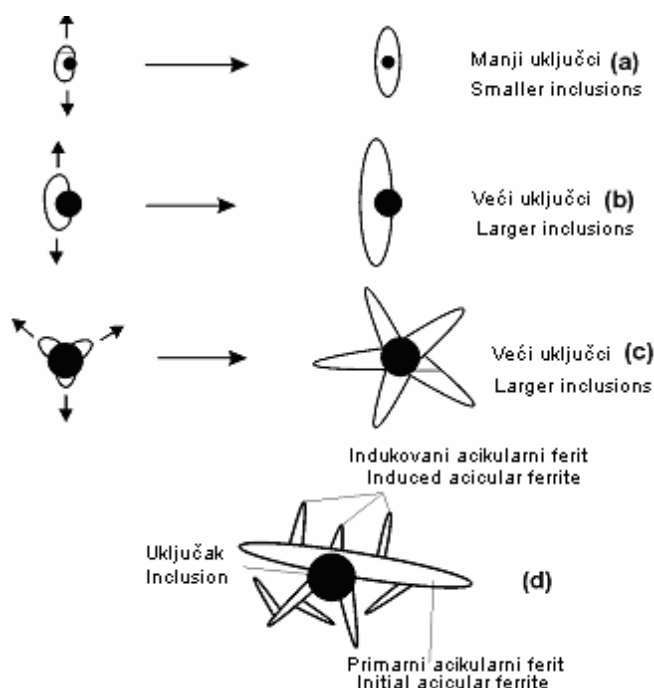
Opinions on mechanisms of acicular ferrite formation are different. According to one notion, acicular ferrite is intragranularly nucleated Widmanstätten ferrite, or intragranularly nucleated bainite, according to others /1,2,11/.

Latest research of C-Mn-Ni welds has shown that the first group of acicular ferrite needles had nucleated at inclusions, confirming that nonmetallic inclusions represent initial nucleation sites for acicular ferrite. The scheme in Fig. 2 presents different types of acicular ferrite nucleation and induced nucleation /12/.

It is clear from Fig. 2 that interrelation between ferrite needles and inclusions changes and depends on growth orientation of the nucleated embryo. Acicular ferrite nucleation and longitudinal directions of growth are indicated by arrows in Figs. 2a and 2b. Nucleation and growth of this AF type creates two morphologies, "engulfed" nucleus inclusion (Fig. 2a), or long ferrite needle contacting the inclusion on one side (Fig. 2b). The first morphology is typical for smaller inclusions and the latter for larger ones. In Figs. 2c and 3 "star-like" nucleation is presented with inclusion located in the centre of ferrite star, i.e. ferrite needles emanate from the inclusion in multiple directions. This nucleation type is also typical for larger inclusions /12,13/. Formation of acicular ferrite laths at inclusions can induce autocatalytic reaction, so the number of active inclusions does not agree to the number of acicular ferrite plates, /6,12/.

In the former text, acicular ferrite nucleation affected by inclusions is described. This is followed by the so-called induced nucleation. Induced ferrite laths normally nucleate from existing acicular ferrite that has formed by nucleation on inclusions. These induced ferrite needles grow at large angles to initial ferrite needles which they nucleated from, and are smaller in size (compared to initial ferrite needles, Figs. 2d and 3) /12,13/. Acicular ferrite can also induce by nucleation on grain boundaries of proeutectoid ferrite and

eutektoidnog ferita i austenita, ali je ova vrsta nukleacije daleko manje prisutna u poređenju sa intragranularnim tipom nukleacije /12/.



Slika 2. Model nukleacije i pravaca rasta acikularnog ferita: a), b) paralelno; c) normalno na površinu uključaka; d) indukovane nukleacije acikularnog ferita na postojećim feritnim iglicama, /12/

Figure 2. Model of nucleation and orientation growth of acicular ferrite: a), b) parallel; c) perpendicular to inclusion surface; d) acicular ferrite nucleation induced at existing ferrite laths, /12/.

Nukleacioni uključci u šavovima sa srednjim (200–300 ppm) i malim (15–30 ppm) sadržajem kiseonika su sličnih dimenzija, ali su najaktivniji uključci prečnika 0,3–0,9  $\mu\text{m}$  (posebno oni prečnika 0,56  $\mu\text{m}$ ), (Žang i Farar /12/). To se slaže sa rezultatima drugih autora /14,15/ koji su utvrdili da su uključci prečnika  $> 0,2 \mu\text{m}$  najvažniji za nukleaciju acikularnog ferita. Hemijski sastav aktivnih uključaka na kojima nukleira acikularni ferit varira. Sve vrste uključaka, kao što su  $\text{TiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$ ,  $\text{MnO-SiO}_2$ ,  $\text{TiO}$  (ili  $\text{Al}_2\text{O}_3$ )- $\text{MnO-SiO}_2$ ,  $\text{MnS}$  (i  $\text{MnS}$  površinska prevlaka),  $(\text{MnCu})\text{S}$  (i njegova prevlaka) /12,13/,  $\text{TiN}$  /6,4/,  $\text{MnOAl}_2\text{O}_3$  /4,13/,  $\text{MnOTiO}_2$  /10/ mogu da nukleišu acikularni ferit u početnim fazama transformacije. Grong /4/ tvrdi da acikularni ferit nukleira na samo 12% od ukupnog broja uključaka.

#### UTICAJ VELIČINE AUSTENITNOG ZRNA I UNETE TOPLOTE

U istom čeliku sa velikim brojem uključaka, pod istim izotermalnim uslovima transformacije mogu se dobiti i konvencionalni beinit i acikularni ferit. Da bi se dobio beinit, austenitno zrno mora da bude malo, što obezbeđuje da se nukleacija odvija na granici  $\gamma$ - $\gamma$ . Kada je austenitno zrno veliko, broj intragranularnih nukleacionih pozicija (uključaka) je relativno veliki, tako da se acikularni ferit javlja pre nego beinit (što se vidi sa sl. 4). Pločice acikularnog ferita nikada ne seku površinu austenitnog zrna, /26/.

austenite, but this type of nucleation is very rare in comparison to the intragranular nucleation type, /12/.



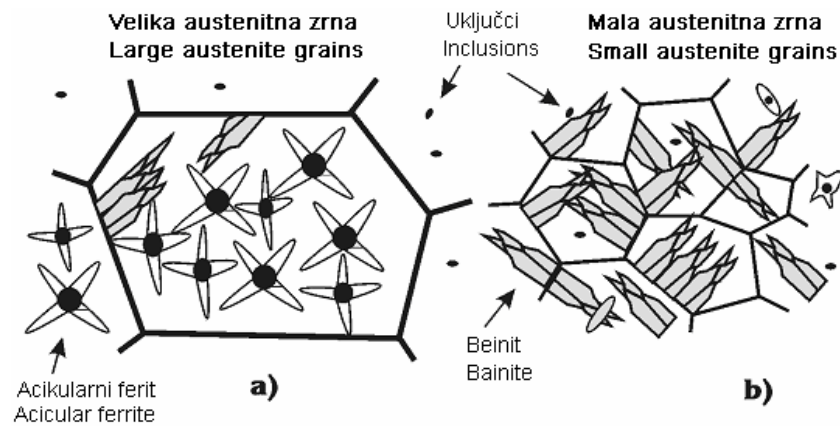
Slika 3. Nukleacija acikularnog ferita na uključcima tipa  $\text{MnOAl}_2\text{O}_3$  ili  $\text{MnS}$  površinska prevlaka, /13/

Figure 3. Acicular ferrite nucleation at inclusions of type  $\text{MnOAl}_2\text{O}_3$  or  $\text{MnS}$  surface coating, /13/.

Nucleation inclusions in welds with mean (200–300 ppm) and low (15–30 ppm) oxygen concentrations are similar in size, but the most active inclusions are 0.3–0.9  $\mu\text{m}$  in diameter (particularly 0.56  $\mu\text{m}$ ), (Zhang and Ferrar, /12/). This agrees with results of other authors /14,15/ who discovered that inclusions  $> 0,2 \mu\text{m}$  in diameter are most important for nucleation of acicular ferrite. The chemical composition of active inclusions, on which acicular ferrite nucleates, varies. All inclusion types, such as  $\text{TiO}_2$ ,  $\text{Al}_2\text{O}_3$ ,  $\text{SiO}_2$ ,  $\text{MnO-SiO}_2$ ,  $\text{TiO}$  (or  $\text{Al}_2\text{O}_3$ )- $\text{MnO-SiO}_2$ ,  $\text{MnS}$  (and  $\text{MnS}$  surface coating),  $(\text{MnCu})\text{S}$  (and its coating) /12,13/,  $\text{TiN}$  /6,4/,  $\text{MnOAl}_2\text{O}_3$  /4,13/,  $\text{MnOTiO}_2$  /10/ can nucleate acicular ferrite in the initial transformation stage. Grong claims /4/ that acicular ferrite nucleates at only 15% of the total inclusions.

#### THE EFFECT OF AUSTENITE GRAIN SIZE AND HEAT INPUT

It is possible to obtain both conventional bainite and acicular ferrite in the same steel with a large number of inclusions under the same isothermal conditions of transformation. In order to obtain bainite, the austenite grain should be fine, assuring nucleation at boundary  $\gamma$ - $\gamma$ . When austenite grain is coarse, the number of intragranular nucleation sites (inclusions) is relatively large, so acicular ferrite will occur rather than bainite (as presented in Fig. 4). Acicular ferrite plates never intersect the austenite grain surface, /26/.



Slika 4. Uticaj veličine austenitnog zrna u određivanju dominantnosti acikularnog feritit beinita u mikrostrukturi: a) Dominantan acikularni ferit; b) Dominantan beinit, /6/  
 Figure 4. The effect of austenite grain size for determining dominance of acicular ferrite or bainite in the microstructure: a) Dominant acicular ferrite; b) Dominant bainite, /6/.

U višeprolaznom zavarenom spoju, svaki naredni prolaz izaziva topljenje površinskog sloja prethodnog prolaza i strukturne promene onih delova prethodnog prolaza koji se zagrevaju iznad temperatura faznih transformacija. Na sl. 5 dat je šematski prikaz uticaja veličine austenitnog zrna i temperatura do kojih su bili zagrejani delovi prethodnog prolaza na udeo acikularnog ferita i ostalih mikrostruktura u ponovo zagrejanom metalu šava mikrolegiranih čelika, /16/.

Pri zavarivanju čelika austenitna zrna u zoni uticaja toplote (ZUT) rastu, a stepen ukupnjavanja zavisi od količine unete toplote. Iz ovoga proizilazi da kada se zavaruju čelici koji sadrže odgovarajuće uključke, količina acikularnog ferita koji se formira u ZUT raste na račun beinita sa porastom količine unete toplote (pri čemu raste i veličina austenitnog zrna), što se vidi sa sl. 6a. Pri veoma velikim količinama unete toplote stepen hlađenja toliko opada da se javljaju veće količine Vidmanštenovog ferita pri čemu dolazi do odgovarajućeg smanjenja količine acikularnog ferita. U čeliku koji ne sadrži odgovarajuće uključke sadržaj acikularnog ferita je uvek veoma mali (sl. 6b), /6/. Pri zavarivanju mikrolegiranih čelika, optimalna uneta količina toplote treba da bude 7–8 kJ/cm, /17/, kao što se vidi na sl. 6, /6/.

#### UTICAJ KISEONIKA U METALU ŠAVA

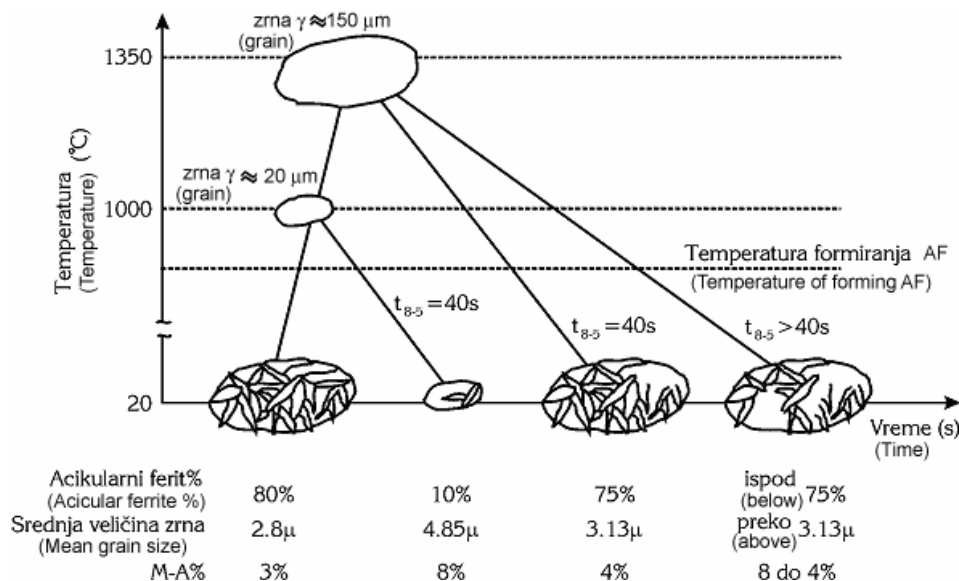
Uticaj kiseonika na mikrostrukturu metala šava je analiziralo više istraživača, /14,18/. Pri zavarivanju topljivom elektrodom u zaštiti inertnog gasa, dodatak kiseonika i/ili ugljendioksida zaštitnom gasu značajno povećava mogućnost apsorpcije kiseonika u metal šava. Međutim, samo deo kiseonika iz atmosfere luka će obrazovati okside sa legirajućim elementima u metalnom kupatilu, jer će većina kiseonika da ode u okolinu. Oksidi će da isplivaju na vrh metalnog kupatila i preći u trosku ili će ostati zarobljeni kao uključci u metalu šava. Kao moguće mesto za nastanak acikularnog ferita ili drugih produkata razlaganja austenita, ovi uključci su važni za određivanje konačne mikrostrukture metala šava.

In multipass welded joints, each subsequent pass melts the surface layer of the previous pass and also alters the structure in regions of the previous pass that are heated above phase transformation temperatures. Figure 5 shows a schematic view of the effects of austenite grain size and the reached temperature in parts of the previous pass on the fraction of acicular ferrite and other microstructures in the re-heated weld metal of microalloyed steel, /16/.

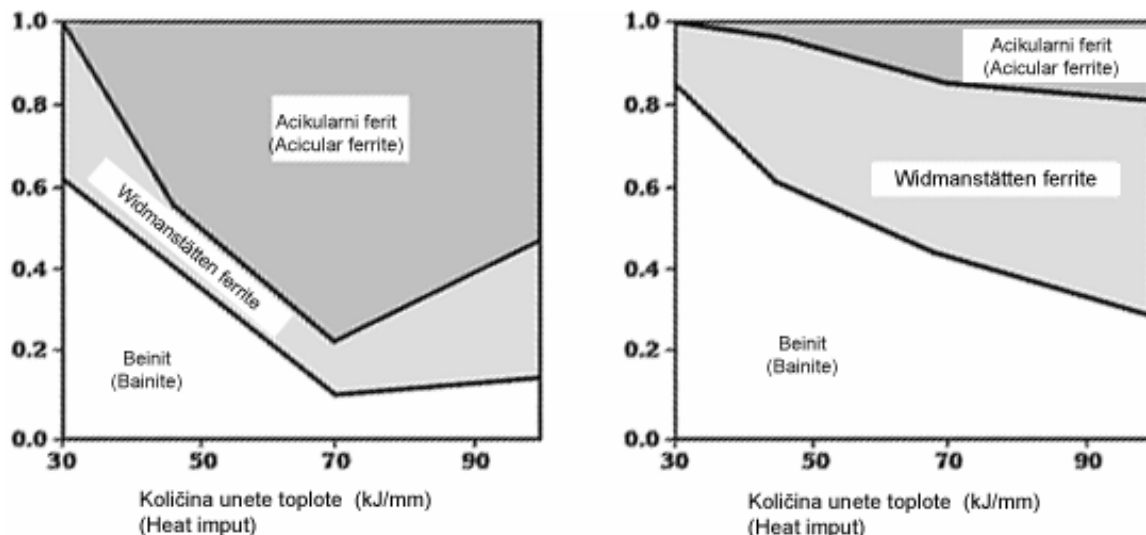
During the welding of steel, austenite grains grow in the heat-affected-zone (HAZ), and the degree of coarsening depends on the heat input. It follows that if steel containing particular inclusions is welded, the amount of acicular ferrite formed in HAZ increases on the account of bainite with increased heat input (austenite grain size is increased at the same time), as presented in Fig. 6a. At extremely high heat inputs, the degree of cooling decreases to the extent producing larger fractions of Widmanstätten ferrite, whilst reducing the corresponding fraction of acicular ferrite. Steel that does not contain the corresponding inclusions always has very small fractions of acicular ferrite (Fig. 6b), /6/. In the case of welding microalloyed steel, the optimal heat input should be 7–8 kJ/cm, /17/, as shown in Fig. 6, /6/.

#### THE EFFECT OF OXYGEN IN WELD METAL

The effect of oxygen on the weld metal microstructure has been analysed by several researchers, /14,18/. When welding with a melting electrode in inert gas shield, the addition of oxygen and/or carbon dioxide to the gas mixture significantly increases the possibility of oxygen absorption in the weld metal. However, only some part of the oxygen from the arc atmosphere will form oxides of alloying elements in the molten pool since most of it will dissipate into the surrounding atmosphere. Oxides will surface in the molten pool and create slag or will retain as inclusions in the weld metal. As possible places for nucleation of acicular ferrite and other products of austenite decomposition these inclusions are important for determining the final weld metal microstructure.



Slika 5. Šematski prikaz promene veličine zrna i mikrostrukture tokom toplotnih ciklusa pri zavarivanju, /16/  
Figure 5. Schematic view of the change in grain size and microstructure during thermal cycles of welding, /16/.



Slika 6. Promena mikrostrukture čelika u ZUT u zavisnosti od unete toplote zavarivanjem:  
a) Čelik koji sadrži čestice TiO, b) Običan čelik bez uključaka, /6/  
Figure 6. Change of HAZ microstructure in function of welding heat input:  
a) Steel containing TiO particles. b) Ordinary steel without inclusions, /6/.

Ito i saradnici su pokazali da se sa porastom koncentracije kiseonika u metalu šava (a time i povećanjem sadržaja uključaka) mikrostruktura, koja sadrži beinit, zamenjuje acikularnim feritom, /6/. Kasnije je pokazano da mala količina kiseonika pomera krivu početka transformacije ka dužim vremenima, ali se pri većoj količini kiseonika dešava suprotno, kako se vidi sa sl. 7, gde su date krive kontinuiranog hlađenja metala šava konstrukcijskih čelika (tačka početka austenitnog razlaganja se menja sa promenom sadržaja kiseonika u metalu šava), /18/. Kada je u metalu šava prisutna manja količina kiseonika (što implicira i manji broj uključaka), odnos dužina/širina iglica AF se povećava, što prouzrokuje pad žilavosti /19/.

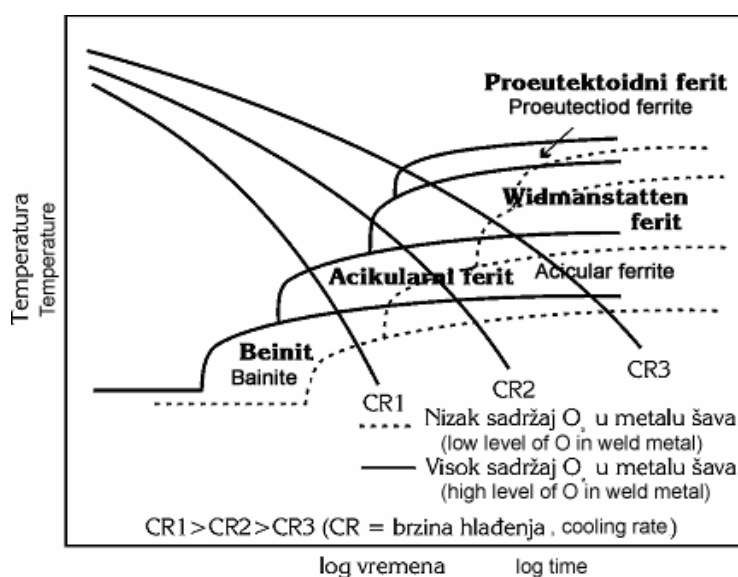
Metal šava sa malom količinom kiseonika, ispod 250 ppm (kao što je slučaj TIG zavarivanja i zavarivanja u zaštiti gasa sa malim ekvivalentom kiseonika), ima krivu početka feritne transformacije pomerenu unapred po vremenskoj skali.

Ito and co-workers have shown that along with increase of oxygen concentration in weld metal (also followed by increase of inclusion content), the microstructure containing bainite is replaced by acicular ferrite, /6/. Later it was shown that small amounts of oxygen shift the transformation initiation curve to longer time, but with higher amounts of oxygen the process is reversed, as seen in Fig. 7, with continuous cooling curves of weld metal for structural steel (the onset of austenite decomposition changes with oxygen content in weld metal), /18/. When small amounts of oxygen are present in weld metal (also indicating smaller number of inclusions), the length/width ratio of AF needles increases, causing drop in toughness /19/.

Weld metal with small amounts of oxygen, below 250 ppm (as is the case with TIG welding and gas shielded welding with small oxygen equivalent), has its curve of ferrite transformation start shifted forward in time.

Ovaj uticaj je sličan uticaju elemenata koji ojačavaju čelik i koji pomažu obrazovanju ferita sa sekundarnim fazama u obliku beinita. Za istu brzinu hlađenja, sa porastom količine kiseonika u zaštitnom gasu, nastaje oksidacija ojačavajućih elemenata, pa se početak feritne transformacije pomera ka kraćim vremenima, što pogoduje obrazovanju dominirajuće strukture acikularnog ferita u metalu šava (sadržaj kiseonika od 250–450 ppm). Sa daljim porastom sadržaja kiseonika u zaštitnom gasu, u mikrostrukturi metala šava počće da dominira Vidmanštetenov ferit, odnosno ferit sa sekundarnom fazom. Oblik KH dijagrama takođe ukazuje na malu osetljivost količine proeutektoidnog ferita koji se izdvaja po granicama zrna na promenu u sastavu zaštitnog gasa, /18,20/.

This effect is similar to the effect of steel hardening by elements that contribute the formation of ferrite with secondary phases in the form of bainite. Oxidation of hardening elements initiates at the same cooling rate with the increase of oxygen concentration in shielding gas, and so the onset of ferritic phase transformation shifts to shorter times and benefits the formation of dominant acicular ferrite in weld metal (oxygen content of 250–450 ppm). Further increase of oxygen in the shielding gas causes a dominating Widmanstätten ferrite microstructure in weld metal, i.e. ferrite with secondary phases. The shape of the CCT diagram also indicates small influence the changes in the shielding gas composition have on proeutectoid ferrite, precipitating at grain boundaries, /18,20/.



Slika 7. KH dijagram koji ilustruje efekt sadržaja kiseonika u metalu šava i brzine hlađenja, /18/  
Figure 7. The CCT diagram illustrating the influences of hydrogen in weld metal and the cooling rate, /18/.

#### UTICAJ LEGIRAJUĆIH ELEMENATA NA FORMIRANJE ACIKULARNOG FERITA

##### Titan i bor

Ispitivanjem je ustanovljeno da Ti i B poboljšavaju mehaničke osobine metala šava /21,22/. Odgovarajućim odnosom Ti i B može da se suzbije nukleacija ferita po granicama zrna (primarnog ferita). Predloženo je više mehanizama za objašnjenje uticaja B na nukleaciju ferita po granicama zrna /21,23/. Jedan od mehanizama ukazuje da B, kao slobodan element, može da difunduje ka granicama prvobitnih austenitnih zrna i smanjuje energiju granica zrna. Ovo smanjenje energije vodi ka povećanju energetske barijere za nukleaciju ferita i smanjenju ferita po granicama zrna. Titan štiti bor od kiseonika i azota. Nitrid titana se formira na višim temperaturama od nitrida bora i omogućava boru da ostane slobodan i da difunduje ka granicama zrna prvobitnog austenita /21,24/. Uključci Ti su se pokazali povoljnim za formiranje jezgara acikularnog ferita unutar zrna.

Optimalna žilavost metala šava čelika povišene čvrstoće (HSLA-100) se javlja pri nivou Ti od 150 ppm. Malo povećanje sadržaja Ti u metalu šava kod ovih čelika značajno smanjuje udarnu žilavost pri  $-60^{\circ}\text{C}$ , tako da posle izvesnog sadržaja Ti postaje nepoželjan u metalu šava, /21/.

#### THE EFFECT OF ALLOYING ELEMENTS ON THE FORMATION OF ACICULAR FERRITE

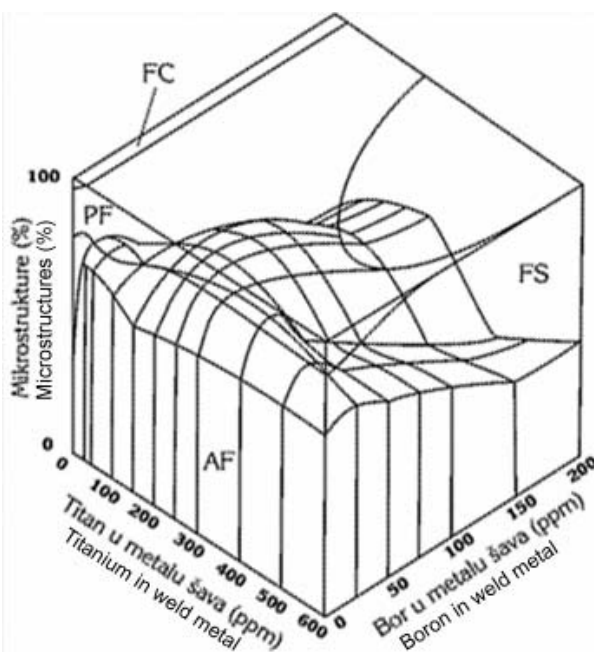
##### Titanium and boron

It has been established by tests that Ti and B improve mechanical properties of the weld metal /21,22/. The corresponding Ti and B ratio makes it possible to suppress ferrite nucleation at grain boundaries (of primary ferrite). Several mechanisms are proposed for the explanation of B affecting nucleation of ferrite at grain boundaries /21,23/. One mechanism indicates that B, as a free element, can segregate to primary austenite grain boundaries and reduce grain boundary energy. This energy reduction causes the increase of energy barrier for ferrite nucleation and reduction of ferrite at grain boundaries. Titanium nitride is formed at higher temperatures than boron nitride and enables B to remain free and segregate to primary austenite grain boundaries /21,24/. Inclusions of Ti have shown to be beneficial for the formation of acicular ferrite inside grain.

Optimum toughness of weld metal in high strength steel (HSLA-100) is achieved for Ti level of 150 ppm. Small increase in Ti in the weld metal of these steels substantially decreases impact toughness at  $-60^{\circ}\text{C}$  and so excess amounts of Ti become undesirable in the weld metal, /21/.

Evans je proučavao uticaj Ti i B na mikrostrukturu i osobine feritnih čelika i dao trodimenzioni model kompjuterski obrađenih podataka (sl. 8). Sa sl. 8 se vidi da se maksimalan sadržaj acikularnog ferita javlja pri 250–400 ppm Ti u kombinaciji sa 40–50 ppm B. Veća količina B dovodi do naglog pada zapreminskog udela acikularnog ferita i ta pojava, na koju takođe utiče prisustvo azota, se još uvek izučava /24/.

Evans studied the effect of Ti and B on microstructure and properties of ferritic steels and proposed three-dimensional model of computational data (Fig. 8). It can be seen from Fig. 8 that maximal concentration of acicular ferrite is for 250–400 ppm of Ti combined with 40–50 ppm of B. Higher amount of B produces sharp drop in acicular ferrite volume fraction and this phenomenon, affected also by nitrogen, and is still the subject of research, /24/.



Slika 8. Mikrostrukturni model metala šava koji sadrži Ti i B (N = 75 ppm), /24/  
Figure 8. Microstructural model of weld metal, containing Ti and B (N = 75 ppm), /24/.

### Mangan, nikal, hrom i molibden

Legirajući elementi, kao što su Mn, Ni, Cr i Mo, ojačavaju metal šava ili čvrstim rastvaranjem (supstitucijsko ojačavanje) ili česticama sekundarnih faza (taložno ojačavanje) i imaju značajan uticaj na konačnu mikrostrukturu, jer reagovanjem sa kiseonikom formiraju uključke koji služe kao jezgra nukleacije, /21/. Prisustvo ovih elemenata u čvrstom rastvoru prouzrokuje smanjenje proeutektoidnog ferita na račun povećanja zapreminskog udela acikularnog ferita (samo do određenog stepena legiranja). Pri većim sadržajima ovih elemenata dolazi do smanjenja zapreminskog udela acikularnog ferita u strukturi /6/ na račun povećanja udela ferita sa sekundarnom fazom /25,26,27/, a u nekim slučajevima i martenzita, /25/.

Rezultati ispitivanja Žanga i Farara /12/ pokazuju da dodaci Ni metalu šava pospešuju obrazovanje acikularnog ferita /21/, pri čemu se povećava i odnos dužina/širina iglica AF /19/, a smanjuje se količina proeutektoidnog ferita pri povećanju sadržaja Mn. Mangan kao primarni legirajući element metala šava stabilizuje austenit na nižim temperaturama, što može dovesti do formiranja beinita i martenzita. Zahvaljujući njegovoj sposobnosti da obrazuje uključke (npr.  $MnO \cdot Al_2O_3$ ), koji se ponašaju kao mesta formiranja acikularnog ferita, dolazi do povećanja čvrstoće, odnosno žilavosti, /21/. Primećen je potencijal Mn jači od potencijala Ni za suzbijanje formiranja Vidmanštetenovog ferita, /28/. Ovo potvrđuje prethodne rezultate Evansa, (sl. 9), /25,28/.

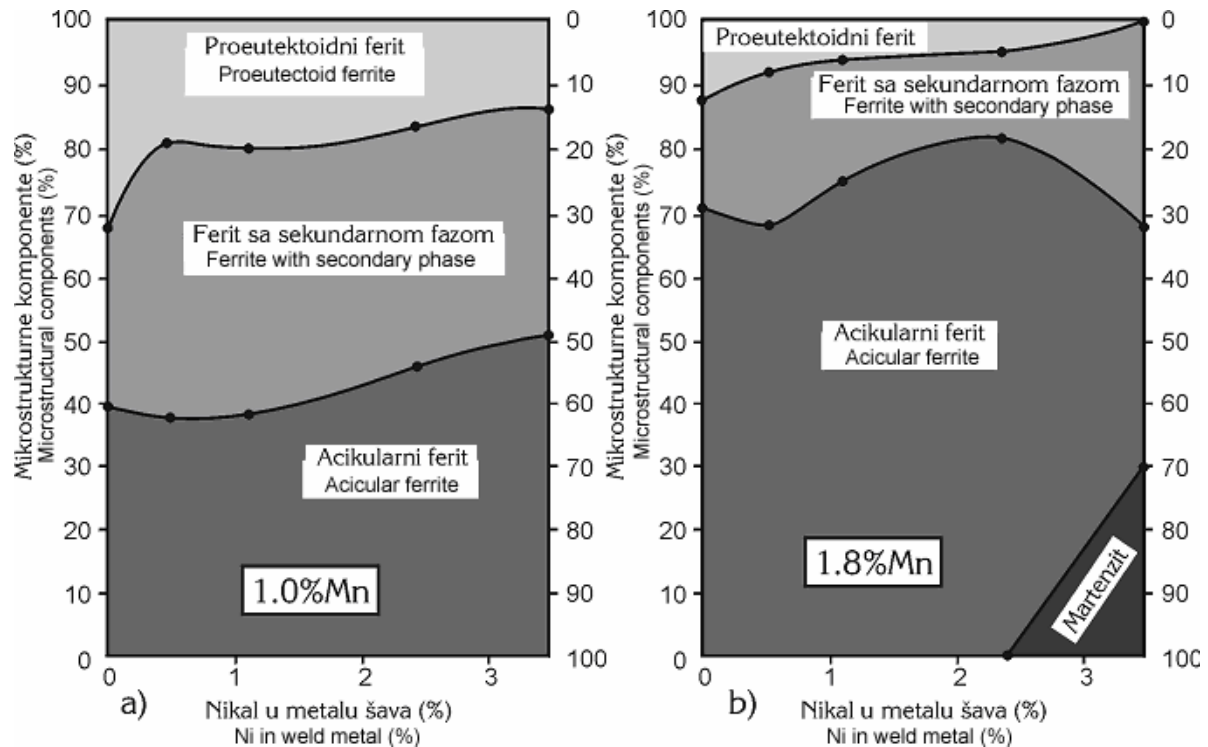
### Manganese, nickel, chromium and molybdenum

Alloying elements such as Mn, Ni, Cr and Mo, strengthen the weld metal either by solid solution (substitution hardening) or by second phase particles (precipitation hardening) and significantly affect the final microstructure, because reacting with oxygen they form inclusions serving as nucleation sites, /21/. The presence of these elements in the solid solution causes decrease in proeutectoid ferrite on the account of the acicular ferrite volume fraction increase (only up to a certain alloying degree). Higher contents of these elements tend to decrease the acicular ferrite volume fraction in the structure /6/ due to the fractional increase in ferrite with secondary phase /25,26,27/, and also martensite in some cases, /25/.

The results of Zhang and Farrar /12/ show that addition of Ni to weld metal intensifies acicular ferrite formation /21/, followed by an increase in length/width ratio of AF needles /19/, and the amount of proeutectoid ferrite decreases with higher Mn content. Manganese, as the primary alloying element of weld metal, stabilizes austenite at lower temperatures which may lead to the formation of bainite and martensite. Owing to its capability to form inclusions (e.g.  $MnO \cdot Al_2O_3$ ) that behave as sites for acicular ferrite formation, the strength and toughness are increased /21/. A stronger potential of Mn, rather than Ni, has been noticed to suppress formation of Widmannstätten ferrite, /28/. This confirms previous results of Evans, (Fig. 9), /25,28/.



Sa sl. 9 se jasno vidi da pri većim sadržajima Mn i Ni, u mikrostrukturi može da se pojavi i martenzit na račun smanjenja acikularnog ferita, /25/.



Slika 9. Uticaj Ni na mikrostrukturu zavarenog spoja pri: a) 1% Mn; b) 1,8% Mn, /25/  
Figure 9. The effect of Ni on the welded joint microstructure, for: a) 1% Mn; b) 1.8% Mn, /25/.

Kombinovanjem rezultata Žanga i Farara sa podacima Harisona, Farara i Evansa dobijena je zavisnost zapreminskog udela acikularnog ferita od odnosa sadržaja Ni i Mn u C-Mn-Ni metalu šava, a pri nivou ugljenika 0,04–0,05%, (sl. 10), /28/.

Slika 10 ukazuje na postojanje optimalnog opsega sadržaja Ni i Mn pri kojem se ostvaruje visok procenat acikularnog ferita. Kombinacijom sadržaja Ni i Mn unutar ovog opsega moguće je postići 70 do 85% acikularnog ferita, dok sastavi van ovog opsega dovode do pojave velike količine proeutektoidnog ferita ili martenzita, što u oba slučaja prouzrokuje smanjenje žilavosti. Sa sl. 10 se vidi da se  $M_s$  linija nalazi u oblasti sastava sa najvećim ostvarenim procentom acikularnog ferita. Ukoliko bi sadržaji Ni i Mn bili iznad  $M_s$  linije, u mikrostrukturi bi se pored velike količine acikularnog ferita pojavila i izvesna količina martenzita, što znatno smanjuje žilavost metala šava. Optimalne vrednosti žilavosti se dobijaju za metal šava kod kojeg je sadržaj Ni i Mn dovoljno daleko od linije  $M_s$ , a iznad oblasti bogate proeutektoidnim feritom, (sl. 11), /28/.

Poređenjem rezultata sa sl. 10 i 11 je zaključeno da se najbolja žilavost dobija sa mikrostrukturama od 50–75% acikularnog ferita sa ostalim proeutektoidnim feritnim komponentama. Mikrostrukture sa većim sadržajem acikularnog ferita (> 75%) ne daju očekivana svojstva jer prisustvo segregacija i/ili martenzita može da neutrališe pozitivne efekte acikularnog ferita. Stoga je potrebno biti pažljiv pri pokušaju da se ostvari visoka proporcija acikularnog ferita povećanjem sadržaja legirajućih elemenata. Ukoliko se zava-

Figure 9 clearly depicts that for higher concentrations of Mn and Ni can also result in the appearance of martensite on the account of decrease in acicular ferrite, /25/.

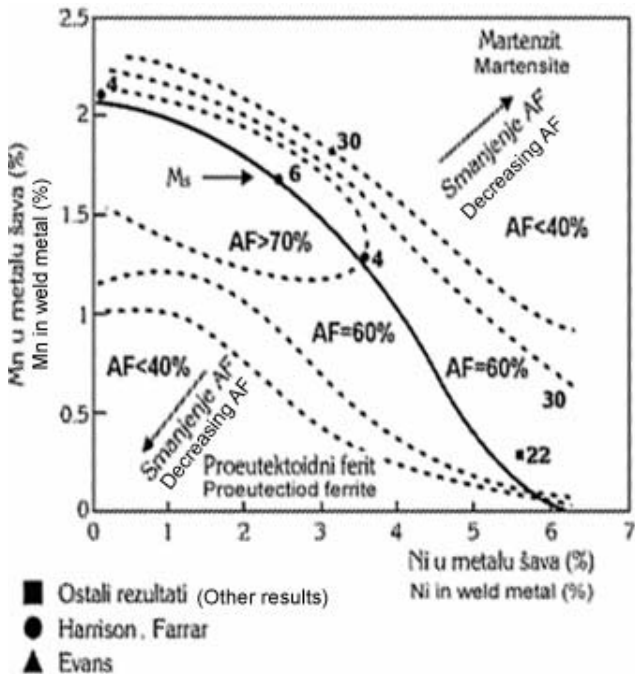
Combining Zhang and Farrar results with data of Harrison, Farrar and Evans gives the dependence of acicular ferrite volume fraction on the content ratio of Ni and Mn in C-Mn-Ni weld metal, at carbon level 0,04–0,05%, (Fig. 10), /28/.

Figure 10 indicates the existence of optimal Ni and Mn content range at which high percentage of acicular ferrite is achieved. By combining Ni and Mn content inside this range it is possible to reach 70 to 85% acicular ferrite, whereas the compositions outside this range allow for high quantity of proeutectoid ferrite or martensite, causing decrease of toughness in both cases. It can be seen from Fig. 10 that the  $M_s$  curve is situated in the composition region with the highest achieved acicular ferrite percentage. If concentrations of Ni and Mn should be above the  $M_s$  curve, some martensitic content would appear in the microstructure, apart from the high level of acicular ferrite, thus significantly decreasing weld metal toughness. Optimal weld metal toughness values are obtained for contents of Ni and Mn that are far from the  $M_s$  curve and above the region rich in proeutectoid ferrite, (Fig. 11), /28/.

Comparison of results in Figs. 10 and 11 has concluded that the best toughness is obtained with microstructures of 50–75% acicular ferrite with other proeutectoid ferrite components. Microstructures with higher acicular ferrite content (> 75%) do not show expected properties because presence of segregations and/or martensite can neutralize positive effects of acicular ferrite. Hence, it is necessary to be cautious attempting to achieve high acicular ferrite proportion by increasing alloying elements. In case of multipass

riavanje izvodi u više prolaza, u ponovo zagrejanim zonama udeo PF se smanjuje na račun povećanja udela AF, /28/.

Hrom pri malim sadržajima u metalu šava utiče na povećanje udela acikularnog ferita u mikrostrukturi na račun smanjenja proeutektoidnog ferita, dok pri većim sadržajima dovodi do povećanja udela ferita sa sekundarnom fazom (FS), /26/, što je prikazano na sl. 12.

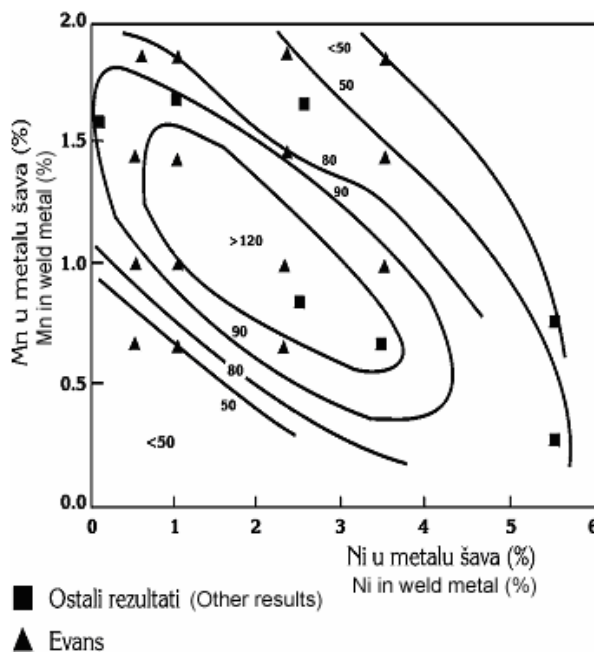


Slika 10. Uticaj sadržaja Mn i Ni na zapreminski udeo acikularnog ferita u metalu šava (C = 0,04–0,05%), sa ucrtanom linijom početka martenzitne transformacije (M<sub>s</sub>), /28/

Figure 10. The effect of Mn and Ni on acicular ferrite volume fraction in weld metal (C = 0.04–0.05%) with the curve of martensite transformation start (M<sub>s</sub>), /28/.

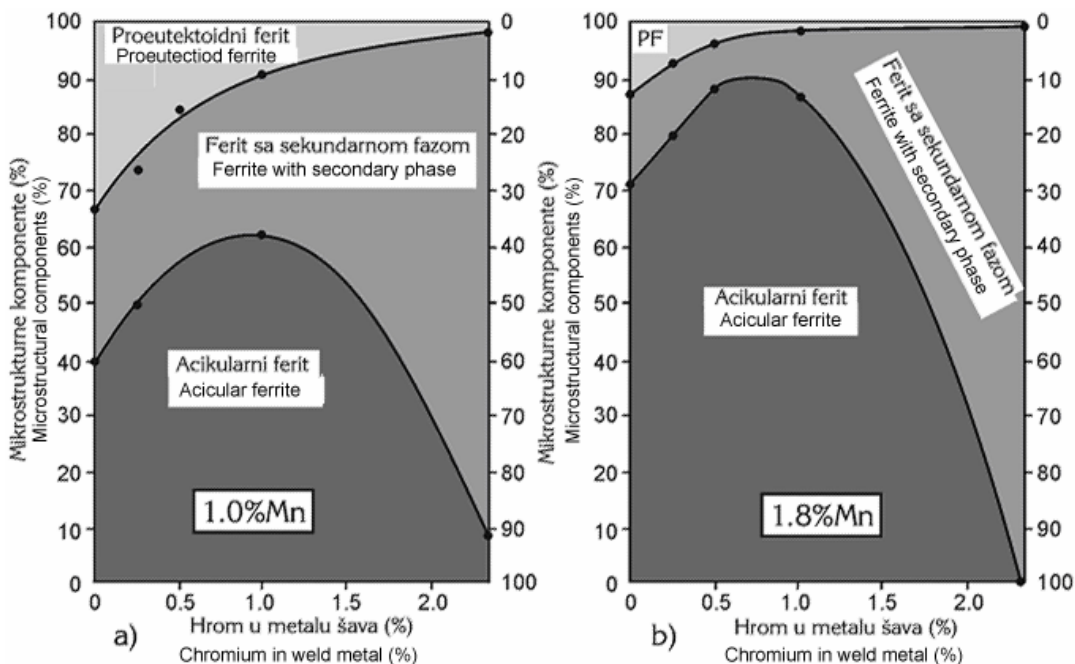
welding, the PF fraction is reduced on the account of increased AF fraction in the reheated zones, /28/.

Small contents of chromium in weld metal affects the increase of acicular ferrite fraction in the microstructure on the account of proeutectoid ferrite decrease, whereas higher content leads to fraction increase of ferrite with secondary phase (FS), /26/, as presented in Fig. 12.



Slika 11. Uticaj sadržaja Mn i Ni u metalu šava na Šarpi energiju, na -50°C, /28/

Figure 11. The effect of Mn and Ni in weld metal on the Charpy energy, at -50°C, /28/.

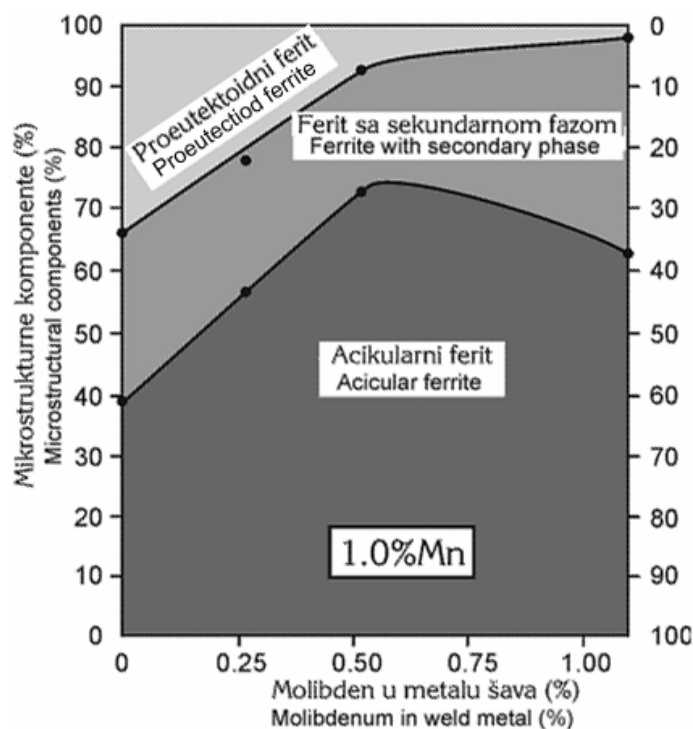


Slika 12. Uticaj sadržaja Cr u metalu šava na mikrostrukturu pri: a) 1,0% Mn; b) 1,8% Mn, /26/

Figure 12. The effect of Cr in weld metal on the microstructure at: a) 1.0% Mn; b) 1.8% Mn, /26/.

Pri 0,25% Cr između iglica acikularnog ferita se nalaze martenzitno/austenitne (M/A) mikrofaze. Prisustvo Mo utiče na smanjenje proeutektoidnog ferita, pa ga pri sadržaju od 1,1% Mo, gotovo nema u mikrostrukтури (sl. 13).

At 0.25% of Cr, the martensite/austenite (M/A) micro phase is found between acicular ferrite laths. The presence of Mo affects the decrease of proeutectoid ferrite and at 1.1% Mo, there is none in the microstructure (Fig. 13).



Slika 13. Uticaj sadržaja Mo na mikrostrukтуру metala šava pri 1% Mn, /27/  
Figure 13. The effect of Mo content in weld metal on the microstructure, at 1% Mn, /27/.

Povećanje sadržaja Mo do 0,5% dovodi do povećanja zapreminskog udela acikularnog ferita, a dalje povećanje sadržaja Mo u metalu šava dovodi do smanjenja AF na račun povećanja udela ferita sa sekundarnom fazom /27/.

I u slučaju legiranja sa Cr i sa Mo, udeo Vidmanštetenovog ferita u feritu sa sekundarnom fazom se smanjuje vrlo malo pri povećanju udela ovih legirajućih elemenata, dok se zapreminski udeo ferita sa sekundarnom fazom drastično povećava posle određenog stepena legiranja, jer se pri tome povećava zapreminski udeo beinita (prisutnog u feritu sa sekundarnom fazom). Ovo je prouzrokovano smanjenjem proeutektoidnog ferita, pa granice austenitnog zrna postaju slobodne za nukleaciju beinita, /6/.

#### ŽILAVOST ACIKULARNOG FERITA

Acikularni ferit ima veoma dobru žilavost zbog male veličine zrna i visokougane granice zrna, pa je propagacija mikroprslina cik-cak (sama se koči) /5,6/. Znači, prslina menja pravac rasta svaki put pri prelazu iz jedne u drugu pločicu acikularnog ferita, koje su međusobno različito orijentisane (sl. 14).

Povećana žilavost acikularne morfologije u odnosu na morfologiju snopova (beinita) je razumljiva ako se zna da su pojedine pločice acikularnog ferita znatno manje od beinitnih snopova, odnosno da u strukturi acikularnog ferita postoji znatno veći broj granica koje primoravaju rastuću prslinu da menja pravac (sl. 14a).

The increase of Mo up to 0.5% leads to the increase of acicular ferrite volume fraction, and a further increase of Mo in the weld metal leads to AF decrease on the account of the fraction increase of ferrite with secondary phase /27/.

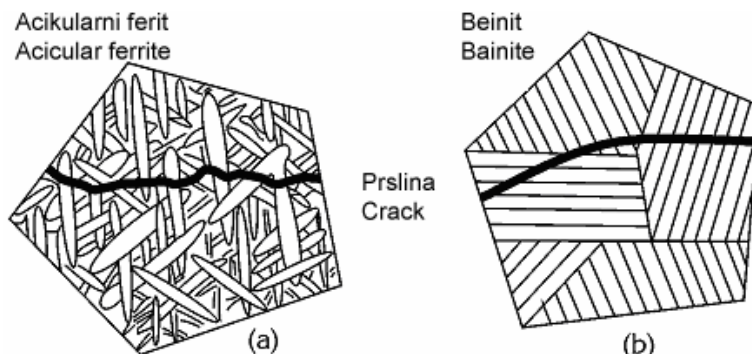
Also, in the case of alloying with both Cr and Mo, when the concentration of these elements increases, the fraction of Widmannstätten ferrite inside the ferrite with secondary phase decreases a small amount, whereas the volume fraction of the ferrite with secondary phase drastically increases after a certain alloying degree, since the volume fraction of bainite increases (existing in ferrite with secondary phase). This is due to decrease in proeutectoid ferrite, so austenite grain boundaries become free for bainite nucleation, /6/.

#### ACICULAR FERRITE TOUGHNESS

Acicular ferrite is characterized by very good toughness due to small grain size and high angle grain boundaries, so the growth of the crack is zigzag (self-arresting crack) /5,6/. This means the crack changes its direction by travelling from one to another acicular ferrite plate that are differently oriented (Fig. 14).

Increased toughness of acicular morphology compared to bundle morphology (bainite) is understandable, knowing that individual plates of acicular ferrite are significantly smaller than bainite bundles, i.e. a larger number of boundaries exist in the acicular ferrite structure forcing the growing crack to change its direction (Fig. 14a).

Kretanje prsline kroz beinitne snopove prikazano je na sl. 14b. Prsline menja pravac rasta kada naiđe na granice različito orijentisanih snopova. Granice pločica ne menjaju pravac rasta prsline jer imaju istu kristalografsku orijentaciju, pa je žilavost morfologije snopova veća ukoliko je prečnik snopova manji, /1,29/.



Slika 14. Šematski prikaz rasta krte prsline kroz: a) acikularni ferit, b) beinitne snopove, /1/  
Figure 14. Scheme of brittle crack growth across: a) acicular ferrite; b) bainite bundles, /1/.

Fleming sa saradnicima se bavio ispitivanjem metala šava čelika povišene čvrstoće i dokazao da su povećana žilavost i čvrstoća metala šava u direktnoj vezi sa sadržajem acikularnog ferita, /21/, tj. da struktura AF ima veliku otpornost na propagaciju prsline, /19/. Bitno je naglasiti da je dužina iglica AF važan faktor koji utiče na žilavost, tj. smanjenjem odnosa dužina/širina iglica AF, povećava se žilavost, /19,30/.

Mnogi istraživači su se bavili određivanjem procentualnog udela AF u strukturi metala šava i njegovog uticaja na žilavost /21,28,31,32/. Tako je Fleming sa saradnicima pokazao da metal šava sa najvećom žilavošću sačinjava u suštini dvofazna mikrostruktura – 60% acikularnog ferita i 30% martenzita, /21/. Farrar i Hanson su došli do zaključka da se najbolja kombinacija svojstava niskolegiranog metala šava može ostvariti pri više od 65% acikularnog ferita, /28,31/. Svensson i Gretoft su takođe istakli pozitivan uticaj od samo 50% acikularnog ferita, /38,32/. Žang i Farrar su ispitivali C-Mn-Ni metal šava i došli su do zaključka da kombinacija 50–75% acikularnog ferita i strukture alotriomorfog ferita na granicama zrna obezbeđuje najbolju žilavost, dok visoka proporcija acikularnog ferita (koja se vezuje za druge mikrostrukturne pojave, kao što su martenzit i strukture segregacije) daje slabija svojstva, /28/.

## ZAKLJUČAK

U ovom radu je analizirana nestandardna morfologija ferita, tj. acikularni ferit, čije prisustvo direktno utiče na mehanička svojstva metala šava. Kako su u strukturi metala šava mikrolegiranih čelika zastupljeni različiti morfološki oblici ferita, njegova mehanička svojstva, a naročito žilavost zavise od najzastupljenije morfologije. Pokazalo se da je acikularni ferit najpoželjniji morfološki oblik ferita. Zato treba poznavati sve faktore koji utiču na pojavu ne samo acikularnog ferita, nego i drugih oblika ferita, jer se acikularni ferit nikada ne javlja samostalno. Tako se može, izborom odgovarajućih parametara, postići morfologija koja daje najbolje karakteristike metala šava.

Crack movement across bainite bundles is presented in Fig. 14b. The crack changes its direction when it reaches boundaries of differently oriented bundles. Plate boundaries do not change crack growth direction, because they have the same crystallographic orientation, so bundle morphology toughness is higher for smaller bundle diameter, /1,29/.

Fleming and co-workers investigated the weld metal of high strength steel and proved that increased toughness and strength are directly correlated to acicular ferrite concentration, /21/, i.e. that the AF structure has great resistance to crack growth, /19/. It is emphasized that AF needle length is an important factor affecting toughness, i.e. by decreasing the length/width ratio of AF needles, the toughness increases, /19,30/.

Many researchers investigated determining the fraction percentage of AF in weld metal structure and its effect on the toughness /21,28,31,32/. Thus, Flemming and co-workers had shown in fact that the microstructure of weld metal of the highest toughness is consisted of two phases – 60% of acicular ferrite and 30% of martensite, /21/. Farrar and Hansson came to the conclusion that the best combination of characteristics of low alloyed weld metal can be obtained with over 65% of acicular ferrite, /28,31/. Svensson and Gretoft also emphasized a positive effect of only 50% of acicular ferrite, /38,32/. Zhang and Farrar investigated C-Mn-Ni weld metal and concluded that the combination of 50–75% of acicular ferrite and allotriomorphic ferrite at the grain boundaries assures the best toughness, while the high acicular ferrite proportion (connected with other microstructural phenomena, such as martensite and segregation structures) produces weaker properties, /28/.

## CONCLUSION

In this paper the non-standard ferrite morphology is analysed, i.e. acicular ferrite, whose existence directly affects weld metal mechanical properties. Since different ferrite morphological forms exist in the weld metal structure, its mechanical properties, especially toughness, depend mostly on the dominant morphology. It has been shown that acicular ferrite is the most desirable morphology of ferrite. Hence, it is necessary to know all factors affecting the occurrence not only of acicular ferrite, but also other ferrite forms, since acicular ferrite never occurs singularly. By selecting corresponding parameters, it is possible to obtain the morphology for the best properties of the weld metal.

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