R. Prokić-Cvetković, A. Milosavljević, A. Sedmak, Z. Burzić

UTICAJ UNETE KOLIČINE TOPLOTE PRI ZAVARIVANJU NA ŽILAVOST METALA ŠAVA MIKROLEGIRANIH ČELIKA

THE EFFECT OF WELDING HEAT INPUT ON THE WELD METAL TOUGHNESS OF MICRO-ALLOYED STEELS

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Adresa autora / Author's address: R. Prokić-Cvetković, A. Milosavljević, A. Sedmak, Mašinski fakultet, Beograd, 27. marta 80. Z. Burzić, Vojnotehnički institut, Beograd, Katanićeva 15

Ključne reči:
- **zavarivanje u zaštiti gasom**
- **mešavina gasova**
- **žilavost metala šava**
- **mikrolegirani čelici**
- **količina unete toplote**

Keywords:
- **gas shielded welding**
- **shielded gas mixture**
- **weld metal toughness**
- **microalloyed steels**
- **heat input**

Izvod

Žilavost metala šava, jedan od kriterijuma prihvatljivosti zavarenog spoja, zavisi od količine unete toplote. Udarna žilavost metala šava dva toplo valjana mikrolegirana čelika, zavarena elektrolučnim postupkom u zaštiti mešavine gasova (Ar+5% CO_2+0,91% O_2) je ispitana merenjem energije loma na instrumentiranom Šarpijevom klatnu. Utvrđeno je da je količina unete toplote od 7 kJ/cm optimalna za žilavost metala šava oba ispitivana čelika. Energija rasta prsline, kao bitna za žilavost metala šava, je za ovu količinu unete toplote veća od kritične, pa se ovako zavareni spoj može preporučiti za konstrukcije koje rade na niskim temperaturama.

Abstract

Weld metal toughness, one of weldment acceptability criteria, depends on heat input. Weld metal impact toughness of two hot rolled microalloyed steels, welded by electric arc with mixture gases shielding (Ar+5% CO_2+0,91% O_2) is tested by measuring impact energy on instrumented Charpy pendulum. It has been found that heat input of 7 kJ/cm is optimal for weld metal toughness of both investigated steels. Crack growth energy, as substantial for weld metal toughness, is for this heat input higher than critical, and welded joint, produced in this way, can be recommended for manufacturing of welded structures for low temperature application.

UVOD

Za zavarivanje savremenih mikrolegiranih čelika se sve češće koriste postupci sa zaštitom pomoću mešavine gasa. Količina unete toplote pri zavarivanju ovih čelika u velikoj meri utiče na osobine zavarenog spoja. Taj se uticaj najviše iskazuje na žilavost konstituenata zavarenog spoja, a naročito na žilavost metala šava.

Za uspešnu primenu mikrolegiranih čelika za zavarene konstrukcije preduslov je zadovoljavajuća žilavost zavarenog spoja i metala šava. Zbog toga je u ovom radu eksperiment posvećen analizi uticaja količine unete toplote pri zavarivanju u zaštiti mešavine gasova na žilavost metala šava dva mikrolegirana čelika.

UDARNA ŽILAVOST

Udarna žilavost, važna karakteristika materijala, ni do danas nije potpuno razjašnjena. Značajan korak u razumevanju suštine udarne žilavosti je učinjen instrumentacijom Šarpijevog klatna pomoću osciloskopa, koja omogućava razdvajanja ukupne energije udara E_u na energiju iniciranja E_{inc} i energiju rasta prsline E_{lom}:

$$E_u = E_{inc} + E_{lom}$$

INTRODUCTION

Welding procedures with gas mixture shielding are frequently used for microalloyed steels welding. Heat input by welding of these steels affects strongly the properties of weldment. This effects is mostly expressed on the toughness of welded joint constituents, especially on weld metal toughness.

The precondition for successful use of microalloyed steels for welded structures is satisfactory toughness of weldment and of weld metal. For that, the experiment in this paper is devoted to the analysis of heat input effect on weld metal toughness of two microalloyed steels, welded by shielding with gas mixture.

IMPACT TOUGHNESS

Impact toughness, an important material property, up to now is not completely clarified. Significant step in understanding of impact toughness meaning is made by the instrumentation of Charpy equipment using an oscilloscope. enabling the separation of total impact energy E_u on crack initiation E_{inc} and crack growth E_{lom} parts:

$$E_u = E_{inc} + E_{lom}$$

Kako instrumentirana ispitivanja udarne žilavosti još uvek nisu standardizovana, treba koristiti eksperimentalno proverene preporuke, npr. izdate od strane Evropskog društva za integritet konstrukcija - ESIS /1/.

Ukoliko dva materijala imaju jednake vrednosti žilavosti, tj. ukupnu energiju udara, sa aspekta žilavosti biće bolji onaj materijal kod koga je energija iniciranja prsline mala, a energija rasta prsline velika. U nekim slučajevima u ukupnoj energiji udara, iako je ona veća od kritične vrednosti, može da dominira energija za stvaranje prsline, sa malim udelom energije duktilnog loma. U tom slučaju kriterijum ukupne energije udara ne može da garantuje sigurnost prema rastu prsline, pa se ne može isključiti lom sa katastrofalnim posledicama /2/. Drugim rečima, ako prslina već postoji, a sa tim treba računati kod zavarenih spojeva /3/, kritična vrednost žilavosti se odnosi samo na deo energije potreban za rast prsline. Različiti su literaturni podaci o kritičnoj ukupnoj vrednosti žilavosti, od 28 J /4-6/, preko 35 J /7/, sve do preporuke još oštrijeg kriterijuma za mikrolegirane čelike od 40 J /8/.

EKSPERIMENT I PRIKAZ REZULTATA

Zavarene su toplovaljane trake dva mikrolegirana čelika hemijskog sastava datog u tab. 1, i mehaničkih osobina, datih u tab. 2. Debljina čelika mikrolegiranog niobijumom (N) je 11 mm, a mikrolegiranog titanom, niobijumom i vanadijumom (T) 7,2 mm.

Tabela 1. Hemijski sastav mikrolegiranih čelika
Table 1. Chemical composition of micro-alloyed steel

Materijal Material	Hemijski element u % Chemical elements in %											
	C	Si	Mn	P	S	Cu	Al	Nb	Ti	Cr	Ni	V
N	0.07	0.15	0.66	0.016	0.010	0.13	0.092	0.077	-	0.042	0.036	-
T	0.056	0.32	1.28	0.012	0.005	0.031	0.049	0.045	0.02	-	-	0.054

Zavarivanje je izvedeno MAG postupkom u zaštiti mešavine gasova (Ar + 5% CO_2 + 0,91% O_2), a kao dodatni materijal korišćena je elektrodna žica VAC 60 Ni, ∅1,2 mm. Predgrevanje nije bilo potrebno, jer je ekvivalent ugljenika:

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

za čelik N je CE = 0,20, a za čelik T je CE = 0,34.

Od oba čelika su izvedeni V spojevi sa tri različite unete količine toplote, navedene u tab. 3. Iz svih ploča su napravljene epruvete sa V zarezom za ispitivanje žilavosti metala šava, dimenzija prema raspoloživom materijalu: za N čelik 55×10×9, a za T čelik 55×10×6. Dobijene vrednosti žilavosti su radi poređenja rezultata preračunate uobičajenim postupkom na standardnu epruvetu. Žilavost je određivana na instrumentiranom Šarpijevom klatnu sa osciloskopom, tako da je energija udara razdvojena na energiju stvaranja (E_{inc}) i energiju rasta prsline (E_{lom}) /1/. Ispitivanja su izvedena na sobnoj temperaturi (20 °C), na -40 °C i na -55 °C, a rezultati su prikazani na sl. 1. do 3. za čelik N i na sl. 4 . do 6. za T čelik.

Tabela 3. Unete količine toplote pri zavarivanju mikrolegiranih čelika
Table 3. Heat input values for welding micro-alloyed steels

Materijal/ Material	Količina unete toplote / Heat input, Q, kJ/cm		
N	5	7	12
T	4	7	10

Since instrumented impact toughness tests are not standardized yet, it is to apply experimentally proved recommendations, e.g. published by European Structural Integrity Society - ESIS /1/.

If two materials have the same toughness values, e.g. total impact energy values, from toughness aspect the material with lower crack initiation energy and higher crack growth energy is better. In some cases, in the total impact energy, although exceeding the critical value, the crack initiation energy may be dominant, with very small part of ductile fracture energy. In this case, the total energy criterion cannot guarantee safety regarding the crack growth and one can exclude the fracture with catastrophic consequences /2/. In other words, if the crack already exists, and this situation can be accounted for in weldments /3/, critical toughness value includes only the part of energy required for crack growth. The reference data about critical total toughness values are different, from 28 J /4-6/, through 35 J /7/, up to the recommendation of even more severe criterion for microalloyed steels of 40 J /8/.

EXPERIMENT AND PRESENTATION OF RESULTS

Hot rolled sheets of two different micro-alloyed steels of chemical composition given in Table 1, and mechanical properties in Table 2, had been welded. The steel micro-alloyed with niobium (N) is 11 mm thick, and micro-alloyed with titanium, niobium, and vanadium (T) is 7.2 mm thick.

Tabela 2. Mehaničke osobine mikrolegiranih čelika
Table 2. Mechanical characteristics of micro-alloyed steel

Materijal Material	Napon tečenja Yield strength Re, MPa	Zatezna čvrstoća Ultimate tensile strength Rm, MPa	Izduženje Elongation A5, %	Energija udara (Šapri V) Impact energy (Charpy V) KV(-20°C), J
N	448-456	543-551	33-34	129-156
T	510-537	571-595	37-42	152-197

Napomena: Re, Rm, A5 - u pravcu valjanja, KV - normalno na pravac valjanja
Note: Re, Rm, A5 - in the rolling direction, KV - perpendicular to the rolling direction

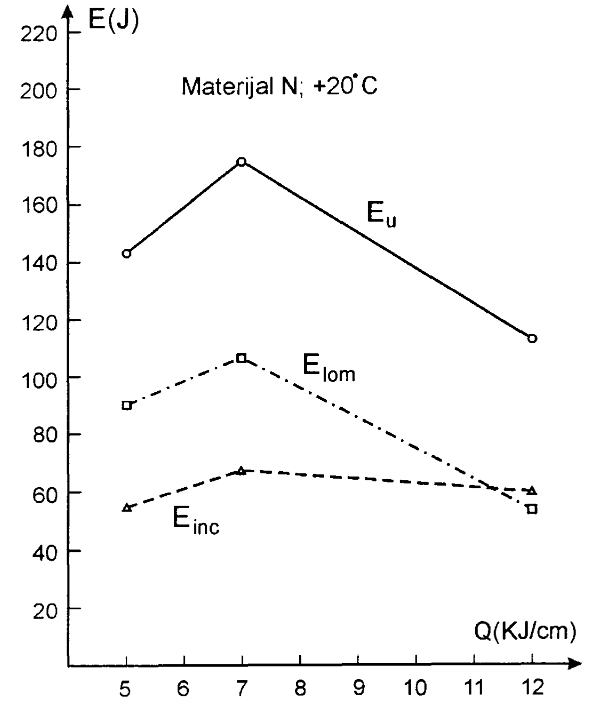
Welding is performed by MIG/MAG process with gas mixture shielding (Ar+5% CO_2 + 0.91% O_2), and the wire VAC 60 Ni, ∅1.2 mm was used as consumable. Preheating is not required, since carbon equivalent:

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15}$$

for the steel N is CE = 0.20, and for the steel T is CE = 0.34.

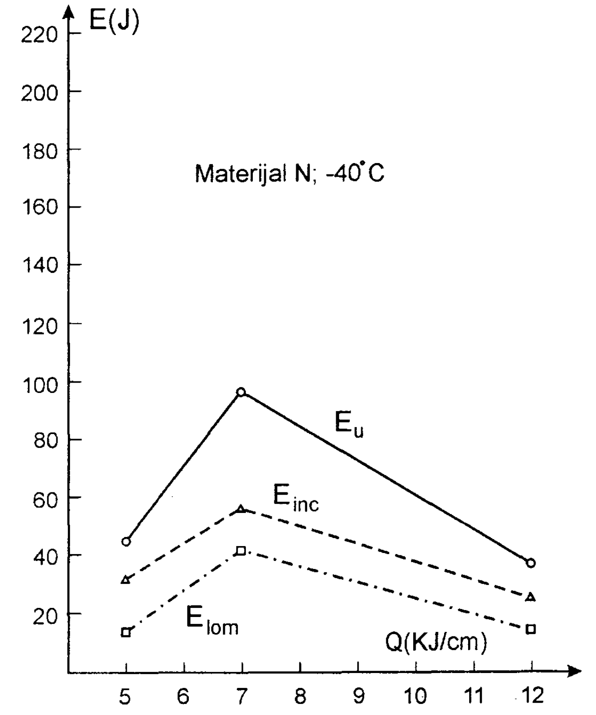
Butt welded joints (V) had been prepared of both steels with three different heat input values, given in Table 3.

From all plates V notched specimens for weld metal toughness testing were produced, sized according to available material: 55×10×9 mm for steel N and 55×10×6 mm for steel T. Obtained toughness values were transferred for comparison by regular procedure to standard specimen values. Toughness was determined on the Charpy pendulum with oscilloscope, and total impact energy is separated to crack initiation energy (E_{inc}) and crack growth energy (E_{lom}) /1/. Tests were performed at room temperature (20°C), at -40 °C and at -55 °C, and are presented in Figs. 1 to 3 for steel N, and on Figs. 4 to 6 for steel T.



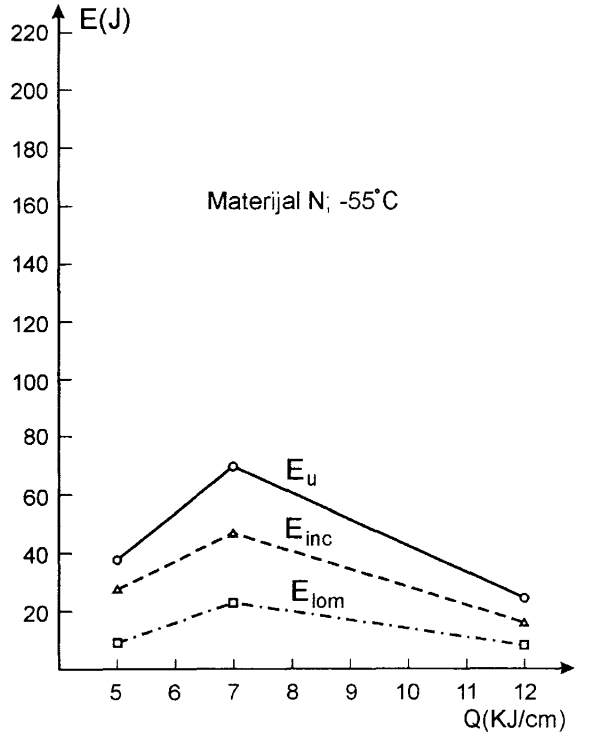
Slika 1. Zavisnost žilavosti metala šava (E_u), energije iniciranja (E_{inc}) i energije rasta prsline (E_{lom}) na +20 °C, od količine unete toplote za čelik N

Figure 1. Weld metal toughness (E_u), crack initiation energy (E_{inc}) and crack growth energy (E_{lom}) at +20 °C vs. heat input *Q* for steel N



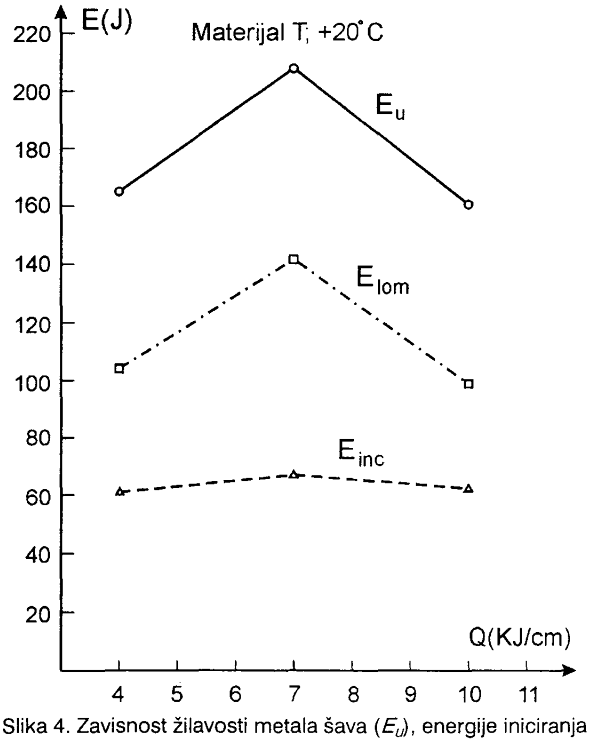
Slika 2. Zavisnost žilavosti metala šava (E_u), energije iniciranja (E_{inc}) i energije rasta prsline (E_{lom}) na -40 °C, od količine unete toplote Q za čelik N

Figure 2. Weld metal toughness (E_u), crack initiation energy (E_{inc}) and crack growth energy (E_{lom}) at -40 °C vs heat input *Q* for steel N



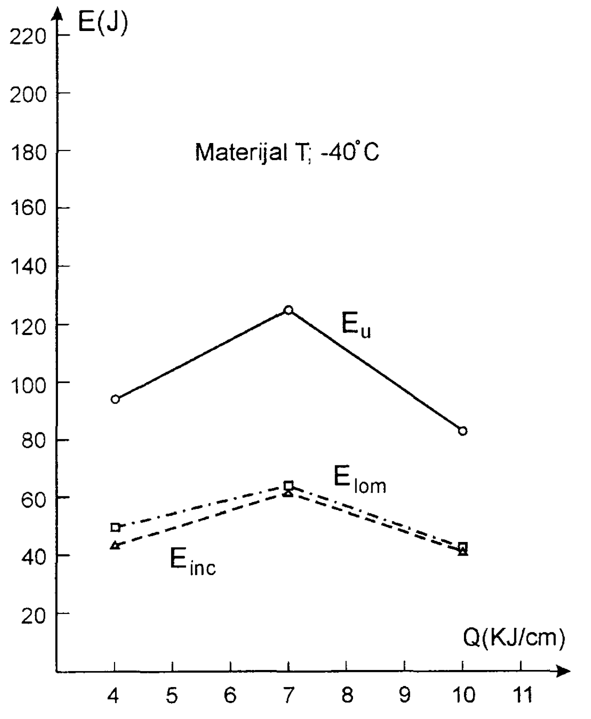
Slika 3. Zavisnost žilavosti metala šava (E_u), energije iniciranja (E_{inc}) i energije rasta prsline (E_{lom}) na -55 °C, od količine unete toplote *Q* za čelik N

Figure 3. Weld metal toughness (E_u), crack initiation energy (E_{inc}) and crack growth energy (E_{lom}) at -55 °C vs. heat input *Q* for steel N



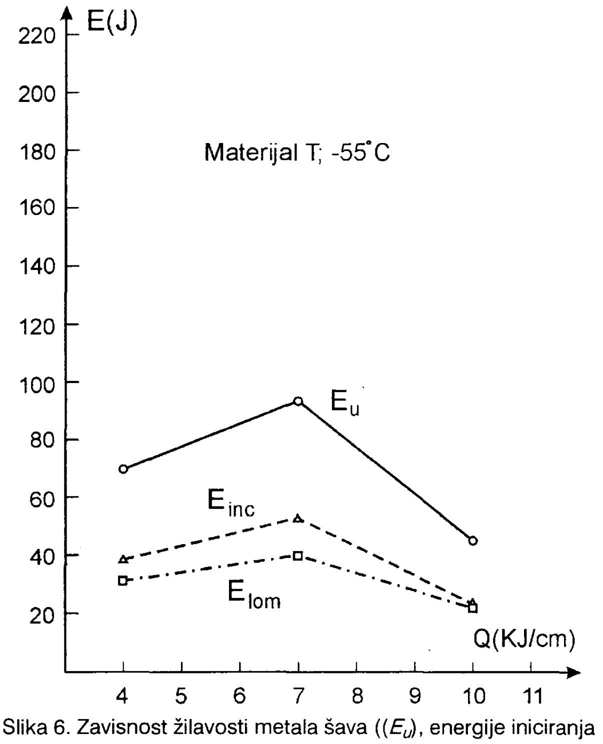
Slika 4. Zavisnost žilavosti metala šava (E_u), energije iniciranja (E_{inc}) i energije rasta prsline (E_{lom}) na +20 °C, od količine unete toplote *Q* za čelik T

Figure 4. Weld metal toughness (E_u), crack initiation energy ((E_{inc}) and crack growth energy (E_{lom}) at +20 °C vs. heat input *Q* for steel T



Slika 5. Zavisnost žilavosti metala šava (E_u), energije iniciranja (E_{inc}) i energije rasta prsline (E_{lom}) na -40 °C, od količine unete toplote Q za čelik T

Figure 5. Weld metal toughness (E_u), crack initiation energy (E_{inc}) and crack growth energy (E_{lom}) at -40 °C vs. heat input Q for steel T



Slika 6. Zavisnost žilavosti metala šava ((E_u), energije iniciranja (E_{inc}) i energije rasta prsline (E_{lom}) na -55 °C, od količine unete toplote Q za čelik T

Figure 6. Weld metal toughness (E_u), crack initiation energy (E_{inc}) and crack growth energy (E_{lom}) at -55 °C vs. heat input Q for steel T

Na sobnoj temperaturi, ukupna energija udara E_u je najveća za unetu količinu toplote 7 kJ/cm i kod metala šava čelika N iznosi 174 J, a kod spojeva od čelika T iznosi 208 J. Pri zavarivanju manjom količinom unete toplote, kao i većom količinom unete toplote ukupna energija udara je manja, što se vidi sa sl. 1. i 4.

Energija iniciranja prsline E_{inc} oba čelika je gotovo ista i ne pokazuje izraženu zavisnost od količine unete toplote, dok energija rasta prsline E_{lom} zavisi od količine unete toplote, slično kao ukupna energija udara E_u, i veća je kod spojeva čelika T. Energija rasta prsline je veća od energije iniciranja prsline u svim slučajevima, osim kod zavarenih spojeva od čelika N pri količini unete toplote 12 kJ/cm, kada je nešto manja od energije iniciranja prsline.

Na temperaturi -40 °C ukupna energija E_u udara je takođe najveća kod spojeva zavarenih unetom količinom toplote 7 kJ/cm i za zavarene spojeve čelika N iznosi 97 J, a za spojeve čelika T iznosi 125 J. Ukupna energija udara metala šava koji su zavareni manjom i većom količinom unete toplote je manja (sl. 2. i 5). Energije iniciranja E_{inc} i rasta prsline E_{inc} se ponašaju slično kao ukupna energija udara E_u, s tim što je kod zavarenih spojeva od čelika N pri sve tri unete količine toplote E_{inc} veća od E_{lom}, što nije slučaj sa zavarenim spojevima od čelika T (E_{lom} je još uvek veća od E_{inc}).

Na temperaturi -55 °C, ukupna energija udara E_u metala šava od čelika N je takođe najveća pri unetoj količini toplote 7 kJ/cm i iznosi 70 J, a kod spojeva od čelika T 93 J. U svim slučajevima, kod oba čelika E_{inc} je veća od E_{lom} (sl. 3. i 6).

At room temperature, the total impact energy E_u is highest for the heat input 7 kJ/cm, and for weld metal of steels N and T amounts to 174 J and 208 J, respectively. Welding with lower heat input, as well as with higher heat input, resulted in lower impact energy values, depicted in Figs. 1 and 4.

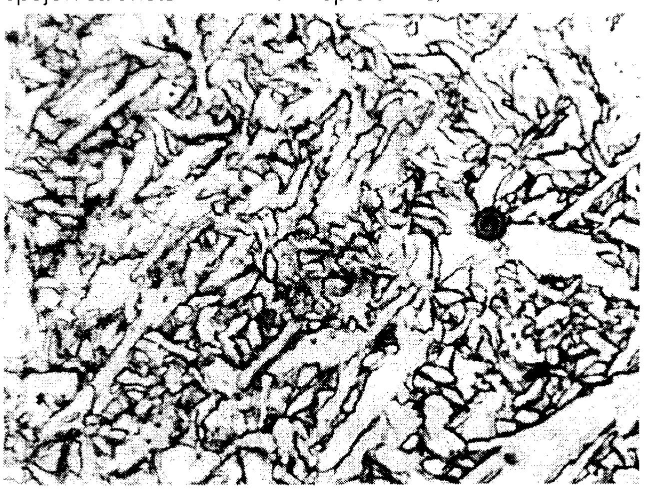
Crack initiation energy E_{inc} for both steels is similar and does not show any visible effect of input heat, while energy E_{lom} for crack growth depends on the heat input in the same way as the total impact energy E_u does, and is larger for steel T joints. Crack growth energy is higher than the crack initiation energy in all cases, except for welded joints of steel N obtained by heat input 12 kJ/cm, when it is a somewhat lower than the crack initiation energy.

At -40 °C the total impact energy E_u is also the highest for welded joints with heat input 7 kJ/cm, and for welded joints of steels N and T the values are 97 J and 125 J, respectively. The total impact energy for weld metals produced by lower and higher heat input is lower (Figs. 2 and 5). Energy released for crack initiation E_{inc} and growth E_{lom} shows the same behaviour as the total impact energy E_u, where, in the case of welded joints of steel N, the E_{inc} is greater than E_{lom} for all three heat inputs, which is not the case for welded joints of material T (E_{lom} is still higher than E_{inc}).

At temperature -55 °C, the total impact energy E_u of steel N weld metal is also the highest for 7 kJ/cm heat input, and is equal to 70 J, and 93 J for joints of steel T. In all cases (for both steels) E_{inc} is higher than E_{lom} (Figs. 3 and 6).

DISKUSIJA

Ukupna energija udara metala šava ispitivanih mikrolegiranih čelika na sobnoj temperaturi je dosta visoka, kao i energija rasta prsline, koja je znatno veća od energije iniciranja prsline, što se vidi sa sl. 1. i 4. Izuzetak su zavareni spojevi čelika N izvedeni sa unetom količinom toplote 12 kJ/cm, kod kojih je i na sobnoj temperaturi energija iniciranja prsline veća od energije rasta prsline. Sa ovako visokim vrednostima energije udara su saglasna i mikrostrukturna ispitivanja koja ukazuju na prisustvo velike količine acikularnog ferita u metalu šava oba materijala, sl. 7 /9/. Sa povećanjem, odnosno sa smanjenjem, količine unete toplote pri zavarivanju energija rasta prsline se značajno smanjuje, na svim temperaturama ispitivanja, pa kod zavarenih spojeva čelika N na -40 °C postaje manja od energije iniciranja prsline, a na -55 °C je i kod spojeva od čelika T manja od energije iniciranja prsline. Kako kod zavarenih spojeva ne sme da se zanemari mogućnost postojanja prsline /3/, to je kriterijum minimalne energije udara nepouzdan, čak i ako se koristi povećana vrednost energije (35 ili 40 J), kao što je preporuka za mikrolegirane čelike /7-8/. Očigledno je da je sigurnost zavarenog spoja obezbeđena jedino ako se kao kriterijum prihvatljivosti usvoji minimalna vrednost energije rasta prsline (40 J) na određenoj temperaturi koja obezbeđuje dovoljnu žilavost zavarenog spoja za sve praktične primene. Imajući u vidu ovaj kriterijum, za zavarene spojeve od čelika N na temperaturi -40 °C, količina unete toplote pri zavarivanju treba da bude 7 kJ/cm, jer je u tom slučaju energija rasta prsline veća od 40 J, dok na -55 °C zavareni spojevi od čelika N nemaju dovoljnu žilavost ni u jednom slučaju. Kod čelika T situacija je povoljnija, pa na temperaturi -40 °C, pri svim ispitivanim količinama unete toplote energija rasta prsline je veća od minimalne (40 J), a na temperaturi -55 °C ovaj uslov obezbeđuju jedino zavareni spojevi sa unetom količinom toplote 7 kJ/cm.



Slika 7. Struktura metala šava - uvećanje 1500×
Figure 7. Weld metal microstructure - magnification 1500×

DISCUSSION

The total impact energy of weld metal of investigated microalloyed steels at room temperature is pretty high, as well as the energy for crack growth, which is much higher than the crack initiation energy, as shown on Figs. 1 and 4. An exception are welded joints of steel N produced with 12 kJ/cm heat input, for which the crack initiation energy was higher than the crack growth energy at room temperature. So high energy values are confirmed by microstructural tests that indicate presence of large amount of acicular ferrite located in the weld metal of both steels, Fig. 7 /9/. The crack growth energy significantly diminishes with higher and lower welding heat input values, at all testing temperatures, and it becomes lower than the crack initiation energy for steel N at -40 °C, and at -55 °C also for steel T. Since the possibility for crack occurrence must not be neglected in welded joints /3/, the minimal impact energy criterion becomes unreliable, even by adopting higher energy values (35 or 40 J), as it is the case with micro-alloyed steels /7-8/. It is clear that welded joint safety is assured only if the criterion of acceptance is given by the minimal crack growth energy value (40 J) at the given temperature for which the welded joint toughness is sufficient for all practical applications. Having in mind this criterion, for welded joints of material N, at -40 °C, the input welding heat should be 7 kJ/cm, since the crack growth energy is higher than 40 J, while at -55 °C welded joints of steel N do not have sufficient toughness in any case. For steel T the situation is better, and at -40 °C the crack growth energy is greater than the minimal value (40 J) for all values of heat input, and at -55 °C this condition is maintained only in welded joints performed by heat input of 7 kJ/cm.

CONCLUSIONS

1. The input heat is an important welding parameter for micro-alloyed steels. For investigated steels the value of 7 kJ/cm can be recommended as optimal.
2. Weld metal toughness of both investigated micro-alloyed steels is extremely sensitive to the welding heat input. The higher and lower heat input compared to the optimal value (7 kJ/cm) exposed negative effect on the weld metal toughness.
3. At -40 °C, the crack growth energy of steel T joints was higher than critical value for all tested heat inputs, and it was slightly higher at -55 °C only in the case of welded joints with optimal welding heat input. Welded structures produced from this steel operating at -55 °C can be recommended for use only when strict control of welding heat input during production is performed.

ZAKLJUČCI

1. Količina unete toplote je važan parametar zavarivanja mikrolegiranih čelika. Za ispitivane čelike količina unete toplote od 7 kJ/cm se može preporučiti kao optimalna.
2. Žilavost metala šava oba ispitivana mikrolegirana čelika je vrlo osetljiva na količinu unete toplote pri zavarivanju. Veća i manja količina unete toplote u odnosu na optimalnu (7 kJ/cm) ispoljava negativan uticaj na žilavost metala šava.
3. Na temperaturi -40 °C, energija rasta prsline spojeva od čelika T pri svim ispitivanim količinama unete toplote je veća od kritične, a na -55 °C samo u slučaju zavarenih spojeva sa optimalnom količinom unete toplote pri zavarivanju je nešto veća od kritične. Zavarene konstrukcije od ovog čelika za rad na -55 °C mogu se preporučiti samo uz strogu kontrolu količine unete toplote pri zavarivanju u toku proizvodnje.

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