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Vpliv vibriranja med varjenjem in po njem na mehanske lastnosti zvarov, zavarjenih v zaščiti močno ioniziranega večkomponentnega plina

The Effect of Vibrational Treatment During and After Welding on the Mechanical Properties of a Transferred Ionized Molten Energy Weld

Bogdan Pučko

Vibriranje za odpravo napetosti (VON - VSR) je eden od načinov odpravljanja zaostalih notranjih napetosti v zvaru. Pri tem se lahko spremene tudi nekatere druge mehanske lastnosti zvarnega spoja.

Namen raziskave je bil primerjati lastnosti večvarkovnih zvarnih spojev, zavarjenih in vibriranih v različnih razmerah. Z osnovnim stanjem smo primerjali žarjeno stanje, stanje z vibriranjem med varjenjem in po njem ter kombinacijo vibriranja in žarjenja. Varili smo po postopku T.I.M.E. (varjenje v zaščiti močno ioniziranega večkomponentnega plina). Z metodami verifikacije varilnega postopka in dodatnimi raziskavami lomne žilavosti smo ocenili razlike med različnimi stanji. Opravili smo mehanske preskuse natezne trdnosti, udarne žilavosti, lomne žilavosti in meritve trdot. Med seboj smo primerjali lastnosti v strjenem zvaru. Izsledki raziskav kažejo izboljšanje udarne in lomne žilavosti, če so zvari vibrirani med varjenjem ali po njem. Na druge mehanske lastnosti ni bilo bistvenega vpliva. Žarjenje nasprotno poslabša omenjene lastnosti ter povzroči zvečanje trdote v toplotno vplivanem področju (TVP) zvara preskušanega jekla.

(Ključne besede: VSR, vibriranje, odprava napetosti, postopek TIME)

The vibrational stress relief (VSR) technique has been shown to reduce the internal residual stresses caused by welding. By lowering or redistributing the stress it is possible to alter the mechanical properties of the weld joint.

The aim of this study was to determine the effect of vibration on the properties of multilayer weld specimens which were welded and vibrated under various conditions. Specimens which were stress annealed, vibrated after and during welding were compared with specimen in the as-welded condition. Each specimen was welded using the T.I.M.E. (transferred ionized molten energy) process. Using weld-procedure-specification methods and the fracture-toughness method we established differences in the properties of the different specimens. Properties were also assessed using the tensile stress test, the Charpy V-notch test, the fracture mechanics test and hardness measurements. Measurements were made primarily in the weld metal. The results show an effect of vibration after, and during, welding on the Charpy and fracture toughness, the other mechanical properties were not seriously affected. Stress annealing, in contrast, lowers the toughness and increases the hardness in the heat-affected zone (HAZ) of the weld.

(Keywords: VSR, vibrational stress relief, TIME process)

0 UVOD

Že v tridesetih letih dvajsetega stoletja zasledimo, da se v konstrukcijah poleg napetosti, kot posledici zunanje obremenitve, pojavljajo tudi tako imenovane notranje zaostale napetosti. V štiridesetih in petdesetih letih so objavili vrsto člankov, v katerih se ukvarjajo s študijem vira, nastanka in meritev teh napetosti. Hkrati s tem so se razvijale tudi metode za

0 INTRODUCTION

By the 1930s researchers had discovered that all stresses in a structure were not just the result of loading. Residual stresses are also formed. In 1940s and 1950s many publications refered to the origin, development and measurement of residual stresses. During that time the reduction or methods for elimination of stresses were develnjihovo zmanjševanje ali odpravljanje. Šele v sredini šestdesetih let se močno razširijo raziskave z mehanskim vibriranjem kot možnim načinom za zmanjševanje napetosti. V velikem številu člankov ugotavljajo ugoden učinek vibriranja na zmanjšanje notranjih mikro napetosti z meritvijo zaostalih napetosti in deformacij ([1] do [9]).

Manj jasen ostaja vpliv vibriranja na mehanske lastnosti osnovnega materiala in zvara. Različni avtorji ugotavljajo zanemarljiv [10] ali celo negativen [2] vpliv na mehanske lastnosti. Vibriranje med varjenjem lahko vpliva na zmanjšanje trdote [11]. Novejše raziskave [12] med drugim podajajo ugoden vpliv višjih frekvenc (80 do 400 Hz) med varjenjem na mehanske lastnosti aluminija. Gnirss [13] v svojem članku poudarja tudi vpliv na delež vodika in njegove razporeditve. Zaradi večje gibljivosti vodika pri vibriranju se ta ugodneje razporedi in tudi laže prodre od dislokacij, kar zmanjša nevarnost hladne pokljivosti. Zmanjšanje zrna pod vplivom vibriranja med varjenjem bi naj bilo premo sorazmerno prostorninski spremembi med strjevanjem ([14] in [15]). Nasprotno Crawmer [16] dokazuje, da pri varjenju ni vpliva na velikost zrna, kar lahko pojasnimo z veliko hitrostjo ohlajanja v primerjavi z litjem. Prav tako je najti trditev [11], da ni vidne spremembe velikosti zrna varka in TVP pri vibriranju med varjenjem. Nekateri avtorji dokazujejo, da vibriranje pospešuje učinke toplotne obdelave [17]. S tem se povečuje hitrost odtaljevanja dodajnega materiala za 10 odstotkov ([16] in [18]), hitrost ohlajanja taline [19] in s tem globina prekalitve [20]. Razlaga teh procesov je povezana z nastankom večjega števila praznin v kristalni strukturi in tako povečanja difuzijskih koeficientov [21]. Z nastankom praznin je povečana gibljivost dislokacij, kar je tudi ena od razlag in je v prid zmanjšanju deformacij kristalne mreže ([1], [6], [11] in [22]). Kot posledica povečane hitrosti odtaljevanja je lahko tudi povečanje hitrosti varjenja, kar je opisano v članku [6]. Vpliv na globino pretaljevanja je opisan v člankih ([11] in [23]). Članki ne ugotavljajo bistvenega vpliva vibracije na globino uvara in na geometrijsko obliko prereza varka.

Da bi se izognili številnim vplivnim dejavnikom, ki se pojavljajo pri varjenju, je večina raziskav izvedena na preprostih preskušancih, običajno na manjših ploščah ali palicah. Varjenje se največkrat omejuje na navarjanje ali pa se simulira vnos napetosti pri varjenju, na primer z valjanjem. Rezultati, predstavljeni v tem članku, so rezultati meritev na večvarkovnih zvarnih spojih, ki po svoji obliki in velikosti ustrezajo zvarom na konstrukcijah. Izmerjene so bile mehanske lastnosti (natezna trdnost, trdota, udarna in lomna žilavost).

1 TEORIJA

VON je v prvi vrsti namenjeno zmanjšanju zaostalih mikro napetosti in povečanju dimenzijske stabilnosti. Metoda se je pokazala uporabna pri vseh

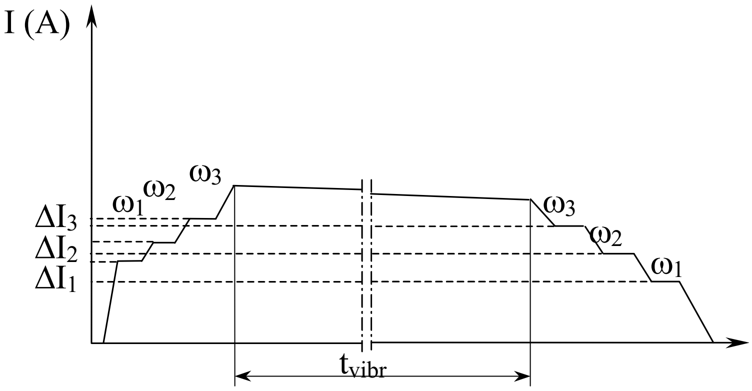
oped. During the 1960s research on mechanical vibrations as a possible method for stress reduction began. Many papers reported positive results with regard to measurements of internal stresses and deformation ([1] to [9]).

The effect of vibration on the base material and the weld metal mechanical properties remains unclear. Many authors found negligible [10] or negative [2] effects on the mechanical properties. Vibration during welding was observed to lower hardness [11] and the latest research on aluminum [12] has shown a positive effect on the mechanical properties when the aluminium is vibrated (80 to 400 Hz) during welding. In his paper [13] Gnirss discusses the effect of vibration on hydrogen distribution. Because of the higher mobility of atoms during vibration, the hydrogen can easily move from dislocations and therefore lower the cold crack sensitivity. Grain refining caused by the vibration during welding should be directly correlated to the volume change during solidification ([14] and [15]), however, Crawmer [16] showed no effect on grain refinement, which could be the result of a very short solidification time within welding in comparison to casting. No change in the grain size has been reported also by other authors [11]. Other reports suggest that vibration can increase the effects of heat treatment [17]. The deposition rate can be increased for about 10 % ([16] and [18]), cooling time can be shortened [19] and weld penetration can be affected [20]. The explanation of these processes is connected with an increase in the number of vacancies in the crystal lattice and therefore an increase in the diffusion rate [21]. With vacancy formation, dislocation movement is increased, which is important in recovery mechanisms ([1], [6], [11] and [22]). A higher deposition rate can also increase welding speed [6]. Penetration of the weld has been discussed ([11] and [23]) and a connection between vibration and weld geometry could not be found.

To avoid a number of the parameters which affect the welding process, most of the research was carried out on simple specimens, usually on small plates or bars. Welding was often reduced to surfacing or residual stresses were simulated, for example, with rolling. Results obtained from welding multilayer weld specimens, which, because of their shape and dimensions, can be compared to construction welds are presented. Mechanical properties were obtained from tensile tests, hardness tests, Charpy toughness and fracture toughness measurement.

1 THEORY

The VSR technique is used to reduce the residual microstresses in a material and increase of dimensional stability. This technique is used for rolled,



Sl. 1. *Shematski prikaz postopka vibriranja po varjenju*
Fig. 1. *Method of vibrational treatment after welding - shematically*

vrstah valjanih, litih, varjenih, kovanih in mehansko obdelanih izdelkih. Primerna je za konstrukcijska, normalizirana, popuščena, kaljiva in nerjavna jekla. VON ni zamenjava za toplotno obdelavo, pri kateri poleg odpravljanja makro napetosti povzročamo metalurške spremembe v mikrostrukturi materiala. V literaturi se učinki te metode največkrat primerjajo z učinki naravnega staranja.

Vsaka konstrukcija ima svojo lastno frekvenco. Resonančne vrhove določimo z meritvijo pred pričetkom vibriranja. S spreminjanjem frekvence od vrednosti nič do končne vrednosti ω merimo velikost toka vibratorja pri nekaj (3 do 5) resonančnih vrhovih (ω_i). Na sliki 1 je shematsko prikazan postopek vibriranja po varjenju. Po vibriranju, običajno 15 do 30 minut pri najvišji harmonični frekvenci, zmanjšujemo hitrost rotorja na vrednost nič in medtem merimo vrednost toka vibratorja pri istih frekvencah kakor pred vibriranjem. Razlika tokov (ΔI_i) rabi kot merilo zmanjšanja napetosti. Včasih, če je padec toka premajhen, je treba postopek ponoviti. Pri tem se lahko napetosti dodatno zmanjšajo. Če ne zaznamo spremembe toka v primerjavi s prejšnjo meritvijo, pomeni, da smo element stabilizirali. Opisan postopek velja za vibriranje po varjenju.

Pri vibriranju med varjenjem v času strjevanja materiala varjenja vibriramo s stalno frekvenco in ne merimo resonančnih vrhov. Med varjenjem se vibriranje izvaja v podresonančnem področju, da ne bi dobili prevelikih nihanj zaradi resonančnih pojavov, kar lahko neugodno vpliva na stabilnost obloka.

V materialu se z vibriranjem pojavlja tako imenovano notranje trenje oziroma dušenje, ki mehansko (vibracijsko) energijo spreminja v toploto. Pojavljajo se mikroplastične deformacije. To se dogaja znatno pod makroskopsko mejo elastičnosti.

Poškodbe materiala pri vibriranju z majhnimi amplitudami so v primerjavi z utrujanjem pri dinamičnem preskušanju izredno majhne [24], prvič zaradi majhne energije vibriranja, drugič zaradi majhnega števila obremenitvenih ponovitev.

Ločimo lahko tri osnovne modele vibriranja. Pri prvem s preobremenitvijo konstrukcije dosežemo

cast, welded, forged and machined parts. We can use it for normalized, tempered, quenched, structure and stainless steels. It cannot be a substitute for thermal annealing, where the relief of macrostresses is accompanied by changes in the microstructure. It is common to compare the VSR technique to natural aging.

Every structure has its own resonant frequency. The method of vibration is schematically presented in Figure 1. The resonant peaks can be found before the vibration starts by changing the frequency from zero to the final value of ω. The values of the vibrator-current consumption at a few (3 to 5) resonant peaks ω_I are recorded. After vibration, usually 15 to 30 min at the highest frequency, the rotor frequency is reduced to zero, and the current consumption at the same resonant peaks is recorded. The current difference (ΔI_i) is an indication of the stress reduction. If the current drop is too small, the procedure has to be repeated to obtain stress reduction. If there is no change in the current compared to the previous measurements, the part or specimen is stabilized.

During welding the resonant peaks are not measured but maximum frequency is used during the weld solidification. In fact, the frequency has to be adjusted to a subresonant value to avoid maximum amplitudes which can have a negative effect on arc stability.

According to internal friction and attenuation, mechanical (vibrational) energy in the material changes to heat. Microplastic deformations can occur, and this process takes place under the macroscopic yield point.

Low-amplitude vibration causes no serious material damage and is smaller than during fatigue testing [24]. The energy of vibration is very low and there is a relatively small number of duty cycles.

We can distinguish three different basic models to explain the vibration effects. The first model zmanjšanje napetosti na račun makroskopskih deformacij. Drugi (standardni) model razlaga zmanjšanje napetosti kot posledico mikroplastičnega tečenja v področju elastično obremenjene konstrukcije ([25] in [26]). Ta model je uporaben pri vibriranju po varjenju. Tretji model je model stabilizacije dislokacij ([11], [21] in [27]). V odvisnosti od temperature je pod vplivom vibracij povečana gibljivost dislokacij in s tem možnost za prenos materiala in medsebojno reakcijo dislokacij ali dislokacij s tujimi atomi, kar zmanjša skupno elastično energijo. Ta model lahko uporabimo pri vibriranju med varjenjem.

suggests that overloading of a structure and macroscopic plastic deformation are the main reason for stress reduction. The second (classical) model explains stress reduction as the result of microplastic flow in elastic stress structure ([25] and [26]). This model can properly explain vibration after welding. The third model refers to dislocation stabilization ([11], [21] and [27]). Dislocation mobility is increased with temperature. With vibration excitation there is a greater possibility of material transport and the reaction of dislocations with dislocations or impurity atoms resulting in a lowering of the elastic energy of the system. This model can explain processes by vibration during welding.

2 EKSPERIMENT

Preiskave, omenjene v tem prispevku, so bile opravljene na jeklu domačega proizvajalca S500 NL1 (EN 10027) s trgovsko oznako NIOMOL 490K, na zavarjenih talonih izmer 1200x400 mm. Zagotovljene mehanske lastnosti so R_m=560 MPa ter R_p=470 MPa za izbrano debelino pločevine 25 mm. Za dodajni material smo izbrali polno žico G3 NiMo (EN 12534) z nekoliko večjimi vrednostmi natezne trdnosti. Kemijska sestava osnovnega (OM) in dodajnega materiala je podana v preglednici 1.

2 EXPERIMENT

The material used in this study was S 500 NL1 (EN 10027) with the trade name NIOMOL 490K. The dimensions of the welded test plate were 1200x400 mm. The minimum mechanical properties were R_m = 560 MPa, R_p = 470 MPa for 25 mm plate thickness. The filler material used was G3 NiMo (EN 12534) solid wire with overmatched material properties. The chemical composition of the base (BM) and filler materials is shown in Table 1.

Preglednica 1. *Kemijska sestava osnovnega (OM) in dodajnega materiala*
Table 1. *Chemical composition of base (BM) and filler material*

element	C	Si	Mn	P	S	Cr	Mo	Ni	Nb	Al
OM/BM	0,07	0,54	0,56	0,008	0,002	0,67	0,35	/	0,062	/
dodajni/filler mat.	0,09	0,62	1,77	0,011	0,003	0,31	0,95	/	/	/

Za postopek varjenja je bil izbran novejši, zelo produktiven postopek, imenovan T.I.M.E. Parametri varjenja so izbrani tako, da je bil vnos toplote do 1,5 kJ/mm zvara, oziroma so bili časi ohlajanja $t_{8/5}$ krajši od 10 s, kar po zagotovilih proizvajalca pločevine še zagotavlja ugodne mehanske lastnosti TVP. Oblika zvara je zaradi načina odvzema preskušancev simetrični zvar K.

Izhodišče za primerjavo rezultatov je bil preskusni talon, zavarjen po načrtovani tehnologiji, brez dodatne obdelave (S1). Drugi talon v seriji je v nasprotju od prvega vključeval žarjenje za odpravo napetosti po varjenju (S2). Tretji način priprave preskusnega talona pomeni standarni način vibriranja (S3). Po končanem varjenju smo ohlajen varjenec vibrirali okoli 20 min. Uporabili smo napravo za vibriranje, ki deluje v frekvenčnem področju do 75 Hz. Podobno kakor pri žarjenju prihaja pri vibriranju po varjenju do premika posameznih atomov in dislokacij, vendar na lokalnih področjih in v isti drsni ravnini. Ne pride do plezanja dislokacij, ampak le do drsenja. Pod vplivom vibriranja pride do manjših premikov dislokacij ter do njihovih reakcij s tujimi atomi, kar vodi do stabilnejše kristalne strukture. Manj uporabljano možnost vibriranja pomeni vibriranje med varjenjem (S4). V tem primeru izrabljamo

The welding process used was the highly efficient T.I.M.E. process. The welding parameters were defined so that heat input did not exceed 1.5 kJ/mm and the cooling time $t_{8/5}$ was shorter than 10 s; this should, according to the steel producer, ensure proper mechanical properties in the heat-affected zone (HAZ). To facilitate and ensure the cutting out of the specimens the symmetrical K weld type of joint was used.

The (S1) specimen, without further mechanical or heat treatment, was used as a control sample. The second specimen in the series (S2) was stress annealed after welding. The third specimen represents (S3) the classical vibration treatment after welding with vibration for about 20 min. The vibration device can operate with frequencies up to 75 Hz. With vibration after welding we can expect the movement of some dislocations and atoms in the same way as with annealing, but in the local area and in the same gliding plane. There is no climbing of the dislocations. The vibrational treatment during welding can promote dislocation movement and hence reactions with impurity atoms, the reaction results in the stabilization of the crystal strucdobro gibljivost atomov zaradi visokih temperatur in notranje trenje na kritičnih mestih kristalne strukture. Primerjalno smo zavarili tudi talon z vibriranjem med varjenjem, ki smo ga po končanem varjenju tudi odžarili za odpravo napetosti (S5). Tako smo želeli oceniti kombinacijo vplivov vibriranja in žarjenja. V preglednici 2 so prikazane oznake za posamezna stanja, ki se pojavljajo tudi v diagramih.

ture (S4). In this case we use the advantage of good atom mobility because of the high temperatures and the internal friction at critical points in the crystal lattice. To evaluate the correlation between vibrating and annealing, one specimen was vibrated during welding and then stress annealed after welding (S5). Table 2 shows the specimens' symbol designation with preparation conditions.

Preglednica 2. *Oznaka talonov glede na stanje zavaritve*
Table 2. *Specimen designation according to condition of preparation*

oznaka/ symbol	stanje / condition
S1	osnovno stanje / as welded
S2	žarjeno / annealed
S3	vibrirano po varjenju / vibrated after welding
S4	vibrirano med varjenjem / vibrated during welding
S5	vibrirano in žarjeno / vibrated and annealed

3 REZULTATI

Pred preskušanjem vzorcev iz zavarjenih talonov so bile najprej izmerjene zaostale vzdolžne in prečne napetosti glede na zvar, merjene prečno čez zvar v sredini talona [28]. Temelj za ovrednotenje mehanskih lastnosti je standard za verifikacijo varilnih postopkov [29] z ustreznimi spremljevalnimi standardi.

Na sliki 2 so prikazani rezultati nateznega preskusa vzorcev, vzetih vzdolžno iz zvara. Vsak stolpec pomeni poprečje dveh meritev. Meritev raztezka in skrčka ni pokazala vpliva vibriranja.

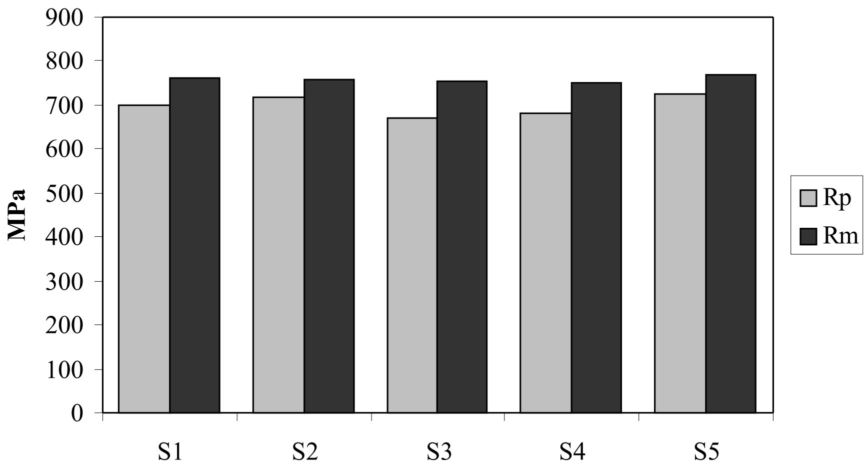
Trdote, prikazane na sliki 3, so bile izmerjene v temenu varka, približno 2 mm pod površino, skozi področje OM-TVP-zvar-TVP-OM.

3 RESULTS

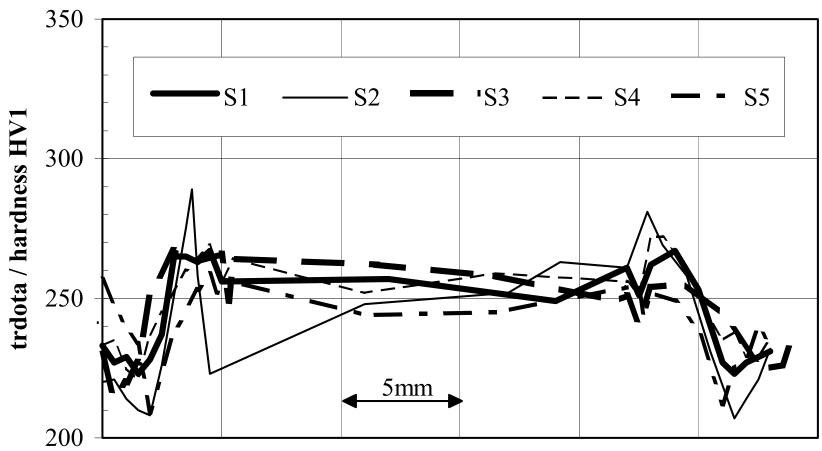
Before testing the welded specimens longitudinal and transverse residual stresses near the center line of the weld were measured across the weld [28]. The basis for the mechanical testing methods was a standard for weld-procedure specification [29] with corresponding standards.

In Figure 2 results of the tensile test specimens are shown. The tensile specimens were machined from the weld metal in the longitudinal direction. Each column represents an average value of two specimens. The measurement of elongation and contraction showed no significant difference.

The hardness measurements in Figure 3 were at the top of the weld, about 2 mm under the surface, across the region BM-HAZ-weld-HAZ-BM.



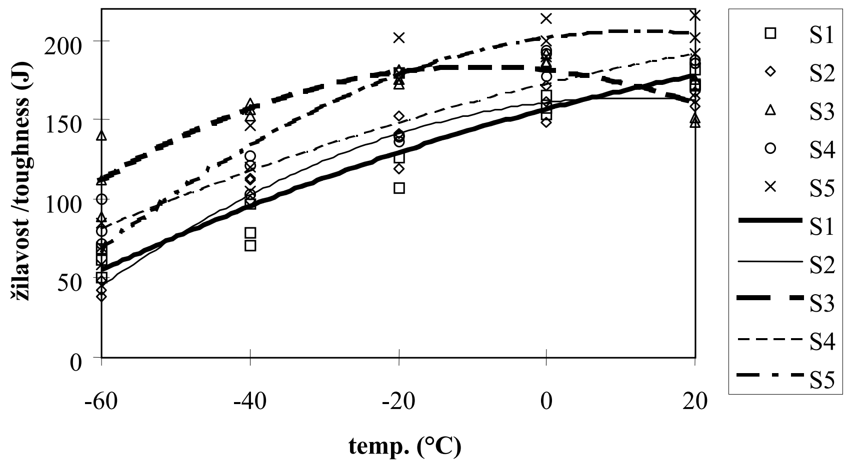
Sl. 2. *Natezna trdnost in napetost tečenja zvara*
Fig. 2. *Tensile strength and yield stress of weld metal*



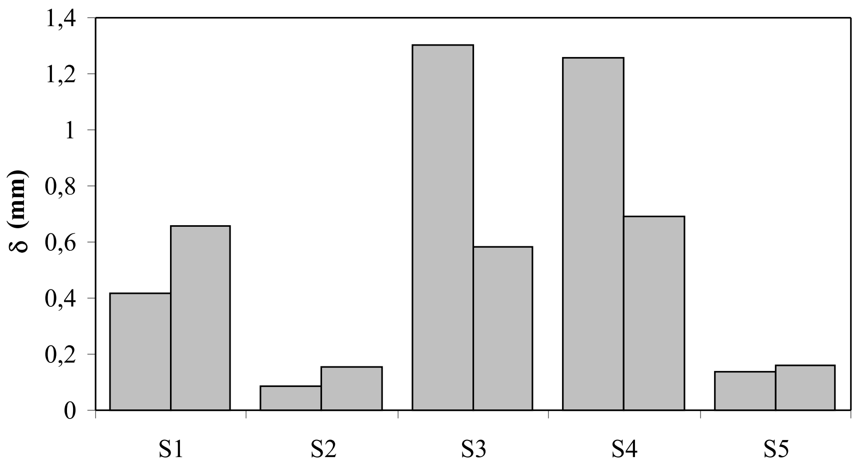
Sl. 3. *Trdota v temenu zvara*
Fig. 3. *Hardness at the top of the weld*

Za vsak način varjenja je bilo izdelanih pet serij preskušancev za preskus udarne žilavosti po Charpyju. Z njimi smo izmerili udarno žilavost v temperaturnem področju od –60°C do +20°C, to je področje, za katero proizvajalec jekla zagotavlja določene mehanske lastnosti. Na sliki 4 velja opozoriti,

For each weld preparation, five series of Charpy V-notch specimens were made. Charpy toughness was measured in the range from –60°C to +20°C, which is the range of guaranteed specified mechanical properties. In Figure 4 it should be noted that all values for the vibrated specimens are higher than for



Sl. 4. *Udarna žilavost zvarov*
Fig. 4. *Charpy toughness of welds*



Sl. 5. *Lomna žilavost zvarov*
Fig. 5. *Fracture toughness of welds*

da so vrednosti žilavosti pri vseh vibriranih stanjih večje kakor osnovno in žarjeno stanje.

Vrednosti lomne žilavosti posameznih epruvet so bile določene na podlagi koncepta lomne mehanike COD (Crack Opening Displacement). Temperatura preskušanja je bila -40 °C. Na sliki 5 vsak stolpec pomeni eno izračunano vrednost parametra lomne žilavosti δ.

4 SKLEPI

Natezna trdnost se z vibriranjem praktično ne spreminja. Vibriranje po varjenju ali med njim za malenkost zmanjša napetost tečenja, kar bi morali potrditi z natančnejšimi preiskavami. Zmanjšanje je v mejah natančnosti metode. Na raztezek in skrček vibriranje nima bistvenega vpliva. Sprememb trdnostnih lastnosti pri vibriranju po varjenju in med njim nismo opazili.

Trdota v strjenem zvaru se z žarjenjem zmanjša, vendar se v TVP pojavijo konice trdot, ki so najverjetneje posledice izločilnih pojavov. V primerjavi z osnovnim stanjem (S1) vibriranje med varjenjem (S3) ali po varjenju (S4) pri tem postopku vidno ne vpliva na trdote v temenu zvara. V stanju vibrirano med varjenjem in žarjeno (S5) pa so se trdotne konice z vibriranjem glede na samo žarjeno stanje (S2) znižale.

Z vibriranjem med varjenjem se žilavost zvara poveča. Vibriranje po varjenju in med njim izboljša žilavost v primerjavi z osnovnim stanjem.

Opaziti je nagnjenje k povečevanju lomne žilavosti zaradi vibriranja. Vendar glede lomne žilavosti ni bistvene razlike pri vibriranju med varjenjem in po njem. Vrednost parametra lomne mehanike δ se zaradi vibriranja močno poveča glede na osnovno stanje.

Žarjenje močno zmanjša lomno žilavost strjenega zvara, tudi kadar ga kombiniramo z vibriranjem. Za obravnavano jeklo žarjenje ni primeren način zmanjševanja zaostalih napetosti.

the unvibrated specimens.

Fracture toughness values are obtained with the Crack Opening Displacement fracture (COD) mechanics method. The testing temperature was -40 °C. In Figure 5 each column refers to one value of the calculated fracture mechanics parameter δ.

4 CONCLUSIONS

There is no significant change in the tensile strength. Vibration after, or during, welding slightly lowers the yield stress, but we should confirm this with additional research. It seems there is no effect on the ductility and contraction. Vibrating after and during welding has a similar effect on the mechanical properties.

The weld hardness drops with annealing, but peaks in the HAZ occur. These peaks are obviously the result of the precipitation of carbides in the HAZ. In comparison to the as-welded condition (S1) vibration after welding (S3) and during welding (S4) seems to have no significant effect on the hardness for this welding process. But the specimen vibrated before annealing (S5) exibits no hardness peaks in the HAZ compared to annealed-only condition (S2).

An increase in the fracture toughness due to vibration is apparent.

There is no difference between vibrating the specimen after or during welding. The increase in fracture toughness is reflected in an increase in the parameter of fracture mechanics δ.

Annealing has a significant effect on the fracture toughness for this material. Vibration cannot remove this effect. For this material annealing is certainly not a suitable method for lowering the residual stresses.

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