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Improving GMAW weld metal and HAZ properties through friction stir processing

Poboljšanje osobina metala šava i ZUT kod zavarivanja MAG postupkom primenom zavarivanja trenjem sa alatom

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Abstract

Steel is one of the most widely used engineering materials and it is popularly welded in fabrication industries using Gas metal arc welding (GMAW) process. The microstructure obtained in the heat affected zone is often characterized with large grain size. Depending on the GMAW process parameters, the weld metal may consist of Allotrimorphic ferrite if the heat input is high. Therefore, the weld metal and the heat affected zone may have poor weld metal toughness. Efforts have been made to modify the microstructure of the weld metal by performing friction stir processing. Initially bead on plate welding was performed on mild steel plate using GMAW process using standard 1.2 mm consumable wire and CO2 as the shielding gas. The top surface of the weld was processed using a tungsten carbide tool. The weld reinforcement was removed using milling process and the area to be processed was made smooth before performing FSP. The plate was secured in an FSW machine and friction stir processing was carried out with a FSW tool having pin length of 2 mm. The GMAW weld and the weld that has been subsequently modified using FSP were characterized using standard techniques. The microstructure of the top face showed an improvement from Widmanstätten to fine equiaxed structure after being friction stir processed. The microstructure in the HAZ also got refined. It is expected that this structure would improve the mechanical properties of the weld particularly on the surface.

Rezime

Čelik je jedan od najčešće korišćenih inženjerskih materijala i u industri se često spaja postupkom zavarivanja topljivom elektrodom u zaštitnoj atmosferi aktivnog gasa (MAG). Mikrostruktura dobijena u zoni pod uticajem toplote najčešće se odlikuje krupnim zrnom. U zavisnosti od MAG procesnih parametara i ako je visoka unešena toplota, metal šava se može sastojati od alotrimorfnog ferita. Zbog toga, metal šava i zona pod uticajem toplote mogu imati nisku žilavost. U ovom radu je prikazan pokušaj da se izvrši modifikacija mikrostrukture metala šava dodatnom obradom primenom zavarivanja trenjem sa alatom FSW. Prvo je izvršeno navarivanje na čeličnu ploču od niskougljeničnog čelika primenom MAG postupka, koristeći standardnu potrošnu elektrodu prečnika od 1,2 mm i u CO_2 zaštitnom gasu. Lice šava obrađeno je pomoću alata od volframovog karbida. Nadvišenje šava uklonjeno je procesom glodanja i površina koju je trebalo obraditi učinjena je glatkom pre izvođenja procesa FSW. Ploča je bila pričvršćena u FSW mašini i obrada trenja alatom je izvedena pomoću alata dužine 2 mm. Karaktristike MAG zavarenog spoja i spoj koji je naknadno modifikovan upotrebom FSW ispitane su standardnim tehnikama. Mikrostruktura lica šava nakon obrade trenjem pokazala je poboljšanje, od Widmanstatten-a do fine usmerene strukture. Mikrostruktura u ZUT-u je takođe usitnjena. Za očekivati je da će nastale strukture posebno poboljšati mehanička svojstva u površinskim slojevima zavarenog spoja.

1. Introduction

Most of the welding of steel in industries is carried out by fusion welding processes like shielded metal arc welding (SMAW), GMAW and submerged arc welding (SAW) process. The microstructure of weld

1. Uvod

Većina zavarivanja čelika u industriji se izvedi postupcima elektrolučnog zavarivanja topljenjem poput zavarivanje u zaštiti gasova i pod prahom. Mikrostruktura metala šava niskougljeničnog čelika (proizveden procesom zavarivanja topljenjem) metal in mild steel (produced by fusion welding processes) mostly consists of allotrimorphic ferrite and Widmanstätten side plates or columnar type ferrite. Although this type of structure shows good tensile and the weld metal consisting of this type of structure lacks toughness [A]. Gas metal arc welding (GMAW) is a popular welding process that is widely used in fabrication industries for joining steel parts. The GMAW process is versatile and can be used to deposit weld metal at an appropriately fast rate. The microstructure obtained in GMAW is often not very favorable and may consist of coarse grain allotrimorphic ferrite and Widmanstätten ferrite [1]. Furthermore, the microstructure is difficult to control and may get largely affected by the atmospheric conditions and process parameters [2]. Friction stir welding being a solid state welding process and is known to impart fine grain structure [3]. The mechanical properties of friction stir welded aluminum alloys have been extensively researched and most of the studies have reported superior mechanical properties of the welds [4]. A good understanding of the current state of research in the area of friction stir welding of aluminum alloys can be found in the study by Threadgill et al. [5]. Most of the initial works on friction stir welding was carried out on low temperature softening alloys like aluminum, magnesium etc., and work on FSW of ferrous alloy were taken up much later [6,7]. The studies on friction stir welding of ferrous alloys have been restricted to tensile properties, and microhardness [8-20]. Very few works, have been carried out on FSP of welded plates. Present work attempts to improve the microstructure of GMAW weld by FSP

2. Experimentation

The work material selected for experimentation was carbon steel plates of 6 mm thickness. The material of AISI grade 1028 was supplied by steel authority of (India) limited (SAIL). The average value of chemical composition of the work material was found by spark spectroscopic analysis and has been presented in Tab. 1 as weight percentages. Bead was made on plate by GMAW process by using copper coated mild steel electrode of 1.2 mm diameter. The current and voltage used was 120 A and 25 Volts respectively. Three runs were made side by side to produce a sufficiently wide weld metal region to carry out FSP. The weld bead was first made smooth on a horizontal shaping machine. This was essential as the tool for FSP can only process on a flat surface.

uglavnom se sastoji od alotrimorfnog ferita i Widmanstatten ferita ili pločastog ferita. Iako ova vrsta strukture pokazuje dobre zatezne osobine zavarenog spoja metala šava, prisutna je niža žilavost [1]. Elektrolučno zavarivanje u zaštitnom gasu (MAG) je popularan postupak zavarivanja koji je široko rasprostranjen u proizvodnoj industriji za spajanje čeličnih delova. MAG postupak je svestran i koristiti se jer se zavarivanje obavlja relativno velikom brzinom. Mikrostruktura dobijena MAG postupkom često nije vrlo povoljna, jer se može sastojati od grubog zrna alotrimorfnogi ferita i Widmanstatten ferita [1]. Takođe, mikrostrukturu je teško kontrolisati i na nju mogu u velikoj meri uticati atmosferski uslovi i parametri procesa [2].

Zavarivanje trenjem sa alatom je proces zavarivanja u čvrstom stanju i poznato je da daje finu strukturu zrna [3]. Mehanička svojstva legure aluminijuma zavarivane trenjem sa alatom su predmet opsežnih istraživanja, a većina studija je pokazala superiornost mehanička svojstva zavarenih spojeva [4]. Trenutno stanje istraživanja u području zavarivanje trenjem sa alatom legura aluminijuma može se naći u studiji Threadgill i saradnika [5]. Većina početnih radova o zavarivanju trenjem sa alatom, odnose se na spajanje legura koje omekšavaju na niskim temperaturama poput aluminijuma, magnezijuma itd., a zavarivanje čelika postupkom FSW razvijeno je mnogo kasnije [6,7]. Studije o zavarivanju trenjem alatom za spajanje željeznih legura bila su ograničene na ispitivanja zateznih svojstva i mikrotvrdoće [8-20]. Vrlo malo radova prikazuje primenu tog procesa pri spajanju čeličnih ploča. Ovaj rad prikazuje pokušaj poboljšanja mikrostrukture zavarenog spoja čelika, prethodno zavarenog postupkom MAG i naknadno obrađen postupkom FSW.

2. Eksperiment

Za eksperimente su izabrane ploče od ugljeničnog čelika debljine 6 mm, kvaliteta AISI 1028 proizvođača (SAIL Indija). Hemijski sastav ispitivanog materijala određena je spektroskopskom analizom i prikazan je u Tabeli 1, kao procenti težine. Navari su izvedeni MAG postupkom upotrebom bakrom presvučena elektrodne žice od niskougljeničnog čelika prečnika 1,2 mm. Korišćena struja i napon su bili 120 A odnosno 25 V. Tri prolaza su napravljena jedan uz drugi da bi se dobio dovoljno širok metal vara za primenu postupka FSW. Metal navara je prvo zaravljen na horizontalnoj glodalici. Ovo je bilo od suštinske važnosti jer alat za FSW može da obrađuje samo ravne površine.

Table 1. *Composition of the Base Plate*
Tabela 1. *Hemijski sastav osnovnog materijala - ploče*

C%	Si%	Mn%	P%	S%	Fe%	Others %
0.165	0.047	0.37	0.007	0.011	99.158	0.2420

The weld metal of GMAW thus prepared was fiction stir processed on an NC controlled FSW machine using tungsten carbide tool. The tool material used for FSP was tungsten carbide with approximately 8% cobalt binder. Approximately 4% of other carbides like TiC and CrC were added in the tool material to improve its wear resistance. The details of tool geometry and process parameters have been given in Tab. 2. The tool pin position was positioned at the middle of the weld metal and FSP was carried out throughout the length of the weld in a straight line. The pin was inserted up to its length and shoulder was plunged by 0.5 mm. Once the material has been sufficiently plasticized, the tool was traversed along the direction of the weld. Metallographic sample was prepared using standard method. Microstructures of the top face of the samples were taken by using optical microscope. Micro hardness test was also carried out using Vickers hardness test using a load of 200 gms. Micro hardness was taken on the top face of the plate. Indentations were made keeping sufficient gaps between each indentation. The friction stir processed region and the weld metal (unprocessed by FSP) were indented and average of several readings were taken. The base material was also separately indented to know the value of the base material hardness.

Tako pripremljeni metal navara nanešen postupkom MAG, je zatim obrađen postupkom trenjem sa alatom na numerički kontrolisanom uređaju za FSW sa alatom od volframovog karbida sa približno 8% veziva kobalta. Približno 4% ostalih karbida poput TiC i CrC dodati su u materijal alata za poboljšanje otpornosti na habanje. Detalji o geometriji alata i parametrima procesa prikazani su u Tabeli 2. Položaj vrha alata bio je pozicioniran na sredini navarenog metala i FSW postupak izveden je u pravoj liniji celom dužinom vara. Vrh alata je uronjen celom dužinom i potoplen još za 0.5 mm. Kada je material dovoljno omekšao, alat je uzdužno vođen u pravcu zavarenog spoja.
Metalografski uzorci su pripremljeni primenom standardnih metoda. Mikrostrukture sa gornje površine uzoraka su analizirane optičkom mikroskopijom. Ispitivanje mikro tvrdoće vršeno je Vickers metodom primenom opterećnja od 200 grama, na gornjoj površini ispitivane ploče. Merenje mikrotvrdoće vršeno je vodeći računa da je razmak između pojedinih otisaka dovoljno veliki. Oblast zavarenog spoja koja je obrađena postupkom FSW i metal šava koji nije procesuiran sa FSW, su razdvojeni i srednja vrednost više merenja je usvajana. Osnovni material je takođe odvojeno ispitivan, kako bi se znale vrednosti tvrdoće za osnovni metal.

Table 2. *Process Parameter & Tool Geometry used in FSW*
Tabela 2. *Procesni parametri i geometrija alata primenjeni u postupku FSW*

Parameters- Parametri	Values in units – Vrednosti u jedinicama
Welding Speed - Brzina zavarivanja	150mm/min
Tool RPM – Broj obrtaja alata	800
Tool Tilt Angle – Ugao naginjanja alata	1.5^{0}
Pin Length – Dužina alata	2.5 mm
Pin shape- Oblik vrha alata	Truncated cone – Zaravljeni konus
Shoulder Diameter – Prečnik gornjeg dela alata	15 mm

3. Results

Defect free beads were obtained using GAW process. The bead on shaping revealed no porosity. FSP of plates produced good quality of processed regions Visual examination revealed no defects and fine ripples were seen on the top surface of the weld.

3. Rezultati

Navareni metal šava dobijen MAG postupkom je bio bez uočenih grešaka. Takodje nije uočeno prisustvo poroznosti. Postupak FSW primenjen na ispitivanim pločama, pokazao je dobar kvalitet u obalastime koje su procesuirane. Vizuelni pregled je pokazao da nisu uočene greške u metalu vara, a konstatovano je prisustvo finih talasa na gornjoj površini vara.

3.1 Microstructural examination

The macrographs of the GMA welded and plate after FSP is shown in Fig. 1(a). Micrographs were observed using optical microscope from different locations of the weldment. The microstructure of the GMAW weld was consisting of Widmanstätten ferrite and little acicular ferrite which is typical of weld nugget of a fusion weld (Fig. 2a). The microstructure of the plate obtained after GMAW and FSP is shown in figure 1. The micrographs of different regions namely the weld metal, heat affected zone, thermo mechanically affected zone and stirred zone are shown in above figure taken at 400 magnification. Fig. 1(a) shows that weld metal comprises of Widmanstätten ferrite, blocky ferrite and a small fraction of pearlite/bainite. Fig. 1(b) indicates presence of equiaxed and refined grains in heat affected zone of surrounding the processed region and affected by the heat of the FSP. The thromechanically affected zone (TMAZ) is shown in figure 1(c) and it consists of elongated grains. In contast to all the other regions, the processed zone consists of very fine equiaxed grains (figure 1(d)).

3.1 Mikrostrukturni pregled

Makrografije mikrostrukture metala vara nakon MAG procesa kao i ploče nakon obrade postupkom FSW su prikazane na slici 1. Mikrostrukture su posmatrane pomoću optičkog mikroskopa na različitim mestima zavarenog spoja. Mikrostruktura MAG metala vara se sastojao od Widmanstatten ferita i malo igličastog ferita što je tipično za metal šava dobijen topljenjem (slika 1a). Mikrostruktura spoja dobijena posle MAG navarivanja i obrade FSW procesom je prikazana na slici 1b). Mikrografije različitih područja, naime metala šava, zone uticaja toplote, termo mehanički obrađene zone i zone nastale mešanjem metala postupkom FSW, prikazane su pri uvećanju od 400 puta.

Slika 1(a) pokazuje da metal vara se sastoji od Widmanstatten-ovog ferita, ferita i malih udela perlita/beinita. Slika 1(b) ukazuje na prisustvo usmerenih i usitnjenih zrna u zoni uticaja toplote koji okružuje obrađenu oblast i rezultat je uticaja toplote procesa FSW. Termomehanički obrađena zona (TMAZ) prikazana je na slici 1(c) i sastoji se od izduženih zrna. Nasuprot svim ostalim oblastima, obrađena zona se sastoji se od vrlo finih usmerenih zrna, slika 1(d).

Figure 1.(a) *Micrograph of the weld metal obtained after GMAW at 400x*
Slika 1.(a) *Mikrostruktura metala vara dobijenog MAG postupkom, uvećanje 400 puta*

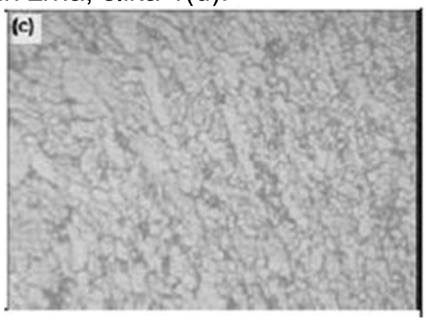

Figure 1.(b) *Micrograph HAZ surrounding the processed region at 400x*
Slika 1.(b) *Mikrostruktura ZUTa koji okružuje procesuiranu oblast, uvećanje 400 puta*

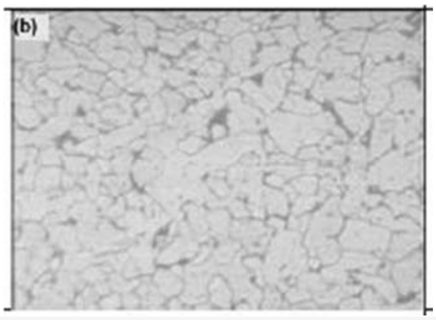

Figure 1.(c) *Micrograph of the TMAZ adjacent to the processed region at 400x*
Slika 1.(c) *Mikrostruktura TMAZ oblasti uz procesuiranu oblast, uvećanje 400 puta*

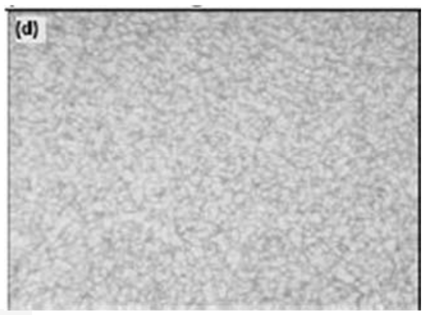

Figure 1.(d) *Micrograph of the processed region at 400x*
Slika 1.(d) *Mikrostruktura procesuirane oblasti postupkom FSW, uvećanje 400 puta*

3.2 Micro-hardness testing

The results of the micro-hardness measurement done in different regions on the top face of the weld have been presented Tab. 3. The microhardness testing revealed the typical hardness values of the weld metal which is more than the hardness of the base material (found to be around 180 HV). The average values of hardness in both the GMAW weld
metal and friction stir processed region are both higher than the base material hardness.

3.2 Ispitivanje mikro tvrdoće

Rezultati merenja mikrotvrdoće koje je izvedeno u različitim oblastima na gornjoj strani zavara su predstavljeni Tabeli 3. Ispitivanje mikrotvrdoća je pokazalo tipične vrednosti tvrdoće metal šava, koja je veća od tvrdoće osnovnog materijala i utvrđeno je da iznosi oko 180 HV. Srednje vrednosti tvrdoće u obe oblasti, MAG metal šava i područje obrađeno sa FSW, su veće od tvrdoće osnovnog materijala ploče.

Table 3. *Microhardness analysis of weld metal and stir zone*
Tabela 3. *Mikrotvrdoća metla šava i oblasti obrađene postupkom FSW*

Region Oblast	Micro-Hardness (HV) Mikrotvrdoća (HV)	Mean Srednja vrednost	Sample standard deviation s Standardna devijacija uzorka s	Population standard deviation σ Standardna devijacija populacije σ
Weld metal Metal šava	179, 202, 181, 213, 240	203	25.14	22.49
Processed zone Procesuirana oblast	198, 195, 193, 196, 197	195.33	2.52	2.05

From above table it can be easily visualized that the average hardness of weld metal is comparable to that of the friction stir processed region. There is a huge variation in the microhardness values at different locations of weld metal whereas the microhardness in the processed zone show almost similar values at different points due to a refined and equiaxed structure. The grains are plastically deformed at very high strain rate followed by dynamic recrystallization results into formation of equiaxed grains. The hardness of processed region is due to refinement of grains whereas hardness of weld metal is due to presence of different phases in which some phases are less hard like blocky ferrite and some phases are much hard like martensite.

4. Conclusions

The following important conclusions can be drawn from this experimental work.

1. Gas metal arc welded plate shows coarse grain Widmanstätten ferrite and blocky ferrite and the amount of acicular ferrite may be very small.
2. Friction Stir Processing. FSP of steel can be successfully carried out at correct set of process parameters using tungsten carbide as a tool material.
3. The microstructure of the weld metal obtained after GMAW can be improved by FSP and the processing results in formation of a fine grained structure. This structure is expected to improve the properties of the weld metal.

Iz rezultata prikazanih u gornjoj tabeli može se uočiti da je srednja vrednost tvrdoće metala šava uporedljiva sa onom dobijenom u oblasti gde je vršena obrada sa FSW procesom. Može se konstatovati velika varijacija vrednosti mikrotvrdoće na različitim lokacijama zavarenog spoja. Mikrotvrdoća u procesuiranoj oblasti pokazuje skoro slične vrednosti na različitim mestima zbog usitnjene i usmerene structure. Zrna su plastično deformisana pri vrlo visokim brzinama deformacije koja je praćena dinamičkom rekristalizacijom koja je rezultovala formiranjem usmerenih zrna. Tvrdoća metala vara je neujednačena zbog prisustva različitih faza u mikrostrukturi pri čemu su neke faze manje tvrde poput pločastog ferita i neke faze su daleko veće tvrdoće poput martenzita.

4. Zaključci

Sledeći važni zaključci mogu biti izvedeni iz ovog eksperimentalnog rada.

1. Čelična ploča zavarena postupkom MAG pokazuje u strukturi gruba zrna Widmanstatten-ovog ferita i pločasti ferit, a količina acirkularnog ferita može biti vrlo mala.
2. Obrada trenjem sa alatom FSW može biti uspešno izvedeno na čeliku sa pravilnim izborom procesnih parametara i uz primenu volfram karbida za materijal alata.
3. Mikrostruktura metala šava dobijene nakon MAG zavarivanja može se poboljšati procesom FSW, a kao rezultat procesa je formiranje fino zrnaste structure. Za očekivati je da takva struktura poboljšava osobine metala šava.

4. There is a huge variation in the microhardness values at different locations of weld metal and therefore it can be expected that the mechanical properties would not be very uniform after GMAW. Subsequent FSP can make the properties more uniform and it is expected that Friction Stir processing of gas metal arc welded steel will help in improving the service life of the component.

4. Postoje velike razlike u vrednosti mikrotvrdoće na različitim lokacijama unutar metala šava i stoga se može očekivati da mehanička svojstva ne bi bila ravnomerna posle zavarivanja MAG postupkom. Naknadna obrada postupkom FSW može obezbediti ujednačenije osobine i za očekivati je da primena FSW postupka nakon zavarivanja čelika postupkom GMA, će pomoći u produženju životnog veka zavarenih komponenti.

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