UDK 621.793:621.792.3

Industrijsko platiranje nerjavnega jekla na malooglji čno jeklo z eksplozijo
Industrial Cladding of Stainless Steel to Low Carbon Steel by Explosion

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Plošče, debele 150 mm iz maloogljičnega jekla, smo eksplozijsko platirali s 4 mm in 5 mm debelini ploščami iz nerjavnega jekla (304L, (AISI), Acroni 11 NC (Slovenske železarne)). Bimetalne plošče so za izdelavo reaktorja za procesno industrijo za delo pri 250 °C in 250 bar. Opisane so posebnosti spajanja z eksplozijo in analiza spoja platiranih plošč. V tem času je reaktor že prevzel naročnik.

The base material (ASTM A-516 Gr. 70, size: 2970 x 9800 × 1 500 mm) was clad by explosion with cladding material (ASTM A 240-304L, same size, 4 and 5 mm thick). The completed clad plate was used for fabrication of a pressure vessel in the processing industry, for working temperatures over 250 °C and a working pressure of 250 bars. In this paper, the basics of the explosive cladding mechanism are presented, together with an analysis of test samples taken from clad plates.

0 UVOD

Rušilne eksplozivne snovi pripadajo skupini virov energij velikih gostot, ki sproščajo energijo velikosti MJ v izjemno kratkem času (nekoliko μs). Energija eksplozije se preoblikuje preprosto brez zapletenih mehanizmov prenosa. Pojav eksplozije je definiran z zakoni porazdelitve in nabiranja ter omogoča upravljanje procesa platiranja.

Hitrost, tlak in moč eksplozije kot njeni parametri ostajajo v področju Newtonovega zakona, zakonov termodinamike, termokemije in kvantne mehanike.

Sproščene energije prisilijo material v novo stanje na popolnoma različen način od običajno poznanih tehnologij.

Udarni valovi, preoblikovani iz detonacijskih valov pri eksploziji rušilnih eksplozivnih snovi, se uporabljajo kot tehnološke energije za obdelavo materialov z eksplozijo (preglednica 1). Dandanes poznamo več ko trideset postopkov:

– spajanje raznovrstnih kovin na ravnih, zakrivljenih in valjastih površinah, notranjih in zunanjih,

– utrjevanje ravnih, razgibanih in valjastih površin,

– armiranje površin s kovinami,

– oblikovanje kovin,

– perforiranje z oblikovanjem in/ali kalibriranje,

– rezanje kovin,

– ravnanje kovin,

– sproščanje zaostalih napetosti v zvarih,

0 INTRODUCTION

Explosives are a source of high-density energy, releasing energy of the order of magnitude MJ in an extremely short time (some μs). Explosion energy is transformed in a simple manner, without any elaborate transfer mechanisms. The phenomenon of explosion is defined by the laws of distribution and cumulation, enabling the cladding process.

The velocity, pressure and power of the explosion, and their parameters, remain within Newtonian laws, laws of thermodynamics, thermochemistry, and quantum mechanics.

Energy released during explosive cladding forces materials into a state quite different from standard transformation technologies.

In explosive cladding, shock waves formed from the detonation waves serve as an energy source for various metalworking operations (Table 1). Today, there are more than different thirty operations:

– welding of different metals on flat, curved and cylindrical surfaces, inside and outside,

– hardening of surfaces by metals,

– forming of metals,

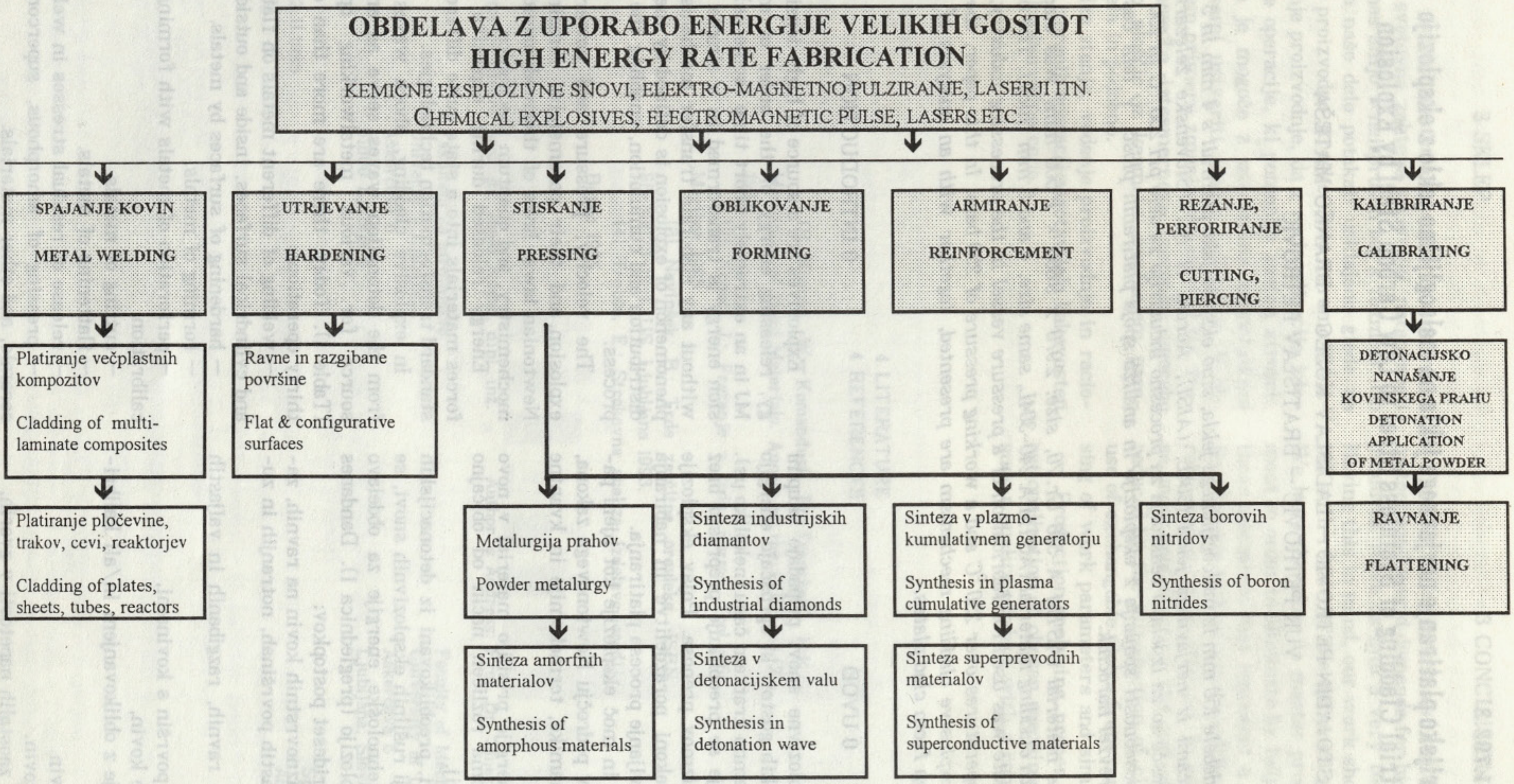
– perforation of metals with forming and/or calibration,

– cutting of metals,

– flattening of metals,

– release of residual stresses in welds,

– pressing of amorphous, superconductive, ceramic, and other materials.



Preglednica 1: *Postopki obdelave materialov z uporabo energije velikih gostot*
Table 1: *Metalworking operations by use of light density energy*

— stiskanje amorfnih, superprevodnih, keramičnih in drugih materialov,
— sinteza novih materialov diamantne strukture,
— polimerizacija akrilamidov, oksidov in drugih spojin,
— detonacijsko nanašanje kovinskega in drugih vrst prašnatih materialov na izrabljene površine,
— sinteza v plazma generatorjih,
— posebne operacije z zelo visokim tlakom in zelo močnim magnetnim udarom.

1 SPAJANJE KOVIN Z EKSPLOZIJO

Operacija spajanja kovin z eksplozijo je zelo hitri poševni udar kovinskih plošč pod delovanjem detonacije z relativno hitrostjo plošč, ki se spajajo pri pojavu visokega dinamičnega tlaka in plastičnih deformacij v obliki valov na meji spoja ob adiabatnem lokalnem segrevanju površinskih slojev kovin v spoju.

Na sliki 1, je prikazana shema spajanja kovin z eksplozijo. Na osnovno ploščo se postavi platirna pločevina, in sicer pod kotom in na določeni oddaljenosti, s slojem eksploziva, ki se sproži z detonatorjem.

Uporabljata se dva postopka varjenja kovin z eksplozijo, odvisno od lege plošč, ki se spajajo:
— postopek vzporednih plošč
— postopek poševnih plošč.

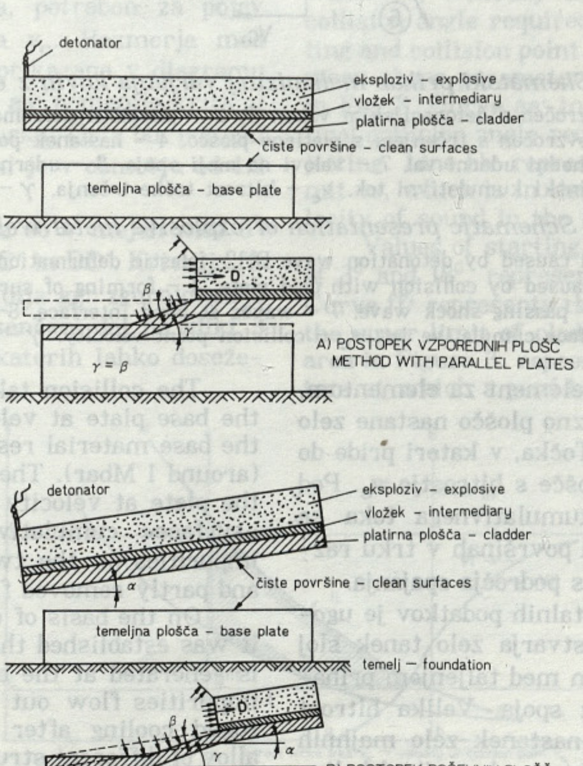
— synthesis of new materials with diamond structure,
— polymerisation of acrylamides, oxides and other compounds
— application of metal and other types of powder onto surface by detonation,
— synthesis in plasma generators,
— operations at high pressure, high power magnetic pulse.

1 EXPLOSIVE METAL WELDING (CLADDING)

Explosive metal cladding is a high-speed angle oblique collision of two or more metal plates caused by detonation, resulting in their welding, under high dynamic pressure and the formation of plastic waves on the bond interface, accompanied by local adiabatic heating of the surface layers of the metals in the bond.

Figure 1 shows the principles of explosive metal cladding. Clad plate is placed onto the base plate, at a specific angle and distance, the explosive layer poured onto the clad plate and the charge initiated.

Basically, there are two cladding methods, depending on the cladding plate positions:
— parallel plate cladding,
— oblique plate cladding.



Sl. 1. *Postopek eksplozijskega varjenja kovin*
Fig. 1. *Explosive metal welding (cladding)*

1.1 Mehanizem spajanja kovin z eksplozijo

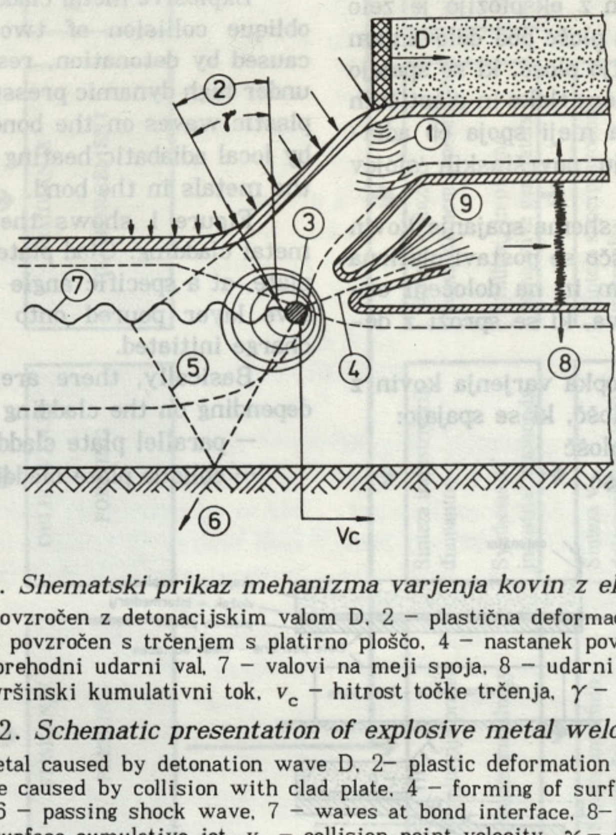
Shematski prikaz mehanizma spajanja kovin z eksplozijo je prikazan na sliki 2. Po sprožitvi detonacije se giblje detonacijski val eksplozivnega polnjenja s stalno hitrostjo *D*, ki je odvisna od lastnosti eksplozivne snovi, gostote in debeline sloja eksploziva.

Detonacijski val se preoblikuje v udarni val v kovini (poz. 1 na sl. 2). Platirna plošča se pod delovanjem produktov detonacije pospešuje, dvakrat upogne in trči s spodnjo nepremično ploščo.

1.1 Explosive metal cladding mechanism

A schematic presentation of explosive metal welding is given on Figure 2. After the initiation of the explosive charge, the detonation wave travels at a constant velocity *D*, which depends on the explosive material characteristics, explosive charge density, and height.

The detonation wave is transformed into a shock wave in the metal (pos. 1 on Fig. 2). The cladding plate, driven by detonation products, accelerates, bends twice and hits the lower immobile plate.



Sl. 2. *Shematski prikaz mehanizma varjenja kovin z eksplozijo*

1 – udarni val v kovini, povzročen z detonacijskim valom D, 2 – plastična deformacija, povzročena z dinamičnim pritiskom, 3 – udarni val, povzročen s trčenjem s platirno ploščo, 4 – nastanek površinskega kumulativnega toka, 5 – odbiti udarni val, 6 – prehodni udarni val, 7 – valovi na meji spoja, 8 – udarni zračni val in njegovo delovanje na ploščo, 9 – površinski kumulativni tok, v_c – hitrost točke trčenja, γ – dinamični kot trčenja

Fig. 2. *Schematic presentation of explosive metal welding mechanisms*

1 – shock wave in the metal caused by detonation wave D, 2– plastic deformation caused by dynamic pressure, 3 – shock wave caused by collision with clad plate, 4 – forming of surface cumulative jet, 5 – reflected shock wave, 6 – passing shock wave, 7 – waves at bond interface, 8– air shock wave and its effects on the plate, 9 – surface cumulative jet, v_c – collision point velocity, γ – dynamic collision angle

Trk nastaja postopno, element za elementom, s hitrostjo v_p. V trku z bazno ploščo nastane zelo visok tlak (okrog 1 Mbar). Točka, v kateri pride do trka, se giblje po dolžini plošče s hitrostjo v_c. Pod vplivom »površinskega« kumulativnega toka se oksidi in druge nečistote na površinah v trku razkrojijo in delno odstranijo s področja spajanja.

Na podlagi eksperimentalnih podatkov je ugotovljeno, da se na spoju ustvarja zelo tanek sloj staljene kovine, pri katerem med taljenjem prihaja do iztekanja nečistot iz spoja. Velika hitrost hlajenja po trku povzroči nastanek zelo majhnih zrnc zlitine drugačne strukture, katerih debelina je približno 1 do 2 μm. Nastanek tega amorfnega sloja na področju spajanja opažamo pri različnih kombinacijah kovin in je temeljni mehanizem pri spajanju kovin z eksplozijo.

The collision takes place successively, along the base plate at velocity v_p. The collision with the base material results in a very high pressure (around 1 Mbar). The collision point travels along the plate at velocity v_c. Under the influence of »surface« cumulative flow, oxides, and other impurities on the two surfaces are decomposed, and partly removed from the bonding area.

On the basis of experimentally obtained data, it was established that a very thin layer of melt is generated at the bond interface, within which impurities flow out of the bond during melting. Rapid cooling after the collision generates an alloy of different structure and very small grains, of average thickness 1 to 2 μm. The generation of such an amorphous layer in the bond area has been noticed with various metal combinations and represents a fundamental mechanism of explosive metal cladding.

1.2 Omejitve pri procesu spajanja kovin z eksplozijo

Proces spajanja z eksplozijo lahko razdelimo na tri stopnje:

— pojav energije eksplozije z detonacijo eksplozivnega polnjenja,

— pospeševanje in deformacijo platirne plošče,

— trk platirne plošče z bazno ploščo.

Na prvi stopnji je zagotovljena potrebna energija za pospeševanje in deformacijo platirne plošče.

Proces pospeševanja je definiran z medsebojno razdaljo med ploščama. Na drugi stopnji dobi platirna plošča določeno kinetično energijo (hitrost in pospešek) in določeno hitrost v_p v točki trka s temeljno nepremično ploščo, pri čemer se kinetična energija spremeni prek mehanskega dela deformacije v toplotno energijo in prihaja do spajanja kovin na tretji stopnji.

Analiza pojava spajanja kovin z eksplozijo potrjuje, da je spajanje neposredna posledica velikih hitrosti trka. Preizkusi prav tako potrjujejo, da obstajajo določene kritične vrednosti za optimalen trk. Glede na kompleksnost tega pojava in na podlagi eksperimentalnih podatkov lahko napovemo nastajanje valov na meji spoja. Ta napoved pomaga pri določanju razponov parametrov, pri katerih lahko nadziramo spajanje.

Ta način se imenuje »okno spajanja«, kjer je kritični parameter kot trka, potreben za pojav curka in hitrost točke trka v_c. Razmerja med temi parametri so grafično prikazana v diagramu na sliki 3. Krivulja na sliki 3 aa' pomenijo kritični kot trka, potreben za pojav curka. Črta bb' pomeni zgornjo mejo za hitrost v_c, ki je v območju od 1,2 do 1,5-kratne hitrosti zvoka.

Vrednosti začetnega kota so v mejah med 3° in 18°, prikazani s smermi CC' in DD'. Krivulja ff' pomeni spodnjo mejo in krivulja gg' zgornjo mejo hitrosti platiranja – v_p. Zasenčeni del na sliki 3 je področje parametrov, pri katerih lahko dosežemo primeren spoj kovin.

1.2 Limitations of explosive metal cladding

The explosive metal cladding process can be divided into three stages:

— generation of explosion energy through the detonation of the explosive charge,

— acceleration and deformation of the cladding plate,

— collision of the cladding plate with the base plate.

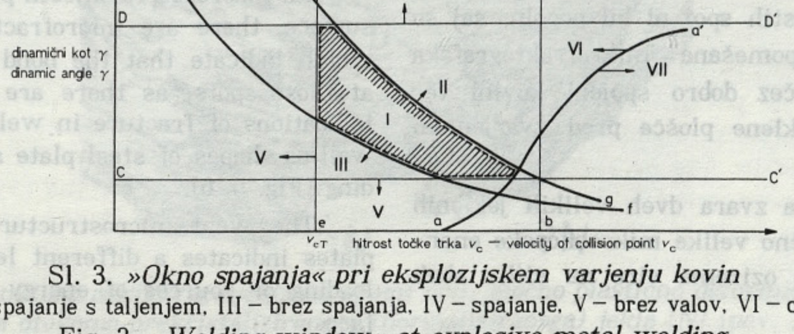
At the first stage, energy necessary for acceleration and deformation of the cladding plate is generated.

Cladding plate acceleration is determined by the distance between plates. In the second stage, the cladding plate receives a certain kinetic energy (velocity and acceleration) and a certain velocity - v_p, at the collision point with the base plate. Kinetic energy is dissipated through the mechanical work of deformation into thermal energy, followed by the welding of metals at the third stage.

Analysis of the explosive metal welding phenomenon confirms that welding is the direct consequence of the high speed of collision. Experiments also confirm that there are critical values for optimum collision. With these parameters in mind, and on the basis of experimental data, one can anticipate the generation of waves on the bond interface. That criterion helps to determine the range of parameters at which one can control bonding.

This set of parameters is called »the welding window«, whereby the critical parameters are: collision angle required for the appearance of jetting and collision point velocity, v_c. Relations between those parameters are graphically presented in Fig. 3. Curve aa' in Fig. 3. represents the critical collision angle required for the appearance of jetting. Line bb' represents the upper velocity limit v_c, which is in the range of 1.2 to 1.5 the velocity of sound in the material being clad.

Values of starting angle are within the range of 3° and 18°, represented by lines CC' and DD'. Curve ff' represents the lower limit and curve gg' the upper limit of clad velocity - V_P. The shaded area in Figure 3. represents the range of parameters at which a good bond can be obtained.



Sl. 3. *»Okno spajanja« pri eksplozijskem varjenju kovin*

I – okno spajanja, II – spajanje s taljenjem, III – brez spajanja, IV – spajanje, V – brez valov, VI – curek, VII – brez curka

Fig. 3. *»Welding window« at explosive metal welding*

I – welding window, II – welding by melting, III – without welding, IV – welding, V – without waves, VI – jetting, VII – without jetting

1.3 Analiza meje spoja

Pri eksplozijskem varjenju nastala trdna vez velikih plošč ogljikovega in nerjavnega avstenitnega jekla ima nekatere posebnosti, po katerih se loči od zvarov istih kovin, izdelanih na drug način (npr. z varjenjem ali valjarniškim platiranjem).

Stična površina jekel, značilna za ta način spajanja, je valovita, z valovno dolžino približno 1 mm in amplitudo približno 0,3 mm.

Trdnost spoja jeklenih plošč smo preverjali s strižnim preizkusom do porušitve. Napake, nastale pri strjevanaju nataljenih otokov, ne vplivajo na porušitev spoja.

Na preizkušanih vzorcih je prelom potekal čez ogljikovo jeklo pretežno skozi nedeformirana področja, delno pa tudi na meji velike deformacije.

Na večjem delu prelomne površine je opaziti periodičnost, ki se ujema z valovitostjo meje obeh jeklenih plošč (sl. 4).

1.3 Bond interface analysis

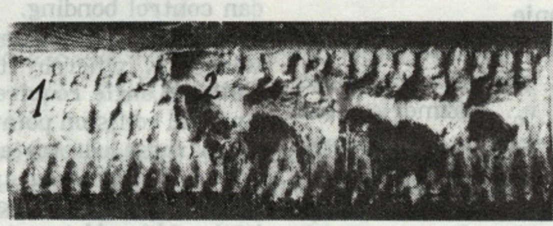
The bond obtained by explosive cladding between large plates of carbon steel and stainless steel has some characteristics which distinguish it from other types of welds of the same grade of materials (i.e. roll bonding or weld overlay).

The characteristic surface (contact) area of the two materials for this type of welding is wavy, with wave length approximately 1 mm and amplitude of approximately 0.3 mm.

Bond strength was tested on shear strength to bond failure. Defects generated during solidification of melts do not influence bond failure.

On test samples, fracture mainly ran through carbon steel, mostly through undeformed areas, partly on the large deformation boundary.

A certain periodicity was observed in a larger part of the failure surface, corresponding to the wavy interface of the two steel plates (Fig. 4).



Sl. 4. *Prelom preizkušanca za merjenje trdnosti spoja jeklenih plošč (povečano pribl. 3×)*

Fig. 4. *Failure on steel plate bond hardness test sample (magn. appr. 3×)*

Ta periodičnost je mestoma pretrgana z večjimi gladkimi polji prelomne površine.

Na večini prelomne površine je tipičen žilav prelom s simetričnimi jamicami.

Na makroskopsko gladkih delih prelomne površine so mikrofraktografski elementi, ki kažejo, da na teh mestih spoj ni bil popoln, saj so na tem mestu pomešana mikrofraktografska znamenja prelom čez dobro spojeni kovini ter oblike površine jeklene plošče pred zvarjenjem (sl. 5, 6).

Mikrostruktura zvara dveh velikih jeklenih plošč kaže na različno velike mikroskopske energijske obremenitve oziroma vire na stiku obeh kovin.

V okolici stične površine jekel so nastale naslednje spremembe:

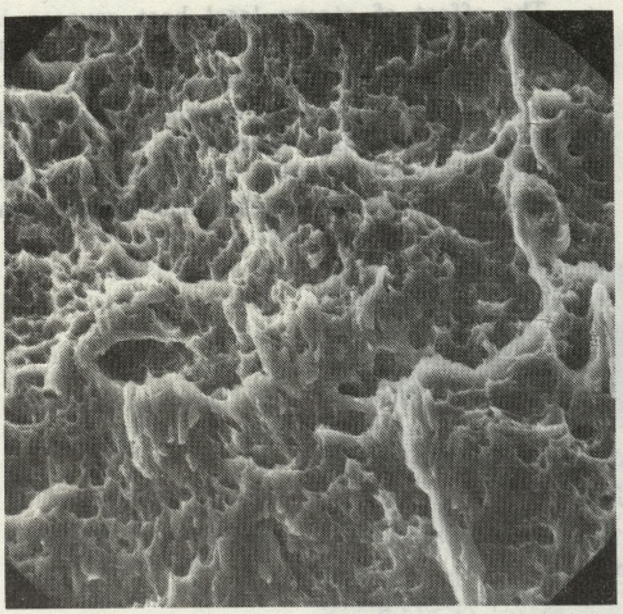
Such a periodic pattern is interspersed in some places with larger smooth areas of failure surface.

On the largest part of the fracture surface there is a typical ductile fracture with asymmetric dimples.

On macroscopic smooth parts of the fracture surface, there are microfractographic elements, which indicate that the bond was not complete at those spots, as there are microfractographic indications of fracture in well bonded metals, as well as shapes of steel plate surface before bonding (Fig. 5, 6).

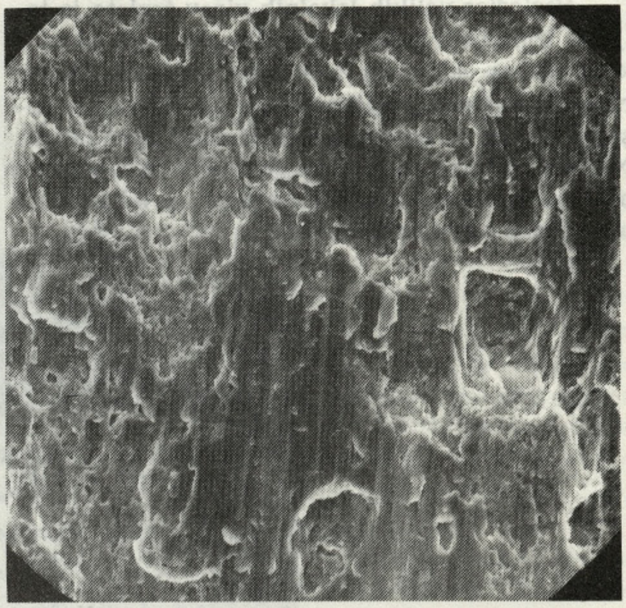
The weld microstructure of the two steel plates indicates a different level of microscopic loading or sources of energy at the bond interface.

In the surrounding area of the steel interface, the following transformations have been noticed:



Sl. 5. *Mikrografija v delu preloma 1 (sl. 4) v področju dobrega spoja; žilav, jamičast prelom (pov. 2000 ×)*

Fig. 5. *Micrography in the fracture area 1 (Fig.1) of the good bond area; ductile fracture with dimples (magn. 2000 ×)*



Sl. 6. *Mikrografija v delu preloma 2 (sl. 4); raze so znak oblike površine jeklene plošče pred spajanjem ter žilav, jamičast prelom (pov. 600 ×)*

Fig. 6. *Micrography in the fracture area 2 (fig.4) scratches are indicators of steel plate surface shape prior to bonding, and ductile fracture with dimples (magn. 600 ×)*

– plastična deformacija obeh jekel;

– prekristalizacija (normalizacija) ogljikovega jekla;

– rekristalizacija deformiranega nerjavnega jekla;

– nastanek taline na stični površini.

Obe jekli sta v okolici stične ploskve močno deformirani. Deformacija je največja v področju gub. Najbolj je opazna v ogljikovem jeklu, kjer je feritno-perlitna mikrostruktura razpotegnjena v vlaknate gruče (sl. 7).

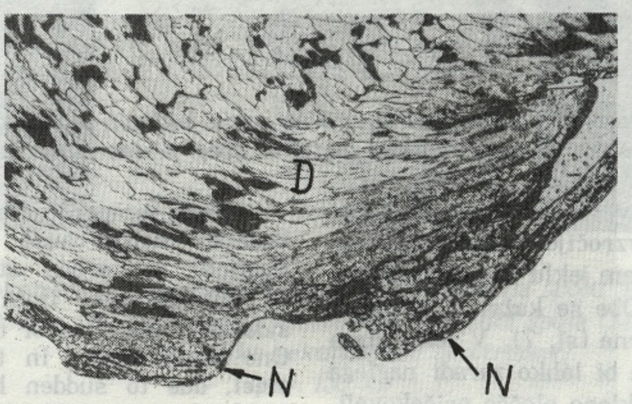
– plastic deformation of both steels,

– recrystallization (normalization) of carbon steel,

– recrystallization of deformed stainless steel,

– melt generation at the interface.

Both steels in the interface area are strongly deformed. The deformation is highest in the wave crest area. It is most noticeable in carbon steel, where the ferritic-perlite microstructure is spread into fiber heaps (Fig. 7).

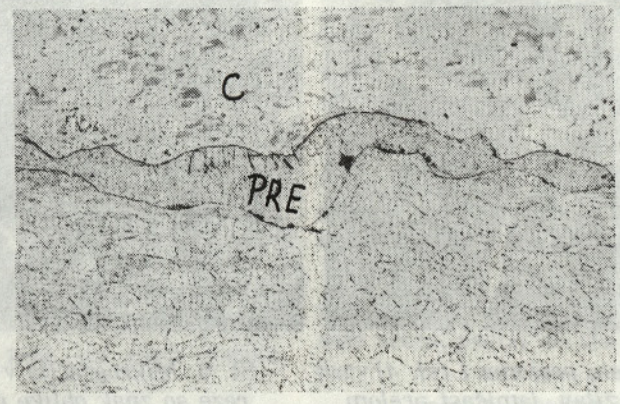


Sl. 7. *Mikrostruktura ogljikovega jekla na spojni črti; močno plastično deformirano jeklo (D) z dvema otokoma prekristaliziranega (normaliziranega) jekla (N) (pov. 200 ×)*

Fig. 7. *Microstructure of carbon steel at bond interface; high plastic deformation of steel (D) with two islands of recrystallized) steel (N) (magn. 200 ×)*

Posledica velikih lokalnih virov toplote je taljenje izoliranih mikropodročij nerjavnega jekla, v katerem se je, kljub kratkemu trajanju taline, raztalilo kar nekaj ogljikovega jekla, tako da je nastala zlitina, ki se dobro loči od obeh jekel (sl. 8). Nastala zlitina (jeklo) ima v enem od izoliranih otočkov naslednjo kemično sestavo: približno 12,2 odstotka Cr in 4 odstotke Ni.

The effect of strong local heat sources is melting of isolated microareas of stainless steel, in which, in spite of the short duration of melting, some carbon steel has melted, resulting in an alloy quite distinct from both steel grades (Fig. 8). The resulting alloy (steel) in one isolated spot has the following chemical composition: around 12.2% Cr and 4% Ni.



Sl. 8. *Mikrostruktura na spoju jeklenih plošč; zgoraj (C) ogljikovo jeklo, v sredini pretaljeni otok (PRE), spodaj nerjavno avstenitno jeklo (pov. 100 ×)*

Fig. 8. *Microstructure at steel plates bond interface; top carbon steel (C), melt (PRE) in the middle, below austenitic stainless steel (magn. 100 ×)*

Pri strjevanju so v teh otočkih nastale značilne napake, mikroporoznost in razpoke (sl. 9, 10).

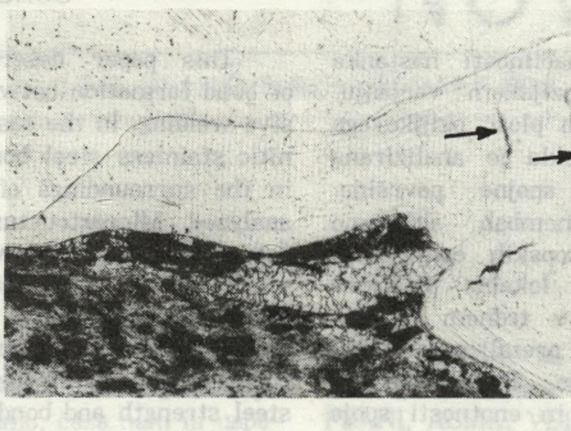
After hardening, significant defects, microporosity, and crevices, were generated (Fig. 9, 10).

Sl. 9. *Mikrolunker v pretaljeni kovini na spoju jeklenih pločevin; (pov. 100 ×)*

Fig. 9. *Microporosity in the remelted metal at steel plates' interface; (magn. 100 ×)*

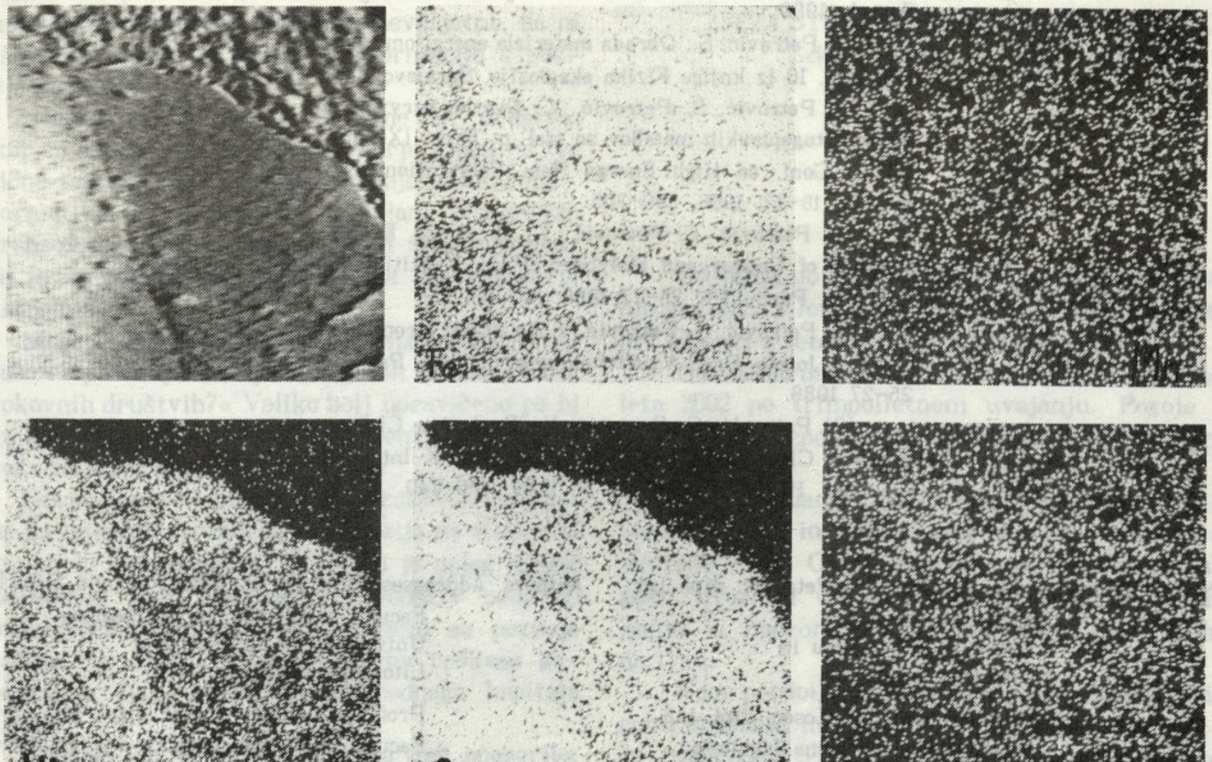
Visoke temperature v okolici izoliranih staljenih otokov kovine povzročijo prekristalizacijo (normalizacijo) v ogljikovem jeklu in rekristalizacijo v nerjavnem jeklu. Obe se kažeta v očitnem zmanjšanju kristalnega zrna (sl. 7). V tem istem področju ogljikovega jekla bi lahko zaradi naglega odvoda toplote v debelo jekleno ploščo pričakovali, da bi lahko nastal tudi martenzit, ki pa nam ga z znanimi metodami ni uspelo odkriti. Prav verjetno je, glede na kemično sestavo v pretaljenih otokih, mikrostruktura iz malooglјičenega martenzita.

High temperatures in the surroundings of isolated melts cause recrystallization (normalization) in carbon steel and recrystallization in stainless steel. Both are manifested in a considerable reduction of the crystal grain (Fig. 7). One could expect in the same area of carbon steel, due to sudden heat transfere into thick steel plate, possible generation of martensite, which could not be detected with methods available to us. It is likely, however, that in terms of chemical composition, the microstructure in the melts is of low carbon martensite.



Sl. 10. *Mikrorazpoke v pretaljeni kovini na stiku jeklenih plošč (pov. 200 ×)*

Fig. 10. *Microcracks in remelted metal at steel plates interface (magn. 200 ×)*



Sl. 11. *Mikrokemična analiza otoka pretaljene kovine na spoju jeklenih plošč; porazdelitev železa (Fe) in legirnih elementov v okolici spoja (Mn, Ni, Cr, Si); levo zgoraj slika sekundarnih elektronov) (pov. 150 ×)*

Fig. 11. *Microchemical analysis of remelted metal at steel plates interface; distribution of iron (Fe) and alloying elements around the bond (Mn, Ni, Cr, Si); left top micrograph of secondary electrons (magn. 150 ×)*

2 SKLEP

V članku so opisane značilnosti nastanka spoja dveh kovin pri eksplozijskem varjenju. Na posebnem primeru spajanja plošč ogljikovega in nerjavnega avstenitnega jekla je analizirana mikrostruktura v okolici spojne površine. Po mikrostrukturnih spremembah sklepamo o delovanju močnih mikroskopskih energijskih virov, ki povzročajo velike lokalne plastične deformacije, fazne premene v trdnem in nataljevanje jekel. Napake v pretaljenem jeklu ne vplivajo na trdnost spoja. Ta je odvisna od trdnosti ogljikovega jekla in enotnosti spoja na mikroskopski ravni.

CONCLUSION

This paper describes the characteristics of bond formation between two metals at explosive welding. In the case of carbon steel - austenitic stainless steel bonding, the microstructure in the surroundings of the bond interface was analyzed. Microstructural transformations indicate the action of powerful sources of energy, which cause large local plastic deformations, phase transformations in solid state and steel melting. Defects in remelted steel have no influence on bond strength. It depends on carbon steel strength and bond homogeneity on the microscopic level.

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3 REFERENCES

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Prejeto: Received: 5.11.1995

Sprejeto: Accepted: 21.12.1995