M. Drobne, U. Klančnik, A. Stergar, S. Novak, B. Košec
Valji d.o.o., Železarska cesta 3, 3220 Štore, Slovenija / Slovenia

Ultrazvočna preiskava metalurških spojev na kompleksnih ulitkih

Ultrasonic Investigation of Metallurgical Bonding in Complex Castings

Povzetek

Valji za vroče valjanje so v osnovi dvo- ali večplastni ingoti sestavljeni iz obstojnejše zunanje plasti iz legirane železove litine, iz žilavega jedra iz litine s kroglastim grafitom ter v nekaterih primerih še iz t. i. vmesne plasti iz sive litine z lamelarnim grafitom. Kot taki se, zaradi različnih sestavnih zlitin, smatrajo za kompleksne ulitke, saj so lastnosti posameznih zlitin med seboj različne.

Ena temeljnih neporušnih preiskav ulitkov je ultrazvočna metoda, kjer z uporabo ultrazvoka lahko zaznamo livarske napake (poroznost, prisotnost večjih nečistoč), z njim pa lahko zaznamo tudi metalurški spoj med različnimi zlitinami ter ocenimo kvaliteto le-tega.

Pričujoča študija prikazuje kako s pomočjo ultrazvoka lahko poleg znanih livarskih napak zaznamo tudi globino plasti posameznih zlitin ter vpliv mikrostrukturnih sestavin, ki nastopajo na mestih metalurških spojev med zlitinami, na odboj ultrazvočnega signala in interpretacijo le-tega.

Ključne besede: ultrazvok, mikrostruktura, delovni valji

Summary

Cast rolls for hot strip rolling are multilayered castings, composed of a harder, more wear resistant outer layer made of alloyed cast iron, a tough core made of nodular cast iron and in some cases also of an intermediate layer made of grey cast iron. As such, they can be considered as complex castings, since the differences between individual alloys comprising such ingots can be significant.

Ultrasonic inspection is one of the most fundamental nondestructive methods for inspecting casts ingots. It is often used for detection of abnormalities such as porosity or large non-metallic inclusions. In the case of multilayered cast rolls, ultrasound can also be used for detection and quality inspection of metallurgical bonding between respective alloys or layers.

The presented paper is focused on the use of ultrasound for centrifugally casted rolls, not only for the detection of casting abnormalities but also on the detection of layer depth and influence of specific microstructural constituents present at the bond on the reflected ultrasound signal.

Key words: ultrasound, microstructure, rolls, centrifugal casting

1 Uvod

Valjanje je ena najpomembnejših metod za proizvodnjo jeklenih izdelkov in polizdelkov, zato morajo biti valji dovolj vzdržni in odporni na morebitne težave na progi. Kot proizvajalci valjev tako vložimo veliko časa in truda v izboljšanje tehnologije izdelave, da končni izdelek zadosti zahtevnim pogojem na posameznih progah v smislu obrabne obstojnosti kot tudi odpornosti na nastanek in napredovanje razpok [1, 2].

Liti valji za vroče valjanje so običajno dvoslojni [3, 4], pri čemer je lahko delovna plast iz različnih zlitin, odvisno od ogrodja na katerem bo valj obratoval. V votel ulitek centrifugalno ulitega delovnega sloja, ki je po svojih lastnostih trši in bolj obstojen na obrabo, se gravitacijsko ulije duktilno jedro iz sive litine s kroglastim grafitom. Med obema zlitinama se ustvari metalurški spoj z nataljevanjem. Tako nastane kompleksen ulitek sestavljen iz dveh zlitin z različnimi lastnostmi.

Metalurški spoj med obema slojema predstavlja kritično točko, kjer lahko zaradi procesa strjevanja nastanejo napake kot so poroznost, vključki, segregacije in ostale livarske napake. K naštetim napakam na spoju so predvsem nagnjeni kompleksni ulitki z visoko legirano delovno plastjo kot npr. HSS (hitrorezno jeklo), semi HSS (prilagojena različica HSS), bela litina z visokim kromom in orodno jeklo z visokim kromom. V kolikor napake na spoju nastopajo v posameznih, omejenih primerih, le-te ne predstavljajo hujšega tveganja med uporabo valja. V nasprotnem primeru, ko so napake gosto porazdeljene po večji površini, pa lahko privede do postopnega popuščanja spoja in posledično do težav na valjavski progi. Postopek toplotne obdelave lahko še dodatno poslabša stanje, saj zaostale natezne napetosti, ki nastanejo kot posledica faznih transformacij in termičnega

1 Introduction

Rolls are one of the most crucial tools in steel production industry. They must be produced in a way to ensure good mill productivity and demanded quality of the mill's final products. Research and development department in roll producing companies dedicate a lot of time and knowledge to investigate how to provide optimal roll performance for each mill in terms of wear resistance as well as other damage resistance that can cause during the roll exploitation [1, 2].

Several types of cast iron are used for work rolls that operate in a hot rolling process. Work rolls which work in hot strip mills are normally double layered [3, 4]. Surface layer is hard and wear resistant and it is cast by using special centrifugal casting machine, while for the ductile core a gravity casting procedure is used. Between those two layers a metallurgical bond is established.

Metallurgical bond between layers is a critical area, where due to the casting procedure porosity, inclusions, segregation and other casting defects could be located. High alloyed work layered roll grades such as HSS (High Speed Steel), semi HSS, High Chromium Iron and High Chromium Steel are prone to fusion zone defects. Isolated defects of this type represent only a minor concern, a pervasive contamination of the flaws on the shell/core interface proportionally weakens the bond line. Further complications of the bonding area are induced by the heat treatment of the roll. Tension residual stresses in this region as a result of the heat treatment with the combination of the incomplete fusion or weak microstructural formations could additionally reduce the endurance of the roll.

To detect all the anomalies, ultrasonic inspection is a suitable method. The raztezanja-krčenja, lahko prispevajo k popuščanju spoja.

Opisane napake lahko dokaj uspešno zaznamo z ultrazvočno preiskavo. Slab spoj med plastmi, ki je lahko posledica različnih dejavnikov, lahko zaradi vpliva visokih termo-mehanskih obremenitev privede do katastrofalnega loma na valjavski progi: luščenje delovne plasti ali celo popolni zlom po preseku.

Tako proizvajalci kot tudi uporabniki valjev se vedno bolj poslužujejo različnih neporušnih metod preiskav, da bi s tem zajezili število incidentov na progi, ki so povezani s kakovostjo valjev. Poleg ročnih prenosnih ultrazvočnih naprav se uporabljajo tudi avtomatizirani sistemi ultrazvočne meritve, ki so običajno nameščeni na brusilnih strojih. Avtomatizirani ultrazvočni sistemi omogočajo jasno zaznavanje lokacije, globine in velikosti napak na spoju valja.

2 Eksperimentalni del

Valji predstavljeni v tem delu so uliti iz treh različnih zlitin, ki v stiku tvorijo metalurški spoj oz. prehod med delovno plastjo in jedrom. Zunanja, centrifugalno lita delovna plast sestoji iz bele litine z visokim kromom. Vmesna plast, ki je prav tako centrifugalno lita, je siva litina z lamelarnim grafitom, jedro pa je gravitacijsko lita perlitna siva litina s kroglićastim grafitom. Kemijske sestave posameznih plasti so predstavljene v Tabeli 1.

Mikrostruktura bele litine z visokim kromom (označena kot HCr) sestoji iz 20 – 30 % evtektskih karbidov tipa M_7C_3 (M = Cr, Fe) in matrice iz popuščenega martenzita z nizkim deležem zaostalega avstenita (< 5 %). S prilagojenim postopkom toplotne obdelave dosežemo izločanje sekundarnih karbidov tipa $M_{23}C_6$ bogatih na

presence of weak bonding due to different reasons, could lead to a catastrophic failure of the roll during the exploitation. With the presence of the huge cycling thermo-mechanical loading on the roll during the hot strip rolling and in combination with the weak bonding, rolls can spall or break through the whole section.

Roll producers and on the other hand also roll users are nowadays increasingly using advanced nondestructive testing procedures in their roll shops in order to prevent roll related incidents on the rolling mills. Beside using the hand portable ultrasonic devices, also automated ultrasonic systems are used, normally installed on grinding machines. Scanning the roll with the on-line system could give clear results of the anomalies' location, depth and size.

2 Experiments

Rolls presented in this study are cast out of three different materials where a metallurgical bond is established between them. Outer centrifugally cast shell is made of High Chromium white cast Iron, intermediate layer, still cast on the centrifugal casting machine is made of lamellar graphite cast iron and for the statically cast core a pearlite nodular graphite cast iron is used. Its chemical composition is presented in Table 1.

Microstructure of the High Chromium Iron is composed of 25 – 30 % eutectic carbides M_7C_3 (M = Cr, Fe) and the rest is tempered martensite with the low value of the retained austenite (< 5 %). With the use of the special heat treatment process a participation of secondary carbides based on Cr type $M_{23}C_6$ could be detected inside the matrix. This kind of microstructure enables us very good wear properties and

Tabela 1. Kemijska sestava treh različnih plasti

Table 1. Chemical composition of three different layers

Plast / Layer	Element mas. % / wt. %					
	C	Si	Cr	Ni	Mo	Mg
HCr	2.5 – 3.0	0.5 – 1.0	16.0 – 18.0	1.0 – 1.5	1.0 – 1.5	/
Vmesna / Intermediate	2.8 – 3.4	2.0 – 2.5	< 0.5	0.5 – 1.5	< 0.15	/
Jedro / Core	2.8 – 3.1	2.0 – 2.75	< 0.15	0.1 – 1.0	< 0,15	0.04 – 0.06

Cr, ki se izločajo znotraj matrice. Takšna mikrostruktura je ugodna s stališča obrabne obstojnosti in odpornosti na nastanek termičnih razpok po površini valja.

Področje spoja je bilo pregledano z ročnim ultrazvočnim aparatom Krautkramer USM-32 z uporabo 1 MHz mono-kristalne sonde tipa K, Slika 1a.

Globina prehoda med plastmi se je določila z zaznavo povišanega odboja. Po opravljenem ročnem pregledu je bil valj pregledan tudi z avtomatiziranim sistemom za ultrazvočno preverjanje z 5 MHz mono-kristalno sondo, Slika 1b.

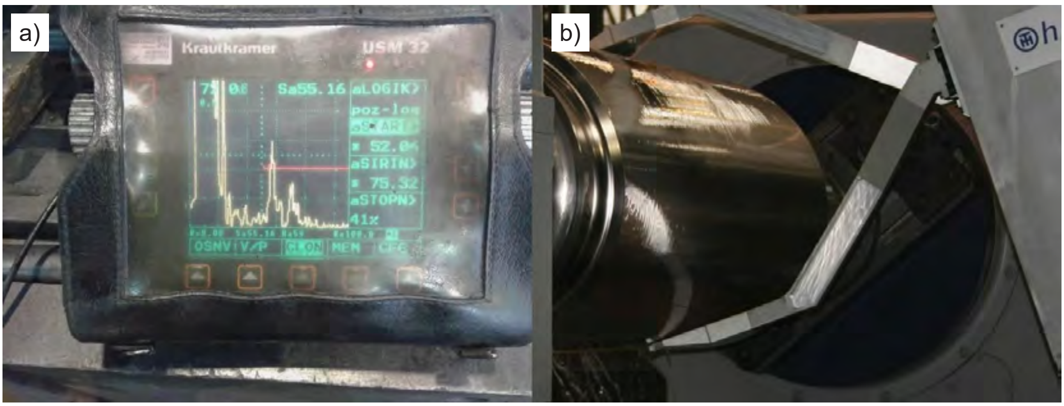
Po ultrazvočnem pregledu so bili na mestih z dobrim spojem in mestih z zaznano morebitno napako odvzeti vzorci v obliki izstruženih segmentov. Vzorci za

good resistance to fire cracking on the surface.

A bonding area was first investigated with the manual portable ultrasonic device Krautkramer USM-32 where 1 MHz mono-crystal probe type K is used, Figure 1a.

By recording the echo from the shell/intermediate/core layer, a depth of the working layer could be determined. Based on this data, the roll was put on the grinder Herkules where an automated ultrasonic test with the mono-crystal 5 MHz probe was performed, Figure 1b.

After the ultrasonic inspection, samples were taken from the ring in the area of a flawless and defected zone. All specimens were cut out of the roll ring segment by using the abrasive water blast technology,



Slika 1. a) Ročni ultrazvočni aparat; b) avtomatizirana ultrazvočna naprava Herkules

Figure 1. a) Manual portable ultrasonic device; b) automated ultrasonic device Herkules

metalografsko preiskavo so bili pripravljeni iz teh segmentov s postopkom vodnega razreza, s čimer smo se izognili nastanku morebitnih toplotno vplivanih con.

Na tako pripravljenih vzorcih je bila opravljena metalografska analiza celotne globine delovne plasti valja z območjem spoja. Vzorci so bili pripravljeni s standardnim postopkom brušenja in poliranja ter jedkani z 2 % Nitalom za analizo mikrostrukture. Za opazovanje mikrostrukture smo uporabili Olympus mikroskop, model BX51M; posnetki so bili zajeti z Olympus SC50 kamero.

Vzorci za natezno preizkušanje so bili pripravljeni na različnih mestih za določanje morebitnih slabših mehanskih lastnosti. Pripravljeni so bili iz jedra kot tudi z območja spoja.

3 Rezultati

Na robovih trupa valja so bili zaznani večkratni odboji na območju prehoda plasti. Sliki 2a in 2b kažeta rezultate preiskave z ročnim ultrazvočnim aparatom.

Prvi odboj z ročnim ultrazvočnim aparatom je bil zaznan na globini 56,19 mm, drugi odboj pa na globini 65,26 mm. Meritev s kljunastim merilom je potrdila ultrazvočno zaznane globine plasti. Prvi prehod (plašč / vmesna plast) je bil izmerjen pri 56,31 mm, Sliki 2c in 2d, drugi prehod (vmesna plast / jedro) pa pri 65,77 mm, Sliki 2e in 2f.

Jedkan metalografski vzorec plasti je razkril podobne rezultate globin/debelin plasti. Meritev trdot po Rockwellu je dodatno potrdila že na pogled opazen prehod, Slika 3.

Vizualna analiza plasti kaže, da pojav večkratnih odbojev ne pomeni nujno napake v področju spoja. Za natančnejše razumevanje, zakaj je en odboj višji od drugega ter za potrditev, da na prehodu

in order to prevent the formation of heat-affected zones due to friction upon cutting.

Metallographic analysis was than performed on these samples throughout the entire working layer material. Specimens were prepared with a standard metallographic procedure of grinding and polishing. A 2 % Nital was used to etch the samples in order to reveal the microstructure. Samples were finally inspected by using an Olympus BX51M optical microscope, equipped with an Olympus DP-12 camera.

To be sure where weak mechanical properties are presented, different tensile tests specimen were made. They were taken from the core material and through all three fused layers.

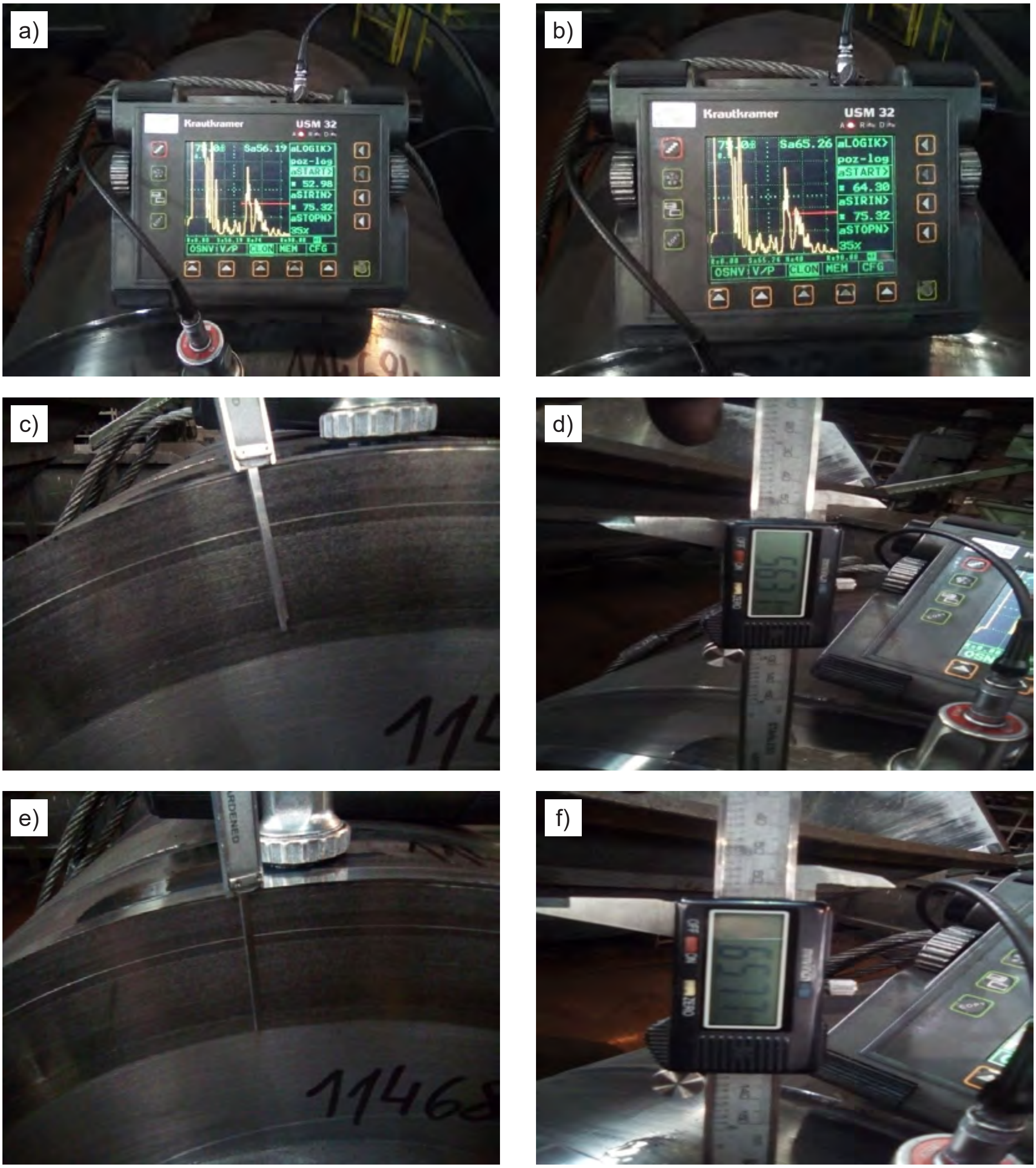
3 Results

Multiple echoes from the bonding area were visible almost through the entire roll body. Figure 2a and 2b presents the results of the hand portable ultrasonic investigation.

It is visible that the first echo is detected at the depth of 56.19 mm, while the second one is at the 65.26 mm depth. Same results were obtained when we measured the value of the depths with the caliper. First interface (shell / intermediate) was visible at the 56.31 mm, Figure 2c and 2d and the second interface (intermediate / core) on 65.77 mm, Figure 2e and 2f.

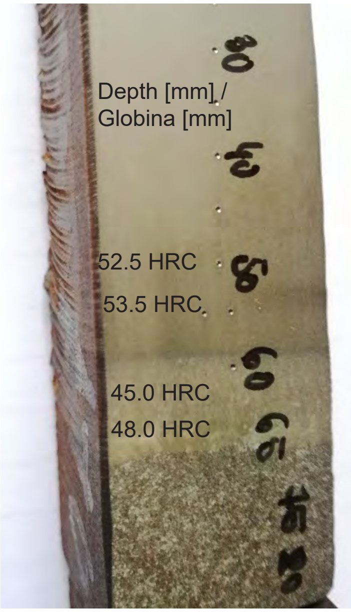
Similar values were obtained when we analyzed the etched sample taken from the roll ring. Visual interfaces were confirmed with the hardness measurement in Rockwell, see Figure 3.

Based on the results it is obvious that the multiple echo phenomena itself does not actually represent a flaw in the bonding area. To understand why one echo is bigger than another one and to prove that there are no anomalies on the bonding



Slika 2. Določanje globine plasti z ročnim ultrazvočnim aparatom: a) detekcija in intenziteta prvega odboja; b) detekcija in intenziteta drugega odboja; c) meritev prvega prehoda (plašč / vmesna plast); d) globina prvega prehoda (plašč / vmesna plast); e) meritev drugega prehoda (vmesna plast / jedro); f) globina drugega prehoda (vmesna plast / jedro)

Figure 2. Manual depth investigation: a) detection of the first echo and its intensity; b) detection of the second echo and its intensity; c) measuring the first interface (shell / intermediate); d) depth value of the first interface (shell / intermediate); e) measuring the second interface (intermediate / core); f) depth value of the second interface (intermediate / core)

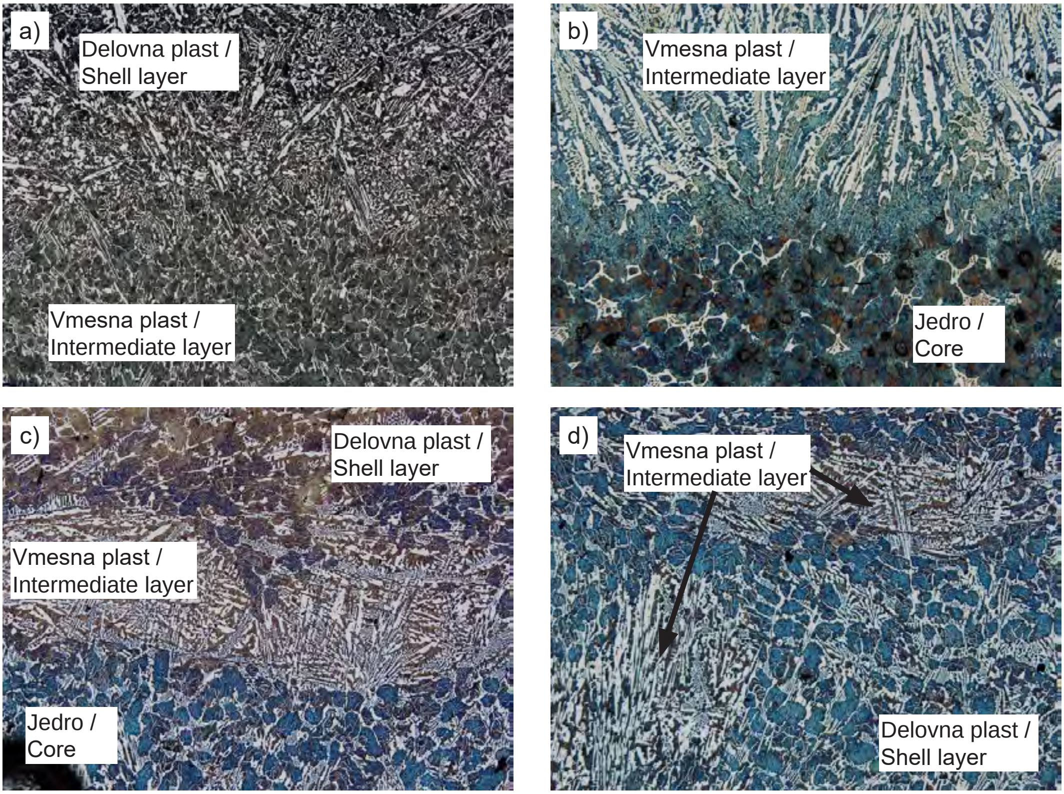


Slika 3. Metalografski vzorec delovne plasti valja z dvema že na pogled opaznima prehodoma. Na prehodu v vmesni plasti je izmerjen znaten padec trdote

Figure 3. Depth of the working layer with two visual interfaces. Hardness drops in intermediate layer

Slika 4. Mikrostruktura na območjih prehoda: a) prvo območje: delovna plast / vmesna plast; b) drugo območje: vmesna plast / jedro; c) obe območji prehoda; d) mešanje plasti - možen vzrok za pojav treh odbojev

Figure 4: Difference in microstructure in the interfaces zones: a) Shell / intermediate; b) intermediate / core; c) both zones; d) possible cause for three echoes observation

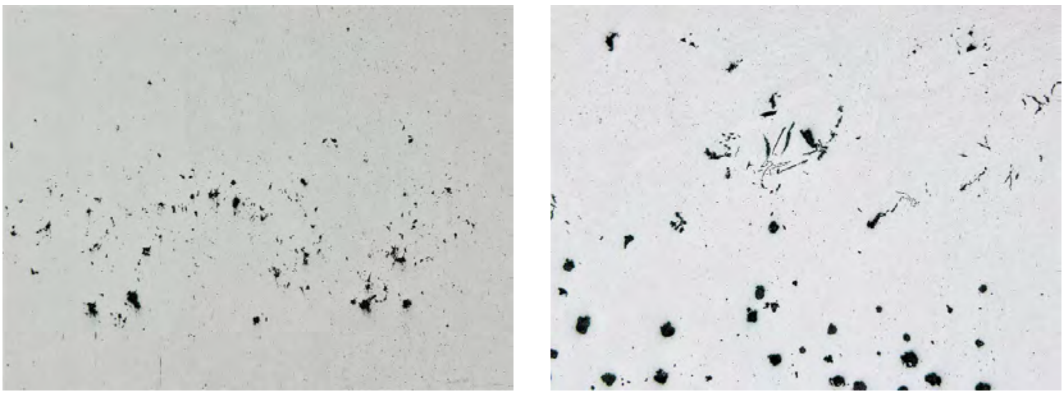


ne prihaja do napak, je bila izvedena podrobnejša analiza mikrostrukture. Mikrostruktura prvega prehoda je prikazana na Sliki 4a. Prehodno območje na prvem spoju je zelo enakomerno za razliko od drugega prehoda med vmesno plastjo in jedrom. Na tem mestu groba mikrostruktura z večjimi bloki cementita preide v perlitno matrico z grafitom in posameznimi otoki ledeburita, Sliki 4b in 4c. Opisani ostri prehodi bi lahko bili razlog zakaj na določenih mestih zaznamo višje ultrazvočne odboje; hitrost širjenja zvoka med močno karbidno mikrostrukturo in perlitno matrico z grafitom je različna.

V redkih primerih je moč zaznati tudi tretji odboj. Slika 4d kaže del vmesne plasti, ki se je ujela v delovno plast. Tako mešanje plasti, do katerega lahko pride na različnih globinah prehoda, lahko privede do pojava tretjega ultrazvočnega odboja. Posledica omenjenega pojava je tudi neenakomerna porazdelitev trdote preko prehoda. Prav tako lahko na takih mestih pride do nastanka razpok, ki so posledica visokih kontaktnih napetosti po Hertzu med delovnim in podpornim valjem, ko se valj med obratovanjem približuje končnemu premeru.

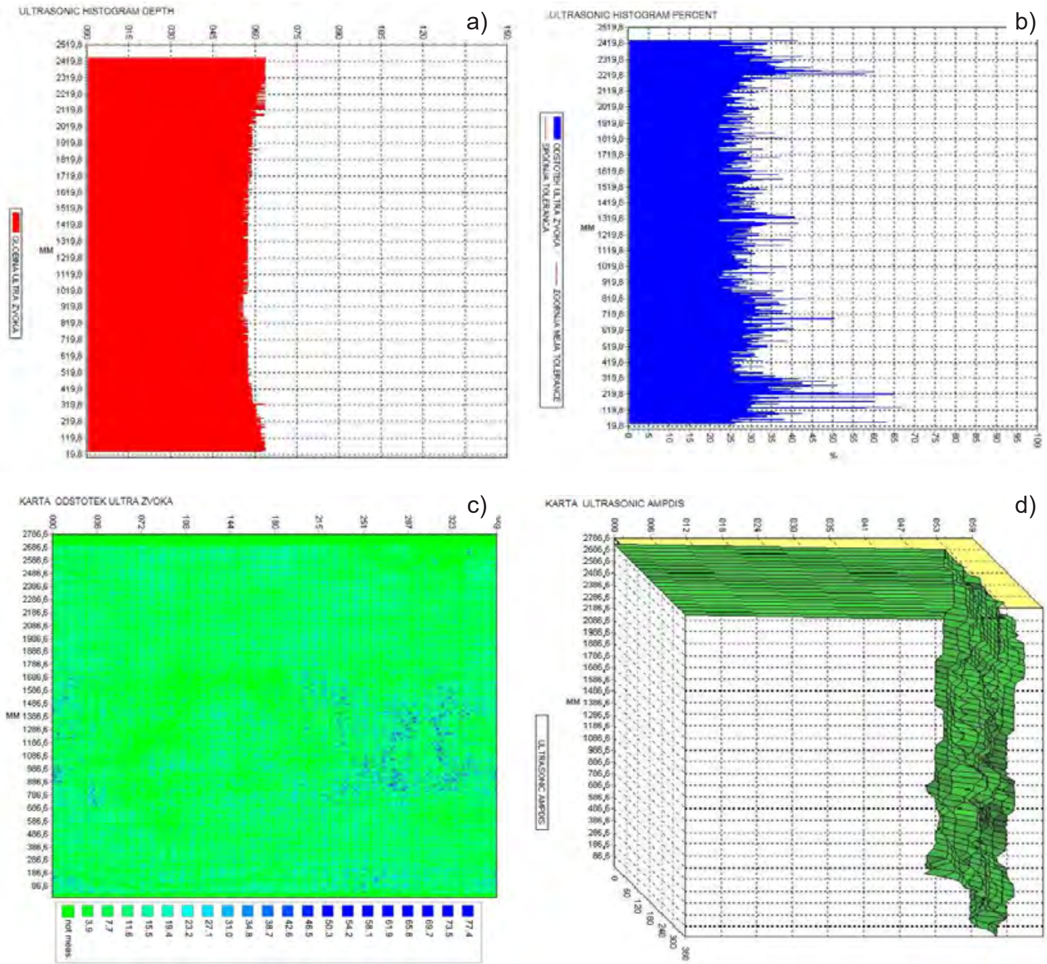
zone, a microstructure analysis was made. Microstructure of the first interface between the shell and intermediate material is presented on the Figure 4a. It can be observed that that the transition zone is quite smooth, and it is totally different as is in the case of second interface zone between intermediate layer and the core. In Figure 4b and 4c, it is observed that within 1 mm of the depth a coarse huge ladder shape carbide area is transformed into the pearlite microstructure with the cementite and graphite phase. These rough transitions could be the reason why in some instances a high echo is detected. Carbide nets have different sound velocity properties as the matrix and graphite.

In some rare cases also a third echo could be detected. A layer can be trapped around another one at different depths, what could lead to a third echo participation. This phenomenon is clearly visible in Figure 4d. Hardness distribution inside the transition section is consequently not equal and can cause a crack initiation problem when a roll is near scrap diameter due to the high Hertzian contact fatigue stresses between work and back up roll.



Slika 5. Mikropore v vmesni plasti

Figure 5. Micropores in the intermediate layer



Slika 6. Izpisi ultrazvočne preiskave opravljene z avtomatiziranim sistemom Herkules: a) globina plasti; b) jakost odbojev; c) ploskovna preslikava odbojev; d) tridimenzionalen prikaz globine plasti in magnitude odboja

Figure 6. Reports from automated on-line ultrasonic system Herkules: a) depth; b) Z-chart; c) C – scan; d) flat pattern view of depth and echo

Na poliranih metalografskih vzorcih se je razkrila mikroporoznost na obeh prehodnih območjih, Slika 5. Z ultrazvočno preiskavo ni mogoče nedvoumno potrditi prisotnost tako majhnih por, saj je širina ultrazvočnega snopa na tej globini preširoka, da bi jasno zaznala posamezne mikro-napake prikazanih velikosti.

Polished samples reveal micropores in both interface areas, Figure 5. With the ultrasonic method, a detection of presented small defects cannot be confirmed. We assume that the ultrasonic beam is too wide at these depths, to be able to clearly detect micro porosity.

Izpisi iz avtomatiziranega sistema ultrazvočne analize so prikazani na Sliki 6. Slika 6a potrjuje prisotnost dvojnih odbojev na robu trupa, medtem ko je na sredini trupa zaznan samo en odboj. Sklepamo lahko, da na mestih z enim odbojem, zaznamo zgolj eno prehodno območje. Na mestu z enim odbojem je jedro v celoti natalilo vmesno plast, medtem ko je bila na robovih trupa debelina vmesne plasti rahlo debelejša zaradi izrivanja mase navzven kot posledica delovanja centrifugalne sile. Slika 6b prikazuje jakost odbojev od prehoda plasti. Prekomerno povišani odboji (preko 100 % skale) niso bili zaznani, kar potrjuje rezultate preiskave z ročnim ultrazvočnim aparatom. Na mestih, kjer so zaznani nekoliko povišani odboji, smo potrdili prisotnost blokastih karbidov cementita na prehodu med vmesno plastjo in jedrom. Sliki 6c in 6d prikazujeta drugačen način izpisa preiskave. Na Sliki 6c je prikazana ploskovna preslikava povišanih odbojev, ki se uporablja za natančno določanje lege morebitnih napak v plasti valja.

Reports from automated ultrasonic system are presented in Figure 6. From Figure 6a it is visible that double echoes are presented on the edges of the roll barrel, while in the middle part only one echo is detected. We can conclude that in case of one echo, only one interface zone could be noticed. This could explain that the intermediate layer was fully fused with the core during the static casting and that the centrifugal force moves the intermediate layer to the position of the end cores of the roll shell. Figure 6b represents the Z-chart of the echoes. No high echoes from the interface zone are detected, what was already confirmed with the manual ultrasonic device. Where higher echo is detected, a layer of ladder shape carbides in the area of intermediate / core interface was observed. Figures 4c and 4d represent another possibility how to print the report. Figure 4c is a C-scan image and it is very useful to get the exact location of the possible anomaly presented inside the roll.

Tabela 2. Natezna trdnost na mestu spoja in jedra

Table 2. Tensile strength of the intermediate and core layer

Plast / Layer	Natezna trdnost, MPa / Tensile strength, MPa
Spoj / Intermediate	405
Jedro / Core	486

Izmerili smo natezni trdnosti na mestu spoja in jedra, da bi preverili razliko med obema območjema. Rezultati so zbrani v Tabeli 2. Natezna trdnost prehoda plasti je nekoliko nižja od natezne trdnosti jedra. Ker je razlika med obema nateznima trdnostnima relativno majhna, lahko sklepamo, da je spoj dober.

A tensile test from the bonding area and the core was performed in order to see the difference in the tensile strengths of the material. Results are presented in Table 2. The results show that the tensile strength is a little bit lower in comparison to the core value. Based on the results where small differences between both values are measured, we can conclude that the bonding area is good.

4 Zaključki

Predstavljena študija predstavlja ultrazvočne preiskave metalurških spojev. Zaradi postopka centrifugalnega ulivanja lahko zaznamo več odbojev na mestu spoja. Ta pojav je posledica dveh zaznanih prehodnih območij. Prvi odboj se sklada s prehodom med delovnim slojem in vmesno plastjo, drugi odboj pa prehod med vmesno plastjo in jedrom. Nekoliko povišane odboje na mestu spoja povezujemo s pojavom blokastih karbidov cementita, ki se zgoščeno pojavijo na mestu prehoda plasti. V nekaterih primerih lahko zaznamo tudi trojne odboje. Ti so posledica mešanja plasti, ko se vmesna plast ujame v delovno plast. Če na teh mestih pride do povišanih kontaktnih napetosti po Hertzu, lahko na teh mestih nastanejo razpoke zaradi občutnih razlik med trdotami in strukturo posameznih plasti. Slednje lahko privede do luščenja delovne plasti.

Avtomatiziran sistem ultrazvočne analize potrjuje izsledke opravljene z ročnim ultrazvočnim aparatom. S pomočjo grafičnih tridimenzionalnih prikazov odboja lahko natančno določimo lokacijo morebitnih napak na prehodu plasti za potrebe nadaljnjih preiskav.

Mikrostrukturna analiza spoja je potrdila prisotnost mikroporoznosti. V kolikor je območje mikroporoznosti majhno, se le-ta ne more nedvoumno potrditi z ultrazvočno preiskavo zaradi širine ultrazvočnega snopa na tej globini. V nasprotnem primeru, ko je območje poroznosti širše od širine snopa, ne zaznamo več odboja od t.i. zadnje stene, kar nakazuje na nesprijetost plasti.

Natezni trdnosti območja spoja in jedra sta si zelo podobni, na podlagi česar lahko sklepamo na dobro kvaliteto spoja.

4 Conclusion

Ultrasonic investigation of the metallurgical bonds is presented in this study. Due to the complex centrifugal casting procedure a multiple echo from the bonding area could be seen. This phenomenon could be explained with the two different interface regions. The first echo represents the interface between shell and intermediate layer while the second one is detected on the place where interface between intermediate layer and the core is located. Higher echoes in the mentioned area relate to the coarse ladder shape carbides segregated there. In some cases, a triple echo could be seen. This is related to the entrapment of the intermediate layer inside the shell material. If the Hertzian contact stresses are high near this area, a small crack could initiate due to the different hardness and structure of the material itself. This can then lead into the full delamination of the roll.

The results of the automated ultrasonic system confirm the manual report. With the advanced graphic presentation flaws could be easily located for further investigation.

Microstructure of the bonding areas reveals a micro porosity. In case of a small micro porosity region, a clear detection of it cannot be performed due to the wide ultrasonic beam. If the area is larger no echo from the roll backwall could be detected which means that the bonding there is no longer presented.

Mechanical properties of the core and intermediate layer have quite similar value of the tensile strength which prove good bonding.

Literatura / Reference

M. Drobne, N. Gubeljak and S. Glodež, Experimental determination of fatigue parameters of high chromium steel under different loading and temperature conditions, Technical Gazette (2014), p.853

M. Drobne, T. Vuherer, I. Samardžič and S. Glodež, Fatigue crack growth and fracture mechanics analysis of a working roll surface layer material, Metallurgy (2014), p.481

K.H. Schröder, Frequently Asked Questions about Hot Strip Mill Work Roll Surface,WMSP, 2004, New Orleans

U. Klančnik, J. Habjan, M. Drobne, P. Mrvar, J. Medved, Characterization of a modified indefinite chill cast iron working layer in rolls, 55th international foundry conference Portorož (2015)