M. Slováček, J. Kubíček, V. Káňa
Brno University of technology (CZ)

Popravila ulitkov z varjenjem

Casting Repairs by Welding

Povzetek

V večini primerov je treba sestavne dele, izdelane z litjem, po proizvodnji popraviti z varjenjem. To velja predvsem za velike ulitke iz jekla. Sicer se z varjenjem popravljajo tudi litoželezni ulitki, vendar po naših izkušnjah napake nastajajo predvsem med delom omenjenih sestavnih delov. So pa popravila ulitkov iz litega železa zaradi njihove krhkosti zelo zapletena. V članku so predstavljeni možni načini popravil z varjenjem in njihova priprava. Na primer, za ulitke iz litega železa obstajajo tri vrste tehnologij za popravila z varjenjem, in sicer s predgrevanjem do vroče, srednje in nizke temperature, kar pomeni, da se razlikujejo temperatura predgretja, način varjenja in material polnila. Tehnologijo varjenja za popravilo je treba izbrati ne le glede na zahteve za popravilo razpok, temveč tudi glede na zahtevano kakovost materiala na območju popravila, ki bo ustrezal delovnim razmeram, kot so dinamični učinek, utrujenost zaradi obremenitev, obraba ali korozija. V večini primerov so pri ulitkih iz jekla po popravilu z varjenjem sestavni deli tudi toplotno obdelani. Trenutna priprava popravil ulitkov s tehnologijo varjenja lahko vključuje sodobne metode, kot so numerična simulacija varjenja, preskusi prototipov in posebno termo-mehansko preverjanje na napravi GLEEBLE. Vsi navedeni sodobni postopki bodo predstavljeni na konkretnih praktičnih primerih tako ulitkov iz jekla kot litega železa. Prikazano bo popravilo ulitka iz jekla kot pokrova turbine iz materiala P91 in optimizacija na podlagi numerične simulacije, kar pomeni, da bo prikazana lokalna struktura materiala, trdota in preostale obremenitve po popravilu. V tem primeru je bila z uporabo stroja GLEEBLE pripravljena lokalna struktura materiala iz toplotno vplivane cone in opravljeni so bili natezni preizkusi, kar pomeni, da so bile ugotovljene lokalne lastnosti materiala. Nazadnje bo prikazano popravilo razpoke v ulitku iz litega železa, ki je del stiskalnega stroja, s polnilom na osnovi niklja, kar pomeni, da je bil opravljen celoten preskus varjenja prototipa ter destruktivno in mehansko preizkušanje, ki je potrdilo zahtevane mehanske parametre.

Ključne besede: jekleni ulitek, litoželezni ulitek, popravilo z varjenjem, numerična simulacija varjenja SYSWELD, preizkusi prototipov, termo-mehansko-fizikalno preizkušanje, GLEEBLE, GX23CrMoV12-1, GJS 700-2

Abstract

In most cases, the components produced by casting have to be repaired using welding technology after production. This mainly concerns large steel castings. However, even cast-iron castings are repaired by welding, but from our experience, defects mainly arise during the operation of the mentioned components. However, repairs of cast iron castings are very complicated due to their brittle behaviour. The article will present possible methods of welding repairs and their preparation. For example, for cast iron castings, there are three types of welding repair technologies as by using hot temperature, middle temperature, and cold. This means the differences are preheating temperature, welding method, and different filler material. The repair welding technology has to be chosen not only according to the requirement for crack repair but also to meet the required material quality in the repair area, which will fit to working conditions as dynamic effects, fatigue loading, abrasion, or corrosion. In most cases for steel casting after welding repair, the steel casting components will also be heat treated. The current preparation of casting repairs by welding technology can include modern methods such as welding numerical simulation, prototype tests, and special thermo-mechanical verification on the GLEEBLE device. All of the above modern procedures will be presented in specific practical cases, for both steel and cast-iron castings. It will be shown one repair of steel casting as turbine cover made from material P91 and optimisation based on numerical simulation, that means it will be shown local material structure, hardness, and residual stresses after repair. Also, in this case, by using the GLEEBLE machine, the local material structure from heat-affected zone has been prepared, and the tensile tests have been done, which means there has been identified local material properties. The last repair of the crack in the cast iron casting, it is part of a press machine by nickel-based filler material will be demonstrated which means the complete prototype welding test and destructive and mechanical testing have been done and have confirmed receiving the required mechanical parameters.

Keywords: steel casting, cast iron casting, welding repair, SYSWELD welding numerical simulation, prototype tests, thermo-mechanical-physical testing, GLEEBLE, GX23CrMoV12-1, GJS 700-2

1 Uvod

Na splošno je vsako popravilo zelo zapleteno, saj ga je v večini primerov treba opraviti tam, kjer popravljena komponenta deluje. Običajno je tudi prostor za učinkovito delo omejen in tako v delavnici ali proizvodnji dela ni mogoče udobno opraviti. V teh pogojih v večini primerov za popravilo ni mogoče uporabiti najboljše ali optimalne tehnologije varjenja, zato je treba uporabiti alternativno tehnologijo. Seveda je treba vsako popravilo pred dokončnim popravilom preizkusiti na pravih delih ter z nedestruktivnim in destruktivnim preizkušanjem potrditi, ali je popravilo izvedeno brez razpok in napak ter ima zahtevane mehanske lastnosti.

Vsak industrijski sestavni del je bil zasnovan z določenimi cilji glede na delovne in okoljske pogoje. To pomeni, da obstajajo zahteve za odpornost v naslednjih stanjih:

- statično stanje,
- dinamično stanje,
- utrujenost (visoka, nizka, vibracijska,

1 Introduction

Generally, each repair is very complicated because, in most cases, it has to be done on a workshop where the repaired component is working. Usually, there is also limited space for effective working, and it cannot be used comfortably, conditions of a manufacturing or production workshop. Based on the stated condition, again in most cases it is not possible to use the best or optimal repair welding technology, and there has to be done some alternative one. Of course, each repair should be tested before doing the final repair on real parts and confirmed by non-destructive testing if the repair is done without cracks and mistakes and has got required mechanical properties.

Each industrial component has been designed with some objectives according to working and environmental conditions. That means there are requirements for resistance to the following states:

- Static condition

toplotna),
- lom zaradi krhkosti,
- lezenje,
- korozija,
- abrazija,
- erozija, itd.

Seveda morajo imeti sestavni deli po popravilu enake ali boljše lastnosti materiala kot osnovni material in se morajo ujemati z zahtevanimi lastnostmi za življenjsko dobo popravljenih sestavnih delov. Pri popravilih predvsem ulitkov iz jekla in litega železa niso mogoča popravila z varjenjem z uporabo dodajnega materiala, ki bi bil iz enakega materiala kot osnovni material, in sicer zaradi možnosti varjenja (razpoke) in tudi dejstva, da dodajni material z enako sestavo in mehanskimi lastnostmi ne obstaja. Seveda se včasih popravljeni sestavni deli po varjenju toplotno obdelajo, pri čemer ne gre le za toplotno obdelavo po varjenju za zmanjšanje zaostalih napetosti, temveč tudi za utrjevanje s hitrim hlajenjem in kaljenjem za spreminjanje lokalnih lastnosti materiala. To pomeni, da je glavni cilj varjenja za popravilo dela ulitka iz jekla ali litega železa popravilo brez nesprejemljivih napak in dosega zahtevanih lastnosti materiala.

Eno od zelo učinkovitih orodij za podporo pri pripravi tehnologije popravila je uporaba sodobnih numeričnih simulacij varjenja. V praksi je mogoče najti in preveriti več različic oziroma modifikacij tehnologije reparaturnega varjenja brez dejanskega preizkušanja v delavnici. Z uporabo numerične simulacije varjenja je kot rezultat mogoče pridobiti naslednje informacije in na podlagi teh rezultatov je mogoče modificirati tehnologijo varjenja, da bi dobili najboljšo za popravilo:
- porazdelitev temperature,
- porazdelitev strukture materiala/faz,
- porazdelitev trdote,
- zrnatost,
- porazdelitev preostalih in notranjih

- Dynamic condition
- Fatigue (high, low, vibrating, thermal)
- Brittle fracture
- Creep
- Corrosion
- Abrasion
- Erosion, etc.

Of course, the components after repair should have the same or better material properties as the basic material, which has to match with required properties for life lifetime of the repaired components. In most of repairs, mainly cast components as steel or iron, it is not possible to repair by welding using the same filler material as the base material due to weldability (cracking), and also that fact that there is no existing filler material with the given material composition and mechanical properties. Of course, sometimes the repaired components after the welding process are heat treated, and it is not only post-weld heat treatment to decrease residual stresses, but it can also be hardening as quenching and tempering to change local material properties. That means the main objectives of repair welding of steel or iron casting parts is that the repair is done without any unacceptable faults and achieves the required material properties.

One of the very powerful tools for supporting during preparation of repair technology is the use of modern welding numerical simulations. It is possible to virtually find and verify various variants or modifications of welding repair technology without real testing in a workshop. By using welding numerical simulation, it is possible to receive the following information as results, and based on these results, the repair welding technology can be modified to receive the best one:
- Temperature distribution
- Distribution of material structure/phases
- Hardness distribution
- Grain size

obremenitev,
- razgradnja materiala s kumulativno plastično deformacijo,
- deformacija.

Seveda je treba končno različico tehnologije varjenja za popravilo tudi zares preizkusiti, saj je treba pripraviti še specifikacijo varilnega postopka (WPS; Welding Procedure Specification) in dokumentacijo kvalificiranosti varilnega postopka (WPQR; Welding Procedure Qualification Record).

2 Reparaturno varjenje

Varjenje za popravilo litega dela lahko razdelimo v dve skupini, in sicer na popravilo jeklenih litih komponent in popravilo železnih litih komponent.

Popravilo ulitka iz jekla ni tako zapleteno, ker gre za jeklo in domnevo, da jeklo ne vsebuje visokih ravni ogljika kot na primer lito železo. Z večjo vsebnostjo ogljika je namreč material bolj občutljiv na nastanek razpok pri ohlajanju. Seveda so materiali z večjo vsebnostjo legirnih elementov, kot so Cr, Mo, W, V, občutljivejši tudi na nastavek razpok pri ohlajanju. Po drugi strani pa imamo v zlitinah elemente, ki povzročajo občutljivost na nastanek razpok pri segrevanju, kot so Ni, Nb itd. Obstajajo tudi negativni vplivi kemičnih elementov, kot so S, P in H, ki prav tako vplivajo na nastanek razpok pri segrevanju in ohlajanju. To pomeni, da so lahko glavne težave med varjenjem pri popravilu (Slika 1 in Slika 2):
- razpoke zaradi ohlajanja,
- razpoke zaradi segrevanja,
- nastanek razpok pri toplotni obdelavi,
- nastanek razpok zaradi premajhne duktilnosti materiala,
- ter tipične napake pri varjenju, kot so korenska razpoka, nepopolno zlitje, poroznost, žlindra, podrez, nepravilno prekrivanje itd.

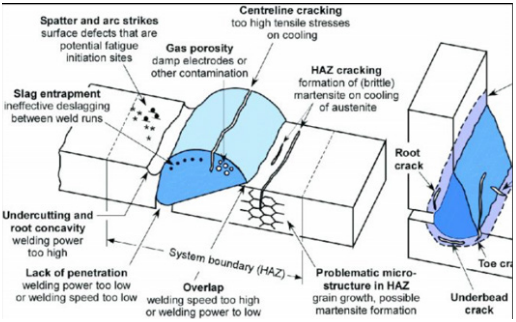
- Residual and internal stressdistribution
- Material degradation by cumulative plastic deformation
- Deformation

Of course, the final repair welding technology variant should be done as real test because it should be also prepared WPS (Welding Procedure Specification) and WPQR (Welding Procedure Qualification Record) documentation.

2 Repair Welding

The repair welding of cast parts can possibly be divided into two groups: the first one is the repair of steel cast components, and the second one is the repair of iron cast components.

The repair of a steel cast part is not so complicated because it is steel, and there is an assumption that steel does not have a high content of carbon, unlike cast iron. But with higher, mainly carbon content, the material is more sensitive to cold cracking. Of course, the material with a higher content of alloying elements as Cr, Mo, W, V, is more sensitive to cold cracking as well. On the other hand, there is existing alloyed elements that causes sensitivity to hot cracking as Ni, Nb, etc. There is also an existing negative influence of chemical elements such as S, P, and H on hot and cold cracking. That means the main problems during repair welding can be (see the Fig. 1 and Fig. 2):
- Cold cracking
- Hot cracking
- Heat treatment cracking
- Cracking due to lack of material ductility
- And typical welding faults as root crack, lack of fusion, porosity, slag, undercut, incorrect overlap, etc.



Slika 1. Razpoke in napake pri varjenju.

Fig. 1. Weld cracks and faults.

Na splošno so na lokalni nastanek razpok po popravilu z varjenjem vplivali naslednji vidiki:

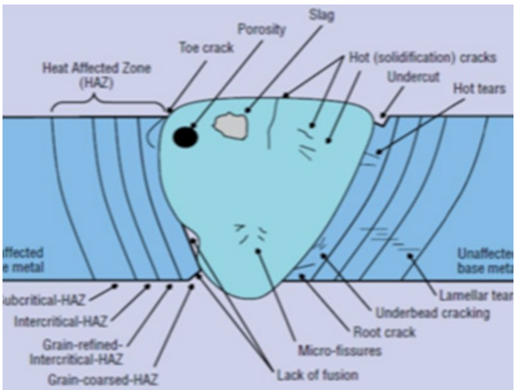
- struktura lokalnega materiala,
- lastnosti lokalnega materiala,
- preostale lokalne obremenitve,
- degradacija lokalnega materiala,
- oblikovanje kemijske sestave lokalnega materiala,
- in tudi napake, ki so jih naredili varilci,
- delovno stanje med življenjsko dobo danih popravljenih sestavnih delov.

Pri popravilih z varjenjem, pri katerih se na zelo majhnem in omejenem mestu uporablja veliko dodajnega materiala, lahko nastanejo tudi razpoke zaradi pomanjkanja lokalne duktilnosti materiala. Vsak varilni sloj povzroči lokalno plastičnost in z uporabo varjenja z več prehodi na nekaterih omejenih mestih, na katera vpliva več temperaturnih ciklov, se lahko lokalna plastičnost v celoti izrabi in lahko nastanejo razpoke. To so tudi tipične razpoke pri popravilu z varjenjem. Seveda vplivajo tudi lokalne zaostale napetosti. Popravilo jeklenega ulitka z varjenjem je mogoče skoraj z vsemi metodami varjenja, vključno z lasersko ali hibridno tehnologijo, odvisno od materiala in zahtevanih mehanskih lastnosti.

Generally, for local creation cracks after the repair welding procedure has been influenced by following aspects:

- Local material structure
- Local material properties
- Local residual stresses
- Local material degradation
- Creation of local material chemical composition
- And also, by the faults that have been made by welders
- Working conditions during the lifetime of the given repaired components

During welding repairs where we are putting a lot of filler materials in very small, limited places where cracks can also be created due to a lack of local material ductility. Each welding deposit causes local plasticity, and using multipass welding in some limited places that are affected by several temperature cycles can be completely utilize local plasticity and cracks can be created. It is also typical of cracks for welding repair. Of course, there is also the influence of local residual stresses. The welding repair of steel cast part can be done by using almost all welding methods, including laser or hybrid technology depending on the given material and required mechanical properties.



Slika 2. Razpoke in napake pri varjenju.

Fig. 2. Weld cracks and faults.

Popravilo ulitka iz jekla ni tako zapleteno, ker gre za jeklo in domnevo, da jeklo ne vsebuje visokih koncentracij ogljika. Jeklene dele je treba popraviti z ustreznimi dodajnimi materiali glede na zahtevane mehanske lastnosti. Seveda je treba v primeru višje vsebnosti ogljika uporabiti predgrevanje, ustrezno temperaturo vmesnega prehoda, ponovno segrevanje, v nekaterih primerih pa tudi toplotno obdelavo po varjenju oziroma popuščanje.

Popravilo ulitka iz litega železa z varjenjem je bolj zapleteno in ga lahko razdelimo na tri tehnološke postopke:

1. **Nizka temperatura.** To je treba narediti z dodajnim materialom na osnovi Ni (Ni je zelo duktilen material in se lahko uporablja za krhko lito železo brez predgretja ali z nizkim predgretjem do 200 °C). Prednost te metode je, da je preprosta, vendar je polnilo na osnovi Ni drago, poleg tega pa je zvar zelo heterogen in ima različne lastnosti materiala.
2. **Srednja temperatura.** To je mogoče doseči s predgrevanjem na približno 300–400 °C, temperaturo vmesnega prehoda in ponovnim segrevanjem z uporabo klasičnega jeklenega dodajnega materiala z večjo duktilnostjo. Gre za standardno tehnologijo varjenja kot na primer popravilo jeklenih ulitkov. Tudi v tem primeru gre za zelo heterogeni zvar z različnimi lastnostmi materiala.
3. **Visoka temperatura.** To je mogoče doseči s približno minimalnim predgrevanjem na 500 °C, temperaturo vmesnega prehoda in ponovnim segrevanjem z uporabo dodajnega materiala iz litega železa (sivih litin). Pomanjkljivost te tehnologije je visoka temperatura predgrevanja, zapleteno varjenje, vendar je po popravilu struktura skoraj homogena.

The repair of steel cast part is not so complicated because it is steel, and there is an assumption that steel does not have a high content of carbon element. The steel parts should be repaired by appropriate filler or filler materials according to receive required mechanical properties. Of course, in case there is a higher carbon equivalent the preheating has to be used, appropriate interpass temperature, reheat, and in some cases, there should be applicate post-weld heat treatment or tempering.

The cast iron part repair by welding is more complicated, and it can be divided into three technological procedures:

1. **Low temperature.** It has to be conducted by using Ni-based filler material (Ni is a very ductile material and can be used for brittle iron without preheating or low preheating up to 200 °C). The advantage of this method is that it is simple, but Ni-based filler material is expensive, and there is a very heterogeneous weld joint with different material properties.
2. **Middle temperature.** It can be conducted by using approximately 300-400 °C preheating, interpass temperature, and reheating by using classical steel filler material with higher ductility. It is standard welding technology as for example, steel cast part repair. Again, there is a very heterogeneous weld joint with different material properties.
3. **High temperature.** It can be done by using approximately a minimal 500 °C preheating, interpass temperature, and reheating by using cast iron filler material. The disadvantage of this technology is high preheating temperature and complicated welding, but after repair, there will be a homogeneous structure.

Na splošno je treba pri varjenju litoželeznih ulitkov za različice srednje in visoke temperature uporabiti metodo varjenja z virom višje moči, saj je potrebno počasno ohlajanje. Za različico z nizko temperaturo je treba uporabiti varjenje z uravnoteženim virom toplote zaradi visoke občutljivosti polnila na osnovi Ni za razpoke, nastale zaradi segrevanja.

Seveda je treba tudi za reparaturno varjenje pripraviti popolno dokumentacijo o varjenju, kar pomeni specifikacijo varilnega postopka (WPS; Welding Procedure Specification) in dokumentacijo kvalificiranosti varilnega postopka (WPQR; Welding Procedure Qualification Record), delo pa morajo opraviti certificirani varilci, ki potrdijo izbrano tehnologijo.

3 Reparaturno varjenje jeklenih ulitkov

Po ulivanju turbinskega ohišja iz materiala GX23CrMoV12-1 (1.4931), odpornega proti koroziji in vročini, ki je podobno materialu P91, je bilo ugotovljenih več razpok [1]. Največja globina razpoke je bila 80 mm na mestu, kjer je debelina stene 300 mm. Najprej je bila vzpostavljena primarna tehnologija popravila in opravljen prvi preizkus prototipa (preizkusno varjenje modela). Na žalost so bile na območju popravila ugotovljene razpoke na globini 10 mm pod površino (Slika 3). V naslednjem koraku je bilo pripravljenih več novih tehnologij varjenja, ki so bile preverjene s sodobno numerično simulacijo varjenja. Optimizirani so bili naslednji parametri:

- uporaba različnih dodajnih materialov (dve vrsti),
- uporaba različnih temperatur predgrevanja,
- uporaba različnih vhodnih moči,
- uporaba različnih toplotnih obdelav.

Generally, for cast iron welding repair for variants of middle and high temperature the welding methods with a higher power source are used due to the fact that slow cooling is needed. For a low-temperature variant, a low-temperature welding method should be used for a balanced heat source, due to the high sensitivity of Ni-based filler material to hot cracking.

Of course, also for welding repair we should prepare complete welding documentation which means WPS (Welding Procedure Specification) and WPQR (Welding Procedure Qualification Record) and use certified welders to confirm the chosen technology.

3 Repair Welding of Steel Cast Part

After casting of turbine casing from corrosion and heat resistance material GX23CrMoV12-1 (1.4931) close to P91 several cracks were found [1]. The maximum depth of the crack was 80 mm in a place where the thickness of the wall is 300 mm. The first primary repair technology was set up, and the first mock-up prototype test was done. Unfortunately, the cracks in an area of 10 mm under the surface in the repair area were identified, see Fig.3. As the next step, several new welding technologies were prepared and verified by modern welding numerical simulation. The following parameters were optimised:

- Use of different filler materials (two types)
- Use of different preheating temperatures
- Use of different input power
- Use of different heat-treatment

The numerical model contains of three types of repairs, see fig.4. In the following figures there are shown material structure and residual stresses for three variants as:

1. Preheating 300 °C, manual metal arc

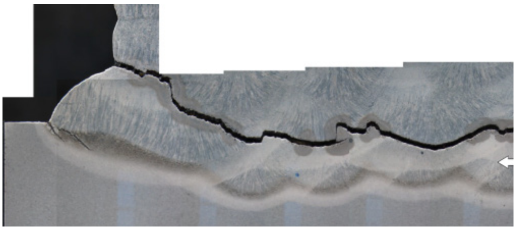
Numerični model vsebuje tri vrste popravil (Slika 4). Na naslednjih slikah so prikazani struktura materiala in preostale napetosti za tri različice:

1. Predgrevanje 300 °C, ročno obločno varjenje kovin itd.
2. Predgrevanje 200 °C, ročno obločno varjenje kovin itd.
3. Predgrevanje 200 °C, ročno obločno varjenje kovin ter različni polnilni materiali itd.

welding, etc.

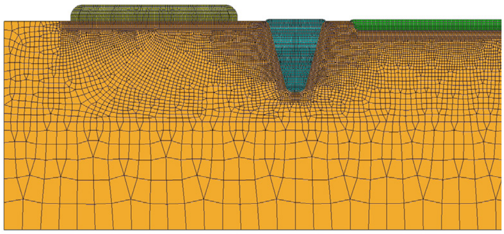
2. Preheating 200 °C, manual metal arc welding, etc.
3. Preheating 200 °C, manual metal arc welding, and different filler materials, etc.

Based on numerical simulation, the best variant is with preheating at 300 °C, technology MMAW, and filler material Chromet 12 MV. There is a structure that is a mixture of bainite and martensite, and it has



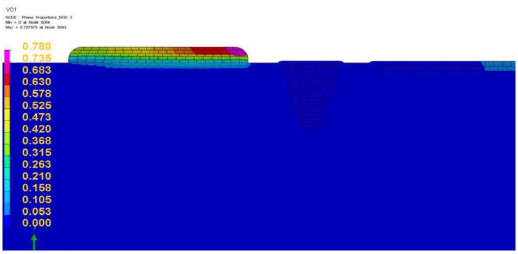
Slika 3. Razpoke v reparaturnih zvarih.

Fig. 3. Weld cracks in repair welds.



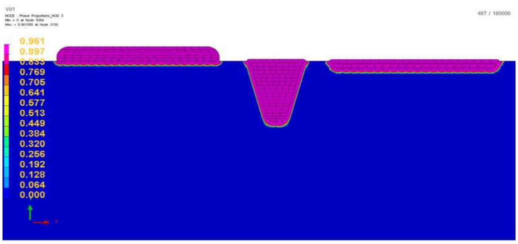
Slika 4. Numerični model.

Fig. 4. Numerical model.



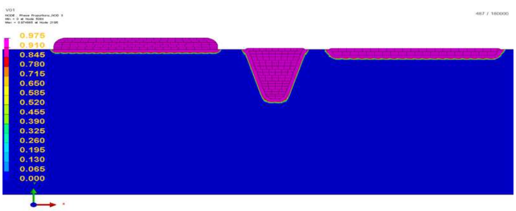
Slika 5. Razporeditev martenzita, različica 1.

Fig. 5. Martensite distribution, variant 1.



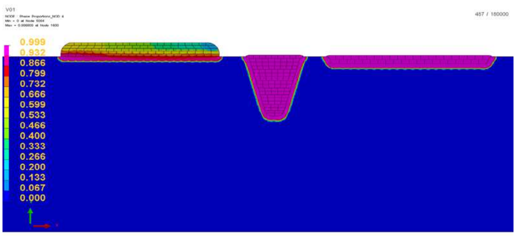
Slika 6. Razporeditev martenzita, različica 2.

Fig. 6. Martensite distribution, variant 2.



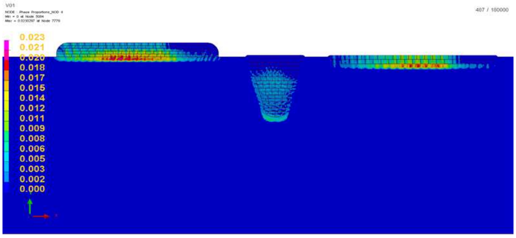
Slika 7. Razporeditev martenzita, različica 3.

Fig. 7. Martensite distribution, variant 3.



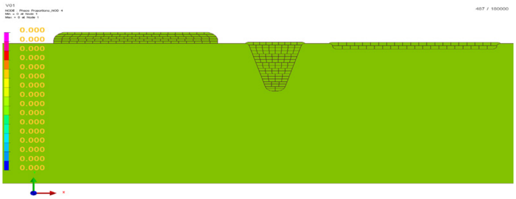
Slika 8. Razporeditev bainita, različica 1.

Fig. 8. Bainite distribution, variant 1.



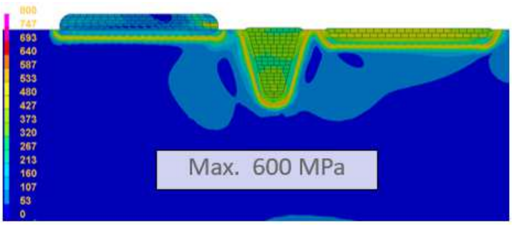
Slika 9. Razporeditev bainita, različica 2.

Fig. 9. Bainite distribution, variant 2.



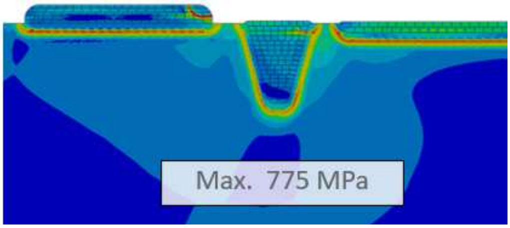
Slika 10. Porazdelitev bainita, različica 2.

Fig. 10. Bainite distribution, variant 2.



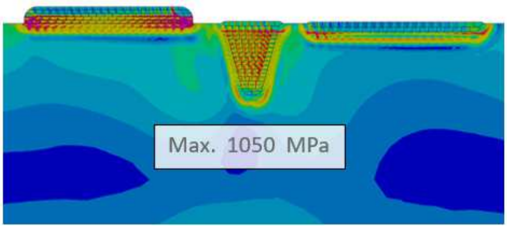
Slika 11. Razporeditev zaostaih napetosti, različica 2.

Fig. 11. Residual stress distribution, variant 1.



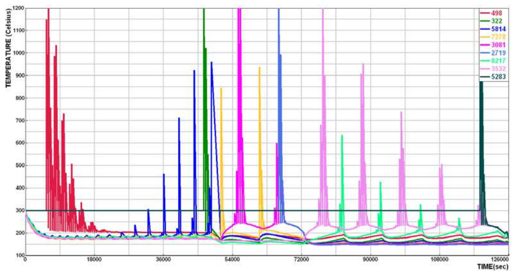
Slika 12. Razporeditev zaostalih napetosti, različica 1.

Fig. 12. Residual stress distribution, variant 2.



Slika 13. Porazdelitev zaostalih napetosti, različica 3.

Fig. 13. Residual stress distribution, variant 3.



Slika 14. Temperaturni cikli.

Fig. 14. Temperature cycles.

Na podlagi numerične simulacije je najboljša različica s predgrevanjem 300 °C, tehnologijo MMAW in dodajnim materialom Chromet 12 MV. V analiziranih različicah je struktura mešanica bainita in martenzita ter najnižja stopnja zaostalih napetosti. Na podlagi izračunanih temperaturnih ciklov z uporabo termo-mehanskega simulatorja GLEEBLE je bilo pripravljenih več vzorcev, na katerih so bili opravljeni natezni

the lowest level of residual stresses among the analysed variants. Additionally, based on calculated temperature cycles using the GLEEBLE thermo-mechanical simulator, several samples were prepared for tensile tests. In Table 1, there are the results of the tested tensile test, which represents the most degraded heat-affected zone.

Based on a combination of welding numerical simulation solution and material

Preglednica 1. Izmerjene vrednosti nateznih preizkusov.

Table 1. Tensile tests measured values.

Temperatura / Temperature [°C]	Meja plastičnosti / Yield stress, Re [MPa]	Največja trdnost / Ultimate strength, Rm [MPa]	Raztezek / Elongation, A80 [%]	Raztezek / Elongation Ag [%]
20	1082	1105	0,22	0,22
20	901	1308	4,39	3,54
180	894	1067	4,55	1,36
180	882	1063	4,71	1,86
210	802	1012	5,02	1,46
210	809	1009	5,02	1,59
250	660	961	6,23	2,81
250	762	939	4,30	1,81

preskusi. V Preglednici 1 so prikazani rezultati izvedenega nateznega preizkusa, ki predstavlja najbolj degradirano toplotno vplivano cono.

Na podlagi kombinacije rešitev numerične simulacije varjenja in preskušanja materiala na stroju GLEEBLE je jasno, da je najboljša različica za popravilo različica 1 in ta različica je bila uspešno uporabljena za dejansko popravilo, seveda s končno naknadno toplotno obdelavo.

Upoštevane so bile tudi tehnologije varjenja za popravilo ohišja turbine za materiale G17CrMoV5-10, G17CrMo5-5, X10CrMoVN9-1, GX23CrMoV12-1 [1]. Tehnologije varjenja za popravila so bile izvedene z uporabo naslednjih dejavnosti: numerična simulacija, prototipno varjenje z destruktivnim in nedestruktivnim preskušanjem, dejansko ter pravo industrijsko popravilo. Na naslednjih slikah so prikazani različni rezultati preskušanja in numerične simulacije. Mehansko preskušanje in numerična simulacija sta bila opravljena na prototipnih zvarih in končnih industrijskih popravilih. Izdelanih je bilo približno 30 tehnoloških različic z različnimi tehnologijami varjenja in materiali. Upoštevane so bile homogene in heterogene tehnologije popravil.

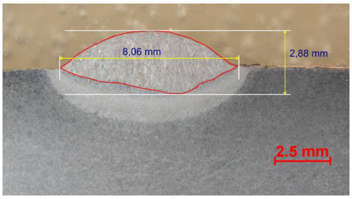
testing on the GLEEBLE machine is clear that the best variant for repair is variant 1, and this variant was successfully used for real repair, of course, with final post-heat treatment.

Additionally, complete repair welding technologies for turbine casting repair for materials such as G17CrMoV5-10, G17CrMo5-5, X10CrMoVN9-1, GX23CrMoV12-1 [1] were also conducted using the following activities such as numerical simulation, prototype welding with destructive and non-destructive testing, and real industrial repair. The following figures show various testing and numerical results. The mechanical testing and numerical simulation were done on prototype welds and final industrial repairs in 30 technology variants with different welding technologies and materials. They were considered as homogeneous and heterogeneous repair technologies.

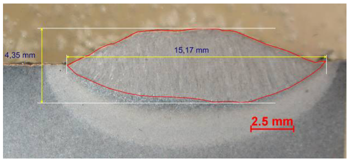
4 Repair welding of cast iron

As was already written the repair of cast iron is very complicated due to the fact that cast iron is a very brittle material and is very sensitive to cold cracking. Three welding repair technologies are existing, see the explanation in chapter 2. Now

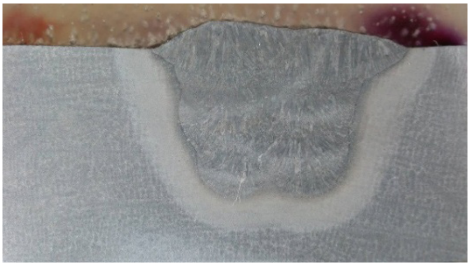
Slika 15. Testiranje reparaturnih zvarov.
Fig. 15. Testing repair welds.



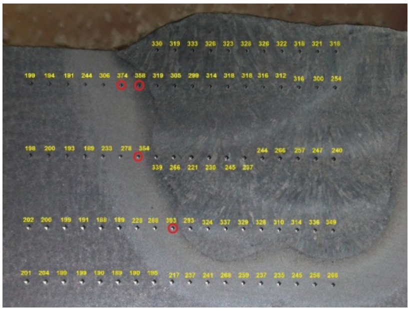
Slika 16. Makro posnetek zvara.
Fig. 16. Macro of weld.



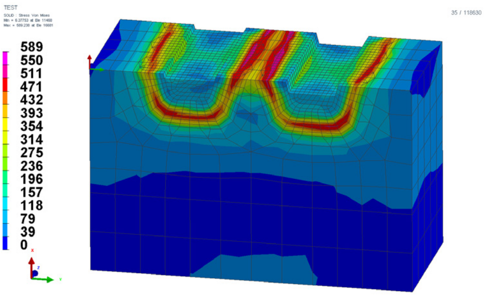
Slika 17. Makro posnetek zvara.
Fig. 17. Macro of weld.



Slika 18. Makro posnetek reparaturnega zvara.
Fig. 18. Macro of weld repair.

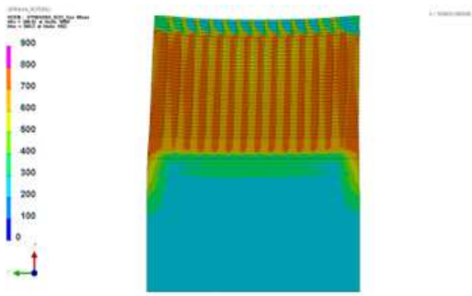


Slika 19. Meritve trdote.
Fig. 19. Hardness measurements.



Slika 20. Zaostale napetosti, predhodno varjenje.

Fig. 20. Residual stresses, protype welding.



Slika 21. Zaostale napetosti, dejansko popravilo z varjenjem.

Fig. 21. Residual stresses, real welding repair.

4 Reparaturno varjenej litoželeznih ulitkov

Kot smo že zapisali, je popravilo litega železa zelo zapleteno, saj je litina zelo krhka in občutljiva na nastanek razpok pri ohlajanju. Obstajajo tri obstoječe tehnologije popravil z varjenjem opisano v poglavju 2. Sedaj so zelo priljubljena popravila litega

it is very modern to do welding repair of cast iron by using Ni-based filler material because there is no need for preheating, but on the other hand the area of repair has very heterogeneous material properties and loses, for example, high surface hardness. That means the welding repair technology should also be chosen based železa z varjenjem z uporabo dodajnega materiala na osnovi Ni, ker ni potrebno predgrevanje, vendar ima po drugi strani območje popravila zelo različne lastnosti materiala in izgublja na primer visoko površinsko trdoto. To pomeni, da je treba tehnologijo reparaturnega varjenja izbrati tudi na podlagi zahtev za končne mehanske lastnosti.

V tezi diplomske naloge [2] je bil raziskan vpliv postopka reparaturnega varjenja na končno kakovost in mehanske lastnosti litine GJS 700-2. Kot postopek CMT so bile uporabljene naslednje metode varjenja: MMAW, TIG in MIG/MAG. Kot dodajni materiali so bili uporabljeni CRONITEX RC 252 C, CRONITEX RC 58, CRONITEX RC 63, Welco 1960, Welco 1790S, Welco A1960, Megafil A760M. Za popravilo so uporabili tudi vmesni sloj in končni površinski sloj, da so dosegli zahtevane lastnosti materiala. Opravljenih je bilo več vrst preskusnih vzorcev:

- Različica 1, dodajni material CRONITEX RC 252C, predgrevanje 250 °C, varjenje TIG
- Različica 2, dodajni material CRONITEX RC 252C in CRONITEX RC 58, predgrevanje 250 °C, varjenje TIG
- Različica 3, dodajni material CRONITEX RC 58, predgrevanje 250 °C, varjenje TIG
- Različica 4, dodajni material Welco 1960 in Welco 1709S, predgrevanje 250 °C, varjenje MMAW
- Različica 5, dodajni material CRONITEX RC 252C in CRONITEX RC 63, predgrevanje 250 °C, varjenje TIG
- Različica 6, dodajni material Welco 1960 in Megafil 760M, predgrevanje 250 °C, varjenje MMAW in MAG CMT

To je le nekaj različic, ki opisujejo različne dodajne materiale in metode

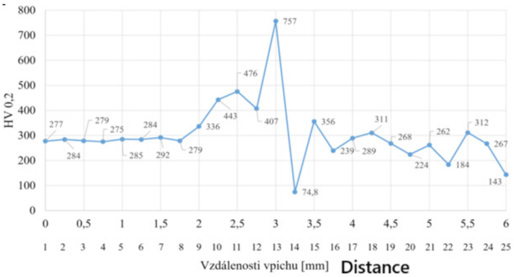
on the requirement for the final mechanical properties.

During the diploma thesis [2] the study as the of the influence of the welding repair process on the final quality and mechanical properties of cast iron GJS 700-2 was done. There were used welding methods as MMAW, TIG, and MIG/MAG, as CMT process. As the filler welding materials, CRONITEX RC 252 C, CRONITEX RC 58, CRONITEX RC 63, Welco 1960, Welco 1790S, Welco A1960, Megafil A760M were used. They were also used for repairing by using an intermediate layer and a final hard-facing layer to achieve the required material properties. Several types of testing samples were conducted:

- Variant 1, filler material CRONITEX RC 252C, preheating 250 °C, TIG welding
- Variant 2, filler material CRONITEX RC 252C and CRONITEX RC 58, preheating 250 °C, TIG welding
- Variant 3, filler material CRONITEX RC 58, preheating 250 °C, TIG welding
- Variant 4, filler material Welco 1960 and Welco 1709S, preheating 250 °C, MMAW welding
- Variant 5, filler material CRONITEX RC 252C and CRONITEX RC 63, preheating 250 °C, TIG welding
- Variant 6, filler material Welco 1960 and Megafil 760M, preheating 250 °C, MMAW and MAG CMT welding

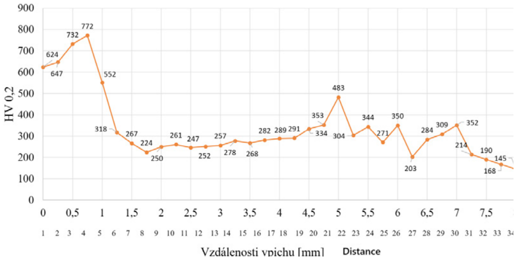
These are only several variants describing different filler materials and welding methods, but different numbers of deposits were also used for the given variants and heat inputs.

The samples were subjected to penetration and metallographic testing, and hardness measurements. The measured hardnesses, which were conducted with welding material, heat-affected zone, and basic material for different variants, are shown in Fig. 22-27.



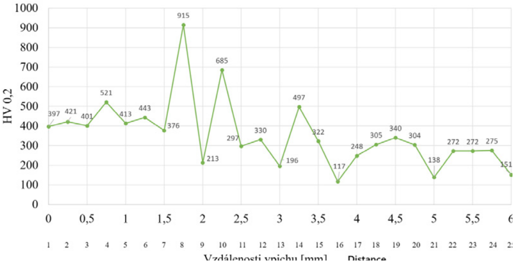
Slika 22. Trdota, različica 1.

Fig. 22. Hardness, variant 1.



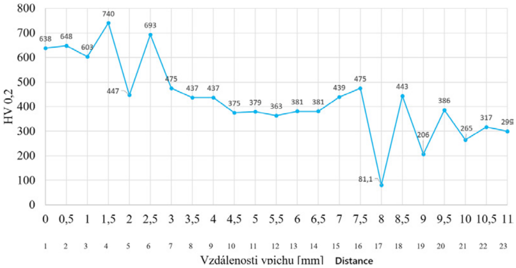
Slika 23. Trdota, različica 2.

Fig. 23. Hardness, variant 2.



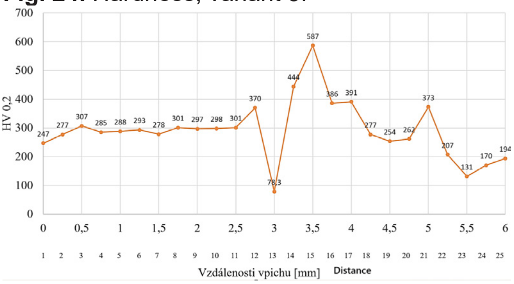
Slika 24. Trdota, različica 3.

Fig. 24. Hardness, variant 3.



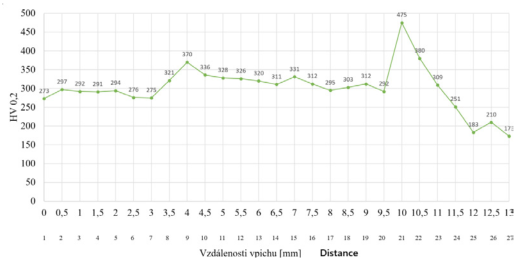
Slika 25. Trdota, različica 4.

Fig. 25. Hardness, variant 4.



Slika 26. Trdota, različica 5.

Fig. 26. Hardness, variant 5.



Slika 27. Trdota, različica 6.

Fig. 27. Hardness, variant 6.

varjenja, vendar je bilo pri teh različicah uporabljeno tudi različno število slojev in toplotnih vnosov.

Vzorci so bili podvrženi penetracijskim in metalografskim preskusom ter meritvam trdote. Izmerjene trdote, ki so bile opravljene skozi dodajni material, toplotno vplivano cono in osnovni material za različne variante, so prikazane na Slikah 22–27.

Among the tested technologies, MMAW produced the best results by achieving the required hardness in the final layer as well as penetration and possible cracks. The TIG method only reached the required hardness in a limited area of the hard facing, suggesting the need for further optimization. The CMT process proved unsuitable due to the inadequate chemical composition of the welding wire. Overall, the results indicate

Med preizkušenimi tehnologijami je MMAW dala najboljše rezultate, saj je dosegla zahtevano trdoto končnega sloja ter tudi penetracijo in morebitne razpoke. Metoda TIG je dosegla zahtevano trdoto le na omejenem območju trdega navarjanja, kar kaže na potrebo po nadaljnji optimizaciji. Postopek CMT se je izkazal za neprimernega zaradi neustrezne kemijske sestave varilne žice. Na splošno rezultati kažejo, da je metoda MMAW najprimernejša za to uporabo.

5 Zaključek

Na splošno so popravila delov ulitkov s tehnologijo varjenja zelo zapletena zaradi uporabe heterogenih materialov kot osnovnih materialov in dodajnih materialov ter zapletene tehnologije varjenja. V večini primerov imajo uliti deli večjo vsebnost ogljika, ki povzroča možnost nastanka razpok pri ohlajanju. Prav tako je v večini primerov treba doseči podobne lastnosti kot jih ima osnovni material, kar je včasih zelo problematično in je treba pri varjenju uporabiti več različnih dodajnih materialov.

Pred končnim popravilom z varjenjem je treba opraviti celostno validacijo tehnologije, kar pomeni, da je priporočljivo opraviti popolno preizkusno varjenje na modelu z varjenjem s celostnim preskušanjem materiala za pridobitev specifikacije varilnega postopka (WPS; Welding Procedure Specification) in dokumentacije kvalificiranosti varilnega postopka (WPQR; Welding Procedure Qualification Record). Seveda je zelo koristna uporaba numeričnih simulacij varjenja, ki lahko dajo veliko informacij o vplivu tehnologije na lastnosti materiala in morebitnem nastanku razpok. Z uporabo numerične simulacije varjenja so mogoče tudi tehnološke različice, kot so preizkusno varjenje na modelu ali dejanska popravila z varjenjem.

that the MMAW method is the most suitable for this application.

5 Conclusion

Generally, the repairs of cast parts by welding technology are very complicated due to needs of using heterogeneous materials as the basic and filler, and the use of complicated welding technology. In most cases, cast parts have a higher content of carbon, which causes creation possible cold cracking. Also, in most cases, there is a requirement to achieve similar material qualities as basic material, and sometimes it is very problematic, and the welding should be done by using several filler materials.

A technology validation should be conducted before the final welding repair is completed which implies a recommendation to conduct complete testing as a welding repair mock-up with material testing to receive WPS and WPQR documentation. Of course, it is very helpful, to use welding numerical simulations, which can give a lot of information about the influence of technology on material properties and possible crack creation. Also, by using welding numerical simulation, it is possible to do several technology variants such as mock-up testing or real welding repairs.

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