A. Nofal
Centralni inštitut za metalurške raziskave in razvoj - CMRDI (EG) /
Central Metallurgical Research and Development Institute - CMRDI (EG)

Raziskave in prenos tehnologije na področju litega železa – študije primerov iz CMRDI

Cast Iron Research and Technology Transfer – Case Studies from CMRDI

Povzetek

V tem poročilu so opisani nekateri projekti prenosa tehnologije in razvoja zlitin, ki jih je Centralni inštitut za raziskave in razvoj na področju metalurgije (CMRDI) izvedel za čim večjo lokalno proizvodnjo rezervnih delov strateškega pomena.

V prvem delu so predstavljene izkušnje s prenosom tehnologije proizvodnje valjev iz nodularne litine v livarsko industrijo v Egiptu. Valjarna je daleč najpomembnejši obrat za vroče in hladno preoblikovanje v kovinski industriji. Metalurške zahteve za valje v valjarnah so precej kompleksne, saj vključujejo visoko odpornost proti obrabi in lomljenju ter neobčutljivost na toplotne razpoke in luščenje. Doseganje ustrezne kombinacije lastnosti je za izdelovalca valjev nenehno velik izziv, saj so si rešitve med seboj nasprotujoče. Obravnavani so primeri projektov raziskav in razvoja, ki so bili izvedeni za povečanje konkurenčnosti valjev, proizvedenih v Egiptu na lokalnih in mednarodnih trgih.

V drugem delu tega poročila so obravnavana prizadevanja inštituta CMRDI za razvoj razmeroma novega materialaaustemprane litine s kroglastim grafitom (ADI), z izjemno kombinacijo lastnosti in izrazitimi potenciali za številne nove vrste uporabe. Poseben poudarek je namenjen nedavnemu delu, ki se ukvarja s termomehansko obdelavo in dinamičnim strjevanjem v ultrazvočnem polju.

Abstract

This report outlines some technology transfer and alloy development projects conducted at CMRDI, aiming to maximize the local production of spare parts of strategic importance.

In the first part of this report, the Egyptian experience with the technology transfer of ductile iron roll production to the Egyptian foundry industry is outlined. The rolling mill is by far the most important means of hot and cold forming in the metal industry. The metallurgical demands placed on rolling mill rolls are quite complex, as they include high resistance to wear and fracture, as well as insensitivity to fire cracking and spalling. The achievement of the proper combination of properties constantly presents serious challenges to the roll maker, as the solutions are mutually contradictory. Examples of R&D projects conducted to increase the competitiveness of Egyptian rolls in local as well as international markets are discussed.

In the second part of this report, CMRDI's efforts to develop the relatively new material, austempered ductile iron (ADI), with an exceptional combination of properties and marked potential for numerous novel applications are discussed. Special emphasis is placed on recent work dealing with thermo-mechanical treatments, as well as dynamic solidification in the ultrasonic field.

1 Uvod

Tehnologija in metalurgija litega železa sta v zadnjih nekaj desetletjih zelo napredovali. Napredek pri nadzoru procesov, tako v livarnah kot v obratih za toplotno obdelavo, omogoča, da se načela fizikalne metalurgije iz teoretičnega vidika prenesejo v prakso. Zato se pričakuje, da se bo uporaba litega železa kot »novega« in najbolj uporabnega razreda materialov zelo povečala.

V tem poročilu so na podlagi rezultatov, pridobljenih na inštitutu CMRDI v zadnjih treh desetletjih, pregledani nekateri glavni dosežki na področju litega železa in njihov vpliv na zmogljivost tega materiala. Prva študija primera je povezana z uvedbo valjev iz litine s kroglastim grafitom v egiptovsko industrijo, druga pa z razvojem novih tehnologij za izboljšanje lastnosti austemprane litine s kroglastim grafitom (ADI) in iskanjem novih možnosti uporabe tega materiala z velikim potencialom.

2 Valji iz sive litine s kroglastim grafitom– metalurški izziv:

Valjarna je daleč najpomembnejši obrat za vroče in hladno preoblikovanje v kovinskopredelovalni industriji. Valji so orodje v valjarni in hitrost njihove degradacije med obratovanjem pomembno vpliva na kakovost valjanih izdelkov in stroške njihove proizvodnje. Obraba valjev se običajno meri s tonažo valjane mase na enoto premera. To zmanjšanje premera temelji na količini, ki jo je treba z valja odstraniti, da se ponovno vzpostavi zadovoljiva delovna plast valja, tako da se v tem smislu vsak dejavnik, ki vpliva na količino, ki jo je treba odstraniti, lahko šteje za obrabo.

Degradacija površine valja v valjarni ni enostaven proces, saj je vključenih več mehanizmov, katerih relativni vpliv je

1 Introduction

Cast iron technology and metallurgy have made great progress in the last few decades. Advances in process control, both in the foundry and in the heat treatment shops, make it possible to take physical metallurgy principles from the realm of theoretical interest to the arena of practical reality. As a result, the application of cast irons as a “new” and most useful class of materials is expected to grow remarkably.

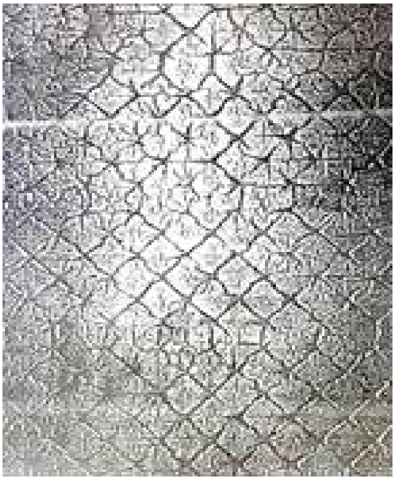
This report reviews some of the main developments of cast iron based on results obtained at CMRDI for the past three decades and their impact on cast iron performance. The first case study is related to the introduction of ductile iron rolls to the Egyptian industry, while the second case deals with the development of new technologies aiming at enhancing the properties of austempered ductile iron (ADI) and searching for novel applications of this very promising material.

2. Ductile Iron Rolls – The Metallurgical Challenge:

The rolling mill is by far the most important means of hot and cold forming in the metalworking industry. Rolls are the tools of the mill, and the rate at which they deteriorate in service has a significant impact on the quality of a rolled product and the cost of its production. Roll wear is normally measured by the tonnage of stock rolled per unit of diameter. This reduction in diameter is based on the amount which has to be dressed off the roll to restore the barrel of the roll to a satisfactory working condition, so that in this sense every factor which influences the amount to be dressed can be considered as wear.

odvisen od izvedenega načina valjanja. Najpomembnejši dejavniki, ki jih je treba upoštevati, so:

- *Abrazija:* je v veliki meri posledica relativnega gibanja materiala in valja. Stopnja abrazije je odvisna od hitrosti valjanja, sile ločevanja valjev in koeficienta trenja. Med vročim valjanjem je običajno prisotna abrazivna oksidna obloga, ki pospešuje obrabo površine valja. Višji oksidi – Fe_3O_4 in Fe_2O_3 – so izjemno trdi na vmesniku in ustvarjajo najzahtevnejše pogoje abrazije.
- *Termični učinki:* Termična utrujenost delovne površine valjev lahko povzroči nastanek razpok oziroma pokanje (crazing). Ta težava je najbolj pereča v primarnih valjarnah in obratih za grobo obdelavo, kjer so zaradi relativno nizke hitrosti valjanja in visoke temperature materiala termične napetosti največje (slika 1).
- *Mehanske napetosti:* Zaradi tlačne obremenitve med valjem in materialom pride do radialnega odklona valjev, katerega velikost je odvisna od



Slika 1. Pokanje na valju

Fig. 1. Fire cracking on roll

The deterioration of a roll surface in the mill is not a simple process as there are a number of mechanisms involved, the relative influence of which depends upon the type of rolling being carried out. The most important factors to consider are:

- *Abrasion:* is largely due to the relative movement between the stock and the roll. The rate of abrasion depends on the speed of rolling, the roll-separating force, and the coefficient of friction. During hot rolling, abrasive oxide scale is normally present, which accelerates the rate at which the roll surface is worn away. The higher oxides – Fe_3O_4 and Fe_2O_3 – are extremely hard on the interface, create the most severe abrasion conditions.
- *Thermal Effects:* The thermal fatigue experienced by the working surface of rolls may lead to the formation of fire cracking (crazing). This problem is most acute in primary and roughing mills, where, due to relatively slow roll speeds and high stock temperatures, thermal stresses are greatest (Fig. 1).
- *Mechanical Stresses:* The compressive loading between the roll and stock causes radial deflection of the rolls, the extent of which depends upon the level of the applied force and the roll diameter. The resulting radial flexing can cause fine surface pitting if the stress fluctuates in the range of the fatigue limit of the roll material. A more serious consequence of these compression forces is the formation of severe cracks and spalls, which require large reductions to remove the damage and, in many cases, can lead to scrapping of the rolls.

Metallurgical demands placed on rolling mills are therefore quite complex, and the main requirements of the roll material should cover:

velikosti uporabljene sile in premera valja. Posledično radialno upogibanje lahko povzroči drobne površinske izjede, če napetost niha v območju meje utrujenosti materiala valja. Resnejša posledica teh tlačnih sil je nastanek hudih razpok in drobcev, kar zahteva obsežno obdelavo valjev, da se odstranijo poškodbe, in v mnogih primerih lahko privede do izločitve valjev.

Metalurške zahteve za valjarne so zato precej zapletene, glavne zahteve materiala za valje pa morajo vključevati:

- visoko odpornost proti obrabi
- visoko odpornost proti zlomu
- neobčutljivost na pokanje in luščenje
- dobro kakovost površine in ustrezno režo za vstop valjanega materiala.

Doseganje visoke kakovosti valjanih izdelkov je kumulativno pri celotnem postopku valjanja in je odvisno od pravilne vrste in kakovosti valja, ki je nameščen na vsakem zaporednem stojalu valjarskega sklopa. Metalurške, mehanske in fizikalne zahteve za valje so precej kompleksne, zlasti v sodobnih valjarnah. S sedanjim metalurškim znanjem in poznavanjem materialov ne bi bilo posebej težko izpolniti nobene od zahtev glede materiala valjev, vendar pa je kombinacija tista, ki proizvajalcem valjev nenehno povzroča resne težave, saj se rešitve medsebojno izključujejo. Na primer, visoke odpornosti proti lomljenju ni enostavno združiti z zahtevo po dobri odpornosti proti obrabi, zato mora proizvajalec skrbno določiti pravilno ravnovesje lastnosti, če želi doseči želene rezultate.

Metalurgijo valjev lahko pravzaprav označimo kot metalurgijo kompromisov. Glavna lastnost valja je odpornost proti obrabi, medtem ko morajo biti vratovi valja dovolj odporni proti lomu, kar preprosto pomeni, da oblikovalec valjev želi doseči

- high wear resistance
- high resistance to fracture
- insensitivity to fire cracking and spalling
- good surface quality and adequate bite with the rolled stock.

The attainment of a high-quality rolled product is cumulative throughout the entire rolling operation and depends on the correct type and quality of roll being located in each successive stand of the rolling train. The metallurgical, mechanical, and physical demands placed on rolling mill rolls are quite complex, particularly in modern mills. With our current metallurgical and material knowledge, it would not be particularly difficult to meet any one of the roll material requirements; the combination, however, constantly presents serious problems to roll makers because the solutions are mutually contradictory. For example, a high resistance to breakage is not easily combined with a requirement for good wear resistance, and achieving the correct balance of properties requires careful specification by the manufacturer to ensure successful results.

Actually, roll metallurgy can be considered the metallurgy of compromise. The primary property of concern in the roll barrel is wear resistance, whereas the roll necks should acquire sufficient resistance to fracture. In contrast, the roll necks should acquire the resistance necessary to fracture, which implies that the roll designer is targeting two contradictory properties in the same roll cast from the same melt. Cast iron microstructures mainly depend on the alloy composition as well as the cooling rate, and the data shown in Table 1 illustrates the contribution of microstructural constituents of the ductile iron to achieve the different metallurgical demands and properties of roll material.

The “mix” of these phases used for any particular application will obviously depend dve nasprotujoči si lastnosti pri istem valju, ulitem iz iste taline. Mikrostruktura litega železa je odvisna predvsem od sestave zlitine in hitrosti ohlajanja, podatki v preglednici (1) pa prikazujejo vpliv mikrostrukturnih sestavin sive litine s kroglastim grafitom pri doseganju različnih metalurških zahtev in lastnosti materiala valja.

»Mešanica« teh faz, ki se uporablja za določeno uporabo, je seveda odvisna od zahtev valjarne, proizvajalec valjev pa določi strukturo, ki zagotavlja najboljšo odpornost proti slabšanju lastnosti površine. Kot primer lahko navedemo dva skrajna primera:

- Valjarniška ogrodja in proge za grobo valjanje blokov morajo vzdržati ekstremne udarne in velike toplotne obremenitve, zato je treba uporabiti trpežen in močan material za valje z dobro odpornostjo proti pokanju. Običajno velja, da je jekleni valj ali valj iz sive litine s kroglastim grafitom s strukturo iz ferita in perlita ali sferoidiziranega perlita najboljša kombinacija lastnosti. Površinska plast valja ima lahko tudi zgornjo bainitno strukturo z dobrimi rezultati, vendar morata imeti sredina in čep strukturo iz sferoidiziranega perlita z največjo žilavostjo.
- Drug primer skrajnega delovanja valjarne so zaključna ogrodja sodobne valjarne za kontinuirano valjanje palic. Pri tem so mehanske in termične obremenitve zanemarljive, zato se lahko izdelovalec valjev osredotoči na doseganje največje odpornosti proti obrabi za natančnejše dimenzije končnega izdelka. Uporabljajo se valji iz bele litine z zelo visoko vsebnostjo karbida (40 %) v martenzitni matrici.

Pri valjarskih nalogah med tema skrajnostma je potrebna večja pozornost

on the mill requirements, and the roll maker will specify a structure that gives the best resistance to surface deterioration. Two extreme cases may be taken as examples:

- Blooming and slabing mill rolls must withstand extreme shock loads and severe thermal stresses so it is essential to use a tough, strong roll material with good fire crack resistance. Typically, a steel or ductile iron roll with a structure of ferrite and pearlite, or spheroidized pearlite, is considered to offer the best combination of properties. The barrel surface layer may also have upper bainite structure with good results, but the center and neck should have spheroidized pearlite structure of maximum toughness.
- The other extreme of mill duty is the finishing stands of a modern continuous rod mill. Here, mechanical and thermal stresses are negligible, and thus the roll maker can concentrate on achieving the maximum wear resistance for more precise dimensions of the finished product. Chilled iron rolls with a very high carbide content (40%) in a martensite matrix are used.

For mill duties between these extremes, the choice of the correct structure requires more care from the roll mill maker due to the influence of other factors such as grip, hardness penetration, and spall resistance. Generally, the trend is to use a progressively harder structure with increasing carbide contents as the thermal and mechanical stresses cease and the need for good stock shape becomes more important. However, in many cases, the choice of role still involves an element of compromise. The efforts of the roll makers in recent years have been directed towards eliminating this need for a compromise as far as possible for many applications. Figure 2 shows some of the rolls produced during izdelovalca valjev pri izbiri pravilne strukture zaradi vpliva drugih dejavnikov, kot so oprijem, globina trdote in odpornost proti luščenju. Na splošno je trend usmerjen v uporabo vedno trše strukture z naraščajočo vsebnostjo karbida, saj se termične in mehanske napetosti zmanjšujejo, potreba po dobri obliki materiala pa postaja vse pomembnejša. Vendar je izbira valja v številnih primerih še vedno povezana s

the early stages of production with sizes up to 4 tons in EGYPTALUM, whereas Figure 3 shows some of the recently produced rolls at Helwan Iron Foundries.

To enhance the competitiveness of the locally produced rolls, several R&D projects have been conducted aiming at either improving the performance of rolls or lowering the production cost. Examples

Preglednica 1. Vpliv sestavin mikrostrukture sive litine s kroglastim grafitom na lastnosti valja.

Table 1. The influence of ductile iron microstructure constituents on the roll properties.

Faza / Phase	Lastnosti valja / Roll Properties	Faza / Phase	Lastnosti valja
Ferit / Ferrite	• odpornost proti poškodbam. • dobra odpornost proti pokanju. • visoka žilavost. • Dober oprijem (reža). • Nizka obraba in visoka trdota.	Martenzit / Martensite	• zelo visoka trdota, dobra površinska obdelava. • zelo dobra odpornost proti obrabi. • slaba odpornost proti pokanju. • nizka žilavost
	• resistance to breakage. • good fire crack resistance. • high toughness. • Good grip (bite). • Poor wear and high hardness.		• very high hardness, good surface finish. • very good wear resistance. • poor fire crack resistance. • low toughness
Lamelarni perlit / Lamellar Pearlite	• dobra trdnost in odpornost na pokanje. • primerna odpornost proti obrabi. • finejši perlit izboljša trdnost in obrabo, vendar na račun duktilnosti in odpornosti proti pokanju. • dober oprijem.	Karbidi / Carbides	• izredno dobra odpornost proti obrabi. • Visoke vsebnosti ogljika povzročajo krhkost. Ta učinek pa je mogoče ublažiti z ustrezno toplotno obdelavo z vsebnostjo C do 1,4 %.
	• good strength and fire crack resistance. • reasonable wear resistance. • finer pearlite improves strength and wear, but at the expense of ductility and fire crack resistance. • good grip.		• extremely good wear resistance. • High C-contents cause embrittlement. But this effect can be alleviated by suitable heat treatment with C-contents up to 1.4%.
Sferoidizirani perlit	• združuje visoko žilavost in primerno odpornost proti obrabi. • dobra odpornost proti pokanju. • relativno mehek. • dober oprijem.	Grafit / Graphite	• izboljša odpornost proti pokanju in drobljenju. • grafit v obliki lističev zmanjša trdnost zaradi učinka notranje zareze, temu učinku pa se v veliki meri izognemo s sferoidizacijo grafita. • izboljša oprijem.
	• combine high toughness with reasonable wear resistance. • good fire crack resistance. • relatively soft. • good grip.		
Bainit / Bainite	• visoka trdnost in trdota ter dobra odpornost proti obrabi. • zgornje bainitne strukture imajo dobro odpornost proti pokanju.		• improves fire crack and spalling resistance. • flake graphite lowers strength due to internal notch effect, this effect is largely avoided by graphite spheroidization. • improves grip.
	• high strength and hardness, together with good wear resistance. • upper bainite structures have good fire crack resistance.		

Slika 2. Valji, izdelani v družbi EGYPTALUM ob koncu prejšnjega stoletja

Figure 2. Rolls produced at EGYPTALUM in the end of the last century

Slika 3. Valji, izdelani v livarni Helwan leta 2021.

Figure 3. Rolls produced at Helwan Iron Foundries in 2021.

sprejemanjem kompromisa. Prizadevanja proizvajalcev valjev so bila v zadnjih letih usmerjena v čim večjo odpravo kompromisov pri številnih aplikacijah. Slika (2) prikazuje nekatere valje, izdelane v zgodnjih fazah proizvodnje, velikosti do 4 tone v podjetju EGYPTALUM, medtem ko Slika (3) prikazuje nekaj nedavno izdelanih valjev v družbi Helwan Iron Foundries.

Za povečanje konkurenčnosti lokalno proizvedenih valjev je bilo izvedenih več projektov raziskav in razvoja, katerih cilj je bil bodisi izboljšati zmogljivost valjev bodisi znižati stroške proizvodnje. Primeri teh programov raziskav in razvoja so prikazani na Sliki (4).

of those R&D programs are illustrated in Figure 4.

The final result of these R&D projects was the replacement of a good part of imported rolls with locally produced ones in all Egyptian steel mills. Moreover, two foundries have exported rolls to European as well as Arab steel mills.

Roll Casting Techniques Adopted in Egyptian Foundries

Rolls can be cast either through static casting or centrifugal casting. All attempts carried out in the five Egyptian foundries have been limited to static casting, and the

Končni rezultat teh projektov raziskav in razvoja je bila zamenjava velikega dela uvoženih valjev z lokalno proizvedenimi v vseh egiptovskih jeklarnah. Poleg tega sta dve livarni izvažali valje v evropske in arabske jeklarne.

Prevzete tehnike litja valjev v egiptovskih livarnah

Valje je mogoče liti s statičnim ali centrifugalnim litjem. Vsi poskusi v petih egiptovskih livarnah so bili omejeni na statično litje, statično uliti valji pa so bili bodisi enojno bodisi dvojno uliti.

Enojno uliti valji

Trdota enojno ulitih železnih valjev je omejena na manj kot 70 Shore C, ker zaradi uravnovešanja trdote valja postaneta struktura jedra in čepa prešibka zaradi razmeroma bele ali trde mikrostrukture, ki se razvije.

Tako mora en sam ulit valj, tj. ena sama talina in sestava, zagotavljati tako odpornost proti obrabi delovne plasti valja kot tudi trdnost, da vzdrži obremenitve valjanja na čepih**.**

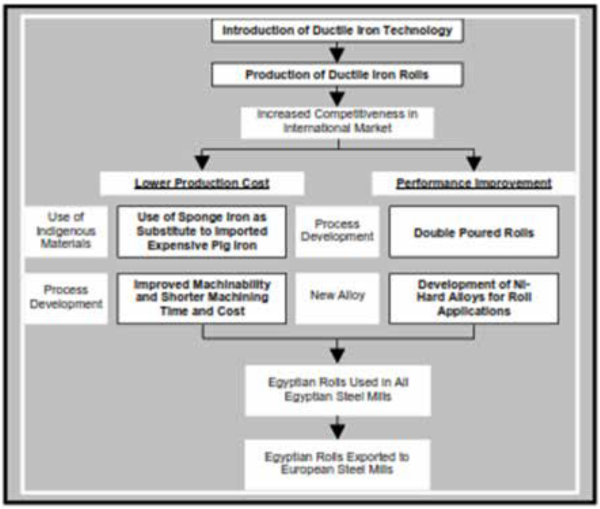
statically cast rolls were either single or double poured.

Single Poured Rolls

Single-poured iron rolls are limited to less than 70 shore C hardness because to balance this barrel hardness, the core and neck structures become too weak due to the relatively white or hard microstructure that develops.

Thus, a single poured roll, that is, a single melt and composition, must provide both wear resistance of the working barrel and strength to withstand rolling loads in the necks**.**

This type of iron roll is characterized by the gradual change in properties through the barrel cross section due to the same composition solidifying in various microstructures under the influence of a changing rate of cooling, when the roll barrel solidifies in a cast iron mold or "chill" whereas the necks solidifying in sand molds (Figure 5). An exception to this characteristic is the "clear chill" roll which solidifies as a true white iron at the barrel surface, but via a narrow "mottled" or eutectic zone, suddenly solidifies as a true gray iron.



Slika 4. Projekti raziskav in razvoja inštituta, ki so privedli do proizvodnje visokokakovostnih in poceni valjev

Figure 4. CMRDI R&D projects leading to production of high quality, low-cost rolls

Za to vrsto železnega valja je značilno postopno spreminjanje lastnosti skozi prerez valja zaradi strjevanja iste sestave v različne mikrostrukture pod vplivom spreminjajoče se hitrosti ohlajanja, ko se jedro valja strjuje v litoželezni formi (kokila), medtem ko se čepi strjujejo v peščenih formah (Slika 5). Izjema pri tej lastnosti je valj, ki se na površini valja strdi kot bela litina, vendar se prek ozke melirane ali evtektične cone nenadoma strdi kot siva litina.

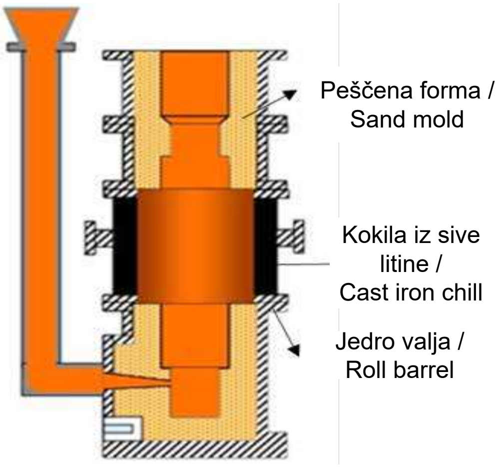
Vendar je profil trdote odvisen od različnih hitrosti ohlajanja med jedrom valja inšepi, tj. od debeline in toplotne prevodnosti litoželezne forme (kokile). Poleg tega ima pravilna izbira legirnih elementov, dodanih v sivo litino s kroglastim grafitom, ki se ulije v formo, predvsem Cr, Ni in Mo, ključno vlogo pri določanju profila trdote valja (slika 6). Opozoriti je treba, da se valji z enojnim litjem uporabljajo le, če zahtevana trdota v valju ni za več kot 50 % višja od trdote v čepih.

Dvojno uliti valji

Kadar je trdota valja za več kot 50 % večja od trdote čepov, je valj ulit iz dveh različnih litin; iz visoko legirane litine z večjo trdoto in odpornostjo proti obrabi v zunanji lupini – delovni plasti valja ter iz bolj žilave litine v jedru valja in čepih. Statično dvojno uliti valji se izdelajo s premikanjem in/ali redčenjem tekoče kovine v orodju z drugo tekočo kovino drugačne sestave. Litoželezni valji z dvojnim litjem se navadno proizvajajo z dodajanjem druge taline skozi dno forme prek istega ulivnega sistema kot prva kovina. Izpodrinjeni in razredčeni presežek se zbira med izlivanjem iz orodja in je nato na voljo kot legirana surovina za naslednje taline.

V orodje se najprej ulije kovina, iz katere se na koncu oblikujejo delovne plasti, lupina ali jedro, pri čemer je raven, do katere napolni orodje, delno na zgornjem čepu.

However, the hardness profile depends on the differential cooling rates between the barrel and the necks, i.e., the thickness as well as the thermal conductivities of the cast iron mold (chill). Moreover, the proper selection of the alloying elements added to the ductile iron poured in the mold; which are mainly Cr, Ni and Mo play a crucial role in determining the hardness profile of the barrel (Figure 6). It should be noted that the single- poured rolls are applicable only when the hardness required in the barrel is not more than 50% higher than the hardness in the necks.



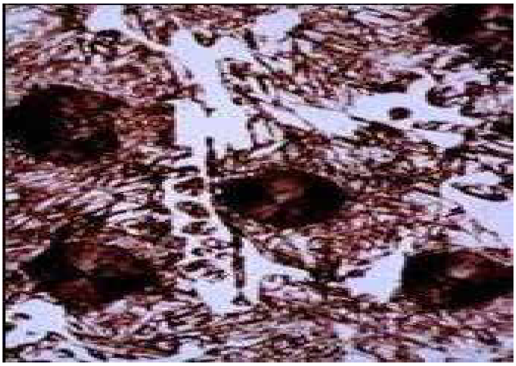
Slika 5. Tehnologija litja enojno ulitih valjev

Figure 5. Casting technology of single poured rolls.

Double Poured Rolls

Whenever the hardness of the barrel is more than 50% harder than that of the necks, the roll is cast from two different irons a highly alloyed iron with higher hardness and wear resistance in the outer shell and a tougher iron in the barrel core and the necks. Static cast double-poured rolls are produced by displacing and/or diluting the

Strjevanje prve kovinske lupine – delovne plasti se začne v kokili takoj po litju. Hitrost strjevanja in s tem globina delovne plasti je odvisna od časa in velikosti ulitka in kokile. Potrebno globino strjevanja delovne plasti določa valjarski obrat, kar pomeni, da je odvisna od najmanjšega premera valja preden se ga zavrže. Po ustreznem času za strjevanje delovne plasti se druga talina ali kovinsko jedro ulije skozi isti ulivni sistem, vendar z nadzorovano in enakomerno hitrostjo ulivanja. Hitrost ulivanja omogoča mešanje, redčenje in premikanje tekoče delovne plasti z mešanjem in nastajanjem sive litine na meji strjene delovne plasti in jedra valja. Uspešnost dvojnega ulivanja je v veliki meri odvisna od temperature in časa ulivanja obeh talin.

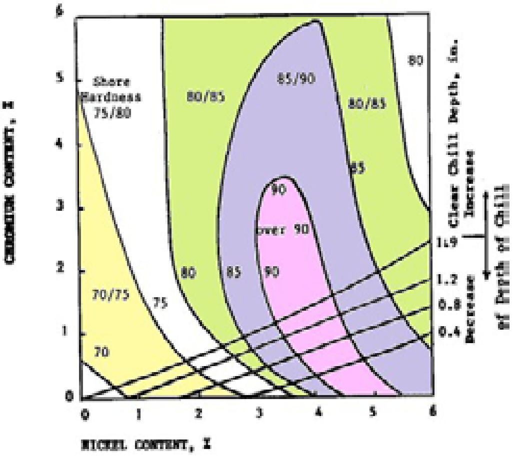


Slika 7. Mikrostruktura SG-Ni Hard z martenzitno karbidno matrico

Figure 7. Microstructure of SG-Ni Hard with martensitic carbidic matrix

Ni-hard, ki je bela litina, legiranega s Cr in Ni, tj. brez grafitnih tvorb v strukturi, se je močno uveljavila pri litju delovne plasti dvojno ulitih valjev, ki se uporabljajo v zadnjih ogrodjih valjarn za vroče trakove. V prejšnjih raziskavah na inštitutu CMRDI je bilo mogoče pridobiti kroglasti grafit (SG) v mikrostrukturi zlitineNi-Hard IV z matrico,

liquid metal inside the mold with a second liquid metal of different composition. Cast iron double-poured rolls are generally produced by adding the second liquid through the bottom of the mold via the same running system as the first metal. The displaced and diluted excess is collected as it pours from the mold and is then available as an alloyed raw material for the next melts.



Slika 6. Vpliv vsebnosti Ni in Cr na trdoto soda in globino ohlajanja

Figure 6. Effect of Ni and Cr contents on the hardness of the barrel and depth of chill

The first metal to be poured into the mold is that which eventually forms of the working layers or shell of the barrel, the level to which it fills the mold is partway up the top neck. Solidification of the first shell metal commences immediately at the casing or permanent mold chiller. Speed of solidification, hence the depth of the shell, is dependent upon time and casting size. The depth of the shell solidification required is determined by the mill, that is, it is dependent upon the reject diameter of the roll under consideration. After due ki vsebuje karbide in martenzit (slika 7), uporabljeni za delovno plast dvojno ulitega valja. To je bilo mogoče z uporabo močnega inokulanta na osnovi bizmuta, kar je omogočilo uporabo razvitega materiala Ni-Hard IV v začetnih valjalnih ogrodjih, kjer je žilavost bolj pomembna. Poleg tega bi lahko strjevanje kroglastega grafita prineslo naslednje koristi:

- Povečana odpornost proti pokanju zaradi večje toplotne prevodnosti, ki zmanjšuje toplotne napetosti.
- Izboljšana obdelovalnost.
- Izboljšano mazanje valjev in boljši oprijem valjev.

ADI – nov revolucionarni material:

V zadnjih treh desetletjih je skupina livarn inštituta CMRDI v veliki meri prispevala k svetovnemu razmahu raziskav in razvoja, ki je sledil napovedi prve proizvodnje novega referenčnega materiala – poboljšane sive litine s kroglastim grafitom (ADI) – v osemdesetih letih prejšnjega stoletja. Odlična kombinacija lastnosti tega materiala je odprla nove možnosti za litino, ki lahko nadomesti jeklene ulitke in kovane elemente v številnih inženirskih aplikacijah z znatnimi stroškovnimi ugodnostmi. Poleg tega so vztrajna prizadevanja avtomobilske industrije po vsem svetu za uporabo lahkih materialov zmanjšala trg težjih železnih ulitkov. Trenutno ADI s svojo izjemno trdnostjo uspešno konkurira lahkim zlitinam, česar pa se številni inženirji še niso v celoti zavedali.

Mehanske lastnosti sive litine s kroglastim grafitom v litem stanju se lahko bistveno izboljšajo s toplotno obdelavo s kaljenjem (slika 8). To je privedlo do novega člana družine litega železa, sive litine s kroglastim grafitom (ADI) z edinstveno mikrostrukturo kroglastega grafita v ausferitni matrici [1].

time for solidification of the shell, the second liquid or core metal is poured through the same running system, but at a controlled and even pouring rate. The rate of pour allows mixing, dilution and displacement of the liquid shell metal with mixing and gray iron formation immediately at the solidified shell boundary. The success of the double pouring depends to a large degree on the pouring temperature and timing of both metals.

Ni-hard, which is Cr, Ni alloyed white iron, i.e., without graphite formations in the structure, has been firmly established for casting of the outer shell of double-poured rolls used in the last stands of hot strip mills. In a previous research at CMRDI, spheroidal graphite (SG) could be precipitated in the Ni-hard IV structure (Figure 7) microstructure of SG-Ni-hard IV shell layer of a double poured roll with a matrix comprising carbides as well as martensite, using a Bi-containing potent inoculant which permitted the developed Ni-hard IV to be used in the earlier stands, where toughness is of higher concern. Moreover, the precipitation of SG could lead to the following benefits:

- Increased resistance to fire cracking by increasing thermal conductivity, which alleviates thermal stresses.
- Improved machinability.
- Improved rolling lubrication and roll bite.

ADI – The Novel Revolutionary Material:

Over the past three decades CMRDI foundry group has been largely contributing to the worldwide explosion of research and development that followed the announcement of the first production of the new benchmark material, the austempered ductile iron (ADI) in the 1980s of the past century. The excellent property combination of this material has opened new horizons for cast iron to replace steel castings and

Transformacijo s kaljenjem v litini ADI lahko opišemo kot dvostopenjsko reakcijo [2]:

Reakcija 1. stopnje (povečanje žilavosti): avstenit (γc) → ferit (α) + visokoogljični stabilizirani avstenit (γHC)

Reakcija 2. stopnje (pojav krhkosti): visokoogljični avstenit (γHC) → ferit (α) + karbidi (ε)

Mehanske lastnosti litine ADI so odvisne od številnih medsebojno povezanih dejavnikov, med katerimi so predvsem temperature in časi avstenitizacije in austempranja ter mikrostruktura, sestava in velikost sklopa. Med njimi je najpomembnejša temperatura austempranja [1]. Te spremembe lastnosti so lahko povezane s spremembami mikrostrukture. Pri nizkih temperaturah austempranja nastane acikularni ferit (igličasti) z le majhno količino zaostalega avstenita. Pri najnižjih temperaturah austempranja lahko struktura vsebuje tudi nekaj martenzita. Ta vrsta mikrostrukture lahko zagotavlja visoko natezno trdnost in trdoto, vendar le ob omejeni duktilnosti in slabi obdelovalnosti. Pri višjih temperaturah austempranja postane ferit bolj grob z

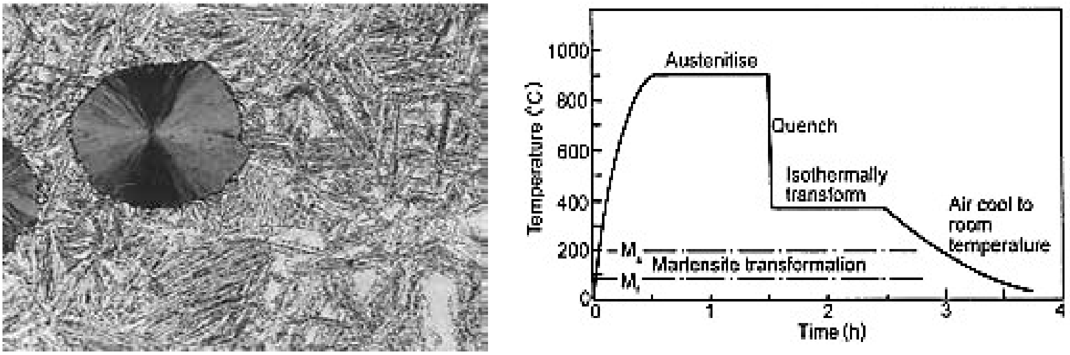
forgings in many engineering applications with considerable cost benefits. Moreover, the sustained efforts worldwide of the automotive industry to use lightweight materials have eroded the market for the heavier iron castings. Currently, ADI, with its super strength, is successfully competing with the lightweight alloys, a point which has yet to be fully realized by many design engineers.

The as-cast mechanical properties of ductile iron can be significantly improved through an austempering heat treatment (Figure 8). This has led to the birth of a new member of the cast iron family; the austempered ductile iron (ADI), with its unique microstructure, spheroidal graphite in an ausferritic matrix [1].

The austempering transformation in ADI can be described as a two-stage reaction [2]:

Stage I Reaction (toughening): austenite (γc) → ferrite (α) + high carbon stabilized austenite (γHC)

Stage II Reaction (embrittlement): high carbon austenite (γHC) → ferrite (α)+ carbides (ε)



a) b)

Slika 8. (a) Tipična mikrostruktura litine ADI, (b) postopek austmpranja

Figure 8. (a) Typical microstructure of ADI, (b) the Austempering process

večjimi količinami zadržanega avstenita (do40 %) z značilno »ausferitno strukturo. S tem se bistveno poveča duktilnost in obdelovalnost pri manjši trdoti. Slika 9 prikazuje konkurenčno prednost litine ADI v primerjavi z drugimi inženirskimi materiali, saj je ta najlažja in hkrati najcenejša, če primerjamo težo in stroške materiala, potrebnega za zagotovitev ene enote trdnosti [3].

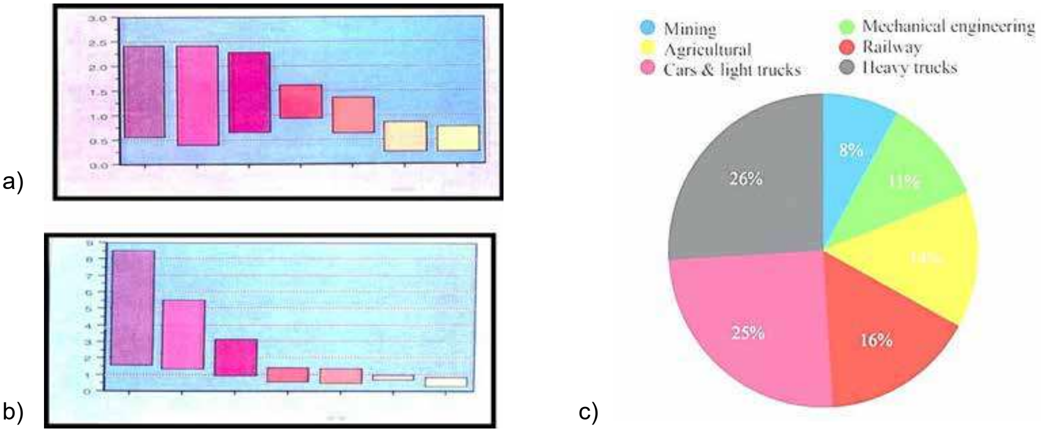
V nadaljevanju so predstavljeni nekateri raziskovalni in razvojni programi, ki jih inštitut CMRDI izvaja samostojno ali v sodelovanju z mednarodnimi partnerji in so namenjeni izboljšanju trdnostnih in triboloških lastnosti litine ADI ter raziskovanju možnosti za nove aplikacije tega dinamičnega in perspektivnega materiala.

Prispevek inštituta CMRDI k razvoju litine razvoju litine ADI:

1. Hladno valjanje litine ADI

Kot pove že ime, se je litina dolga leta proizvajala le z »litjem«. V smeri valjanja

The mechanical properties of ADI depend on a number of interlinked factors, including primarily the austenitizing and austempering temperatures and times, together with the as-cast microstructure, the composition, and the section size. Of these, the austempering temperature is the most important [1]. These variations in properties can be related to the changes in microstructure. At low austempering temperatures, an acicular (needle-like) ferritic phase is formed with only a small amount of retained austenite. At the very lowest austempering temperatures, the structure may also contain some martensite. This type of microstructure can provide high tensile strength and hardness, but only limited ductility and poor machinability. With increased austempering temperatures, the ferrite becomes coarser with increased amounts of retained austenite (up to -40%), with a typical “ausferrite structure. This results in a substantial increase in ductility and machinability with lower hardness. Figure 9 demonstrates the competitive edge of ADI compared with other engineering



Slika 9. Konkurenčna prednost litine ADI: (a) relativna masa na enoto trdnosti, (b) relativni stroški na enoto moči in (c) tržni delež glavnih aplikacij za ADI

Figure 9. The competitive edge of ADI [3]; (a) relative weight per unit of strength, (b) relative cost per unit of strength, c) market share of major applications for ADI

so bili pripravljeni hladno valjani ploščati natezni vzorci ADI, na katerih je bil opravljen natezni preskus [4–6]. Slika 10 prikazuje, da se je z večanjem redukcij pri hladnem valjanju (CR) količina ohranjenega avstenita (ɣr) zmanjšala zaradi delne transformacije ɣr v martenzit. Slika 10a prikazuje, da se količina mehansko ustvarjenega martenzita povečuje s povečevanjem redukcije hladnega valjanja [4]. Kot je razvidno iz slik (10b,c) se raztezek in udarna žilavost zmanjšata, medtem ko se natezna trdnost in trdota povečujeta s povečevanjem redukcij hladnega valjanja. To pripisujemo povečanju utrjevanja zadevne litine ADI s procesi hladne deformacije (deformacijski trakovi in dvojčki) in deformacijsko induciranim martenzitom. Omeniti je treba, da so opažene spremembe mehanskih lastnosti pri lahki hladni deformaciji (7-odstotno zmanjšanje) v glavnem posledica utrjevanja te litine s plastično deformacijo, koncentrirano v ɣr. Pri tej lahki deformaciji je količina mehansko oblikovanega martenzita zelo majhna (Slika 10).

Dobro odpornost proti obrabi pri vsakem materialu običajno dosežemo z zagotavljanjem visoke trdote. Pri nizkih temperaturah austempranja (235–250 °C)

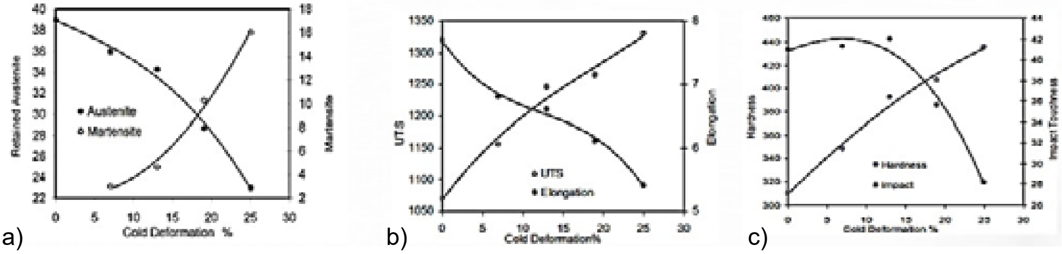
materials. When we compare the weight and cost of material required to give one-unit yield strength, ADI is the lightest and at the same time, the cheapest [3].

The following sections outline some of the research and development programs conducted by CMRDI, either solely or in cooperation with international partners, aiming at the enhancement of strength and tribological properties of ADI and exploring potentials for novel applications of this dynamic and prospective material.

CMRDI Contribution to ADI Development:

1. Cold Rolling of ADI

As its name implies, cast iron has been over years produced only by “casting” process. Cold-rolled ADI flat tensile specimens were prepared along the rolling direction and the specimens were subjected to tensile test [4 - 6]. Figure 10 shows that increasing the cold rolling (CR) reductions, the amount of retained austenite (ɣr) was decreased due to partial transformation of ɣr to martensite. Figure 10a indicates that the amount of mechanically generated martensite increases with increasing CR reduction [4]. As can be seen from Figures



a) b) c)

Slika 10. Učinek odstotka hladne redukcije na: a) prostorninske deleže zadržanega avstenita in mehansko inducirane tvorbe martenzita, b) raztezek in natezno trdnost, c) Trdoto po Vickersu in udarno žilavost [4]

Figure 10. Effect of cold reduction percent on: a) volume fractions of retained austenite and mechanically induced martensite formation, b) elongation and ultimate tensile strength, c) Vickers hardness and impact toughness [4]

nastajajo trdi ADI (~480–550 BHN) in takšne vrste se izberejo, kadar je glavna zahteva dobra odpornost proti obrabi. Z višanjem temperature austempranja se trdota zmanjšuje, kar povzroča večjo obrabo. Vendar mehkejše vrste ADI (navadno 280–320 BHN) vsebujejo velike količine avstenita, ki se lahko ob mehanski obremenitvi na površini deformacijsko utrdi in/ali spremeni v martenzit, pri čemer je odpornost proti obrabi bistveno boljša, kot bi pričakovali. Čeprav ta učinek pri strojni obdelavi ni ugoden, je lahko zelo koristen za nekatere komponente ADI, saj se površina obrablja in jo nenehno nadomešča sveže oblikovana utrjena plast [5, 6].

Zaradi vse pogostejše uporabe litine ADI kot nadomestka za kovana jekla v predelovalnih industrijah je deformacijsko utrjevanje litine ADI deležno vse večje pozornosti, zato je za boljše razumevanje tega pojava potrebnih več raziskav. To je mogoče pripisati naslednjim dejavnikom:

- Sestavni deli iz litine ADI, kot so zobniki menjalnikov, ročične gredi in kolesa železniških vagonov, so med proizvodnjo podvrženi obsežni strojni obdelavi, obnašanje litine ADI zaradi deformacijskega utrjevanja pa močno vpliva na življenjsko dobo orodja za strojno obdelavo in kakovost površine dela.
- V številnih aplikacijah so sestavni deli iz litine ADI izpostavljeni velikim plastičnim obremenitvam (npr. utrujenost, obraba). Na celotno življenjsko dobo teh sestavnih delov torej vplivajo značilnosti deformacijskega utrjevanja materiala.
- Deformacijsko utrjevanje matrice ADI povzroči nastanek martenzita zaradi deformacije, kar prispeva k visoki odpornosti litine ADI proti obrabi.

10b and 10c The elongation and impact toughness decrease, while the ultimate tensile strength and hardness increase with increasing CR reduction. This is attributed to increase of the hardening of the investigated ADI with cold deformation processes (deformation bands and twins) and deformation–induced martensite. It must be mentioned that the observed changes in the mechanical properties at light cold deformation (7% reduction) are mainly attributed to the hardening of this alloy by plastic deformation concentrated in γ_r. At this light deformation, the amount of mechanically formed martensite is very small (Figure 10).

Good wear resistance is usually obtained in any material by ensuring a high hardness. Low austempering temperatures (235-250 °C) produce hard ADI (~480-550 BHN), and such grades would be selected when good wear resistance is the main requirement. As the austempering temperature increases, the hardness decreases, resulting in more wear. However, the softer grades of ADI (typically 280-320 BHN) contain large amounts of austenite, and this can work harden and/or transform to martensite when subjected to mechanical strain at the surface, with wear resistance significantly better than would be expected. Although this effect is disadvantageous when machining, it can be very beneficial for certain ADI components, since as the surface is worn away, it is continuously replaced by a freshly formed hardened layer [5, 6].

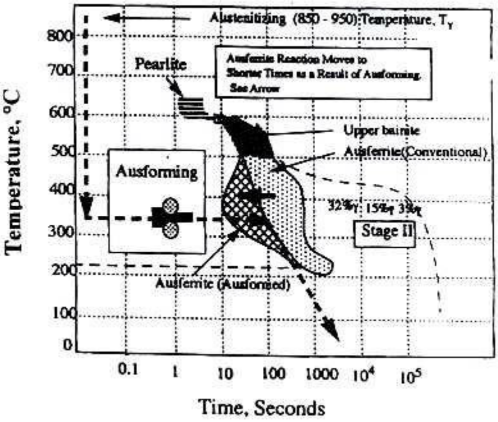
With increasing applications of ADI as a substitute for forged steels in manufacturing industries, strain hardening of ADI is attracting more attention, and more research is required for a better understanding of this phenomenon. This may be attributed to the following factors:

2. Poboljšana siva litina s kroglastim grafitom z ausformingom (AADI)

Izkazalo se je [7,8], da lahko hitrost nastajanja ferita med austempranjem na prvi stopnji nadzorujemo z naslednjimi spremenljivkami obdelave:

- **Kemijsko** – vključno z izbiro vsebnosti zlitine zaradi kaljivosti in izbiro temperature avstenitizacije, ki nadzoruje vsebnost ogljika v matrici.
- **Termično** – vključno s temperaturo in časom austempranja.
- **Mehansko** – vključno z mehansko deformacijo, ki se v načrt austempranja vključi takoj po gašenju, vendar pred kakršno koli bistveno transformacijo avstenita (ausforming) (Slika 11).

Seveda bi lahko optimalno končno mikrostrukturo dosegli z vključitvijo elementov vseh treh spremenljivk obdelave. Pokazalo se je [9–11], da lahko mehanska obdelava ADI deluje kot krmilni ventil za reakcijo austempranja na prvi stopnji. Pri poboljšani sivi litini s kroglastim grafitom z ausformingom (AADI) mehanska deformacija vpliva na mikrostrukturo



Slika 11. Shematski prikaz postopka kaljenja v vroči kopeli [7]

Figure 11. Schematic representation of the austempering process [7]

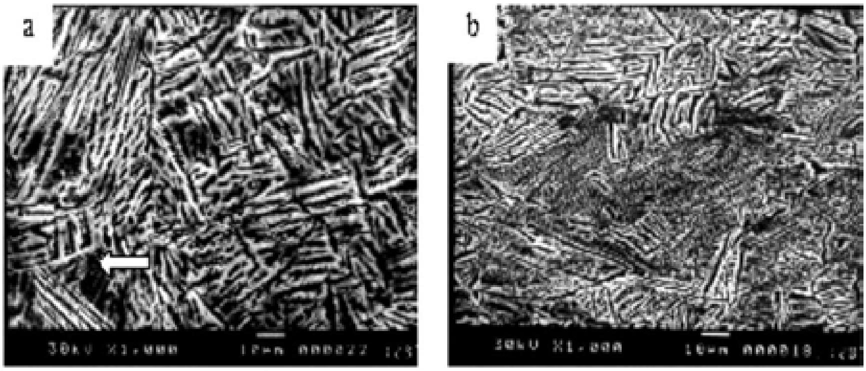
- ADI components such as transmission gears, crankshafts, and train car wheels are subjected to extensive machining during manufacturing, and the strain-hardening behavior of ADI has a profound influence on machining tool life and part surface finish.
- In many applications, ADI components undergo substantial plastic strains (e.g., fatigue, wear). The total life cycle of those components is, therefore, influenced by the strain-hardening characteristics of the material.
- Strain-hardening of the ADI matrix causes strain-induced martensite formation, and this contributes to the high wear resistance of ADI.

2. Ausformed Austempered Ductile Iron (AADI)

It has been shown [7,8] that the rate of ferrite formation during stage I austempering may be controlled by the following processing variables:

- **Chemical** – including alloy content selection for hardenability purposes, together with the austenitization temperature selection, which controls the matrix carbon content.
- **Thermal** – including austempering temperature and time.
- **Mechanical** – including mechanical deformation introduced into the austempering schedule just after quenching, but before any substantial transformation of austenite (ausforming) (Figure 11).

Naturally, an optimum final microstructure could be produced by including elements of all three processing variables. It has been shown [9 - 11] that mechanical processing of ADI can act as a control valve for the stage I austempering reaction. In ausformed austempered ductile



Slika 12. Mikrografije z vrstično elektronsko mikroskopijo za litine ADI, legirane z 2 % Ni, ki je bil 1 minuto kaljen pri 375 °C. (a) Običajno obdelan, (b) ausformiran na 25 %, puščice kažejo na krhek martenzit, ki je nastal v številnih conah v običajno obdelani litini ADI. [8]

Figure 12. SEM micrographs of ADI alloyed with 2% Ni austempered at 375 °C for 1 minute. (a) Conventionally processed; (b) Ausformed to 25% reduction arrows indicate the brittle martensite formed in many zones in the conventionally processed ADI. [8]

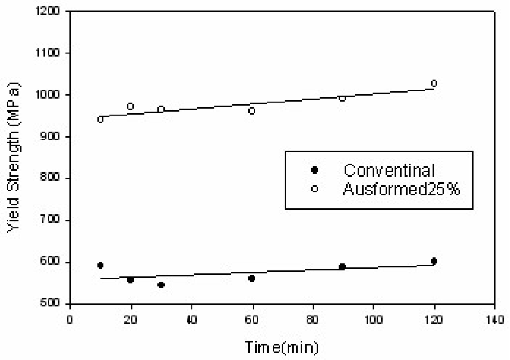
in posledično na mehanske lastnosti sive litine s kroglastim grafitmolitine zaradi pospeševanja ausferitne reakcije, izboljšanja mikrostrukture in povečanja strukturne homogenosti.

Izkazalo se je [9], da je ausforming do 25-odstotnega zmanjšanja višine med valjanjem prispeval k dodajanju komponente mehanske obdelave konvencionalni toplotni obdelavi litine ADI, kar je povečalo hitrost nastajanja ausferita in privedlo do veliko bolj finega in homogenega ausferitnega izdelka **(Slika 12)**. Vpliv ausforminga na vrednosti trdnosti je bil precej dramatičen **(Slika 13)** (do 70- oziroma 50-odstotno povečanje meje plastičnosti in meje trdnosti). Predlagamo lahko mehanizem, ki vključuje izboljšano mikrostrukturno raven zaradi okrepljene nukleacije feritov in povečane gostote dislokacij. Za povečanje možnosti utrjevanja ulitkov debelih profilov se običajno dodajo elementi za utrjevanje, kot sta Ni in Mo, pri čemer je bilo ugotovljeno, da je za ublažitev škodljivih učinkov segregacije litine na duktilnost potrebno oblikovanje do višjih stopenj deformacije [9].

iron (AADI), mechanical deformation is utilized to affect the microstructure and, consequently, the mechanical properties of ductile iron due to acceleration of ausferrite reaction, refining the microstructure, and increase of the structural homogeneity.

It has been has shown [9] that ausforming up to 25% reduction in height during a rolling operation contributed to add a mechanical processing component to the conventional ADI heat treatment, thus increasing the rate of ausferrite formation and leading to a much finer and more homogeneous ausferrite product **(Figure 12)**. The effect of ausforming on the strength values was quite dramatic **(Figure 13)** (up to 70 and 50% increase in the yield and ultimate strength respectively). A mechanism involving both a refined microstructural scale as a result of enhanced ferrite nucleation, together with an elevated dislocation density, may be suggested. Hardenability elements such as Ni and Mo are usually added to increase the hardenability of thick-section castings, and ausforming to higher degrees of deformation was found necessary to

Bolj praktično je, da se prednosti ausformiranja izkoristijo s kovanjem kot z valjanjem. Postopek kovanja se lahko izvede na ulitih predhodnih formah, ki se avstenitizirajo in gasijo na temperaturo austempranja, vstavijo v kokilo, stisnejo ali kujejo v končno obliko in nato vrnejo nazaj v kopel za austempranje, da se zaključi pospešena transformacija. Minimalne stopnje deformacije po običajnih standardih kovanja, tj. povprečna deformacija 25 %, bi zadostovala za oblikovni del postopka obdelave. Poročali so [10], da v primerih, ko pride do zelo močne deformacije, obdelovanca morda ne bo treba vrniti v kopel za kaljenje za dokončanje pretvorbe v ausferit, saj bo ta končana, ko bo obdelovanec izvlečen iz kokile.



Slika 13. Trdnost v odvisnosti od časa kaljenja in zmanjšanja ausformiranja za ADI, legirane z 2 % Ni [8]

Figure 13. Yield strength vs austempering time and ausforming reduction for ADI’s alloyed with 2% Ni [8]

Zamisel o izdelavi predhodnih form iz sive litine s kroglastim grafitom in njihovem oblikovanju do končne oblike bi bila lahko precej učinkovita za relativno preproste oblikovane ulitke, ki morajo izpolnjevati visoke zahteve glede trdnosti in duktilnosti, alleviate the deleterious effects of alloy segregation on ductility [9].

It is more practical that the advantages of ausforming would be taken by forging rather than by rolling. The forging process may be performed on cast preforms, austenitized and quenched to the austempering temperature, inserted into a die, pressed or forged to the final shape, and then returned back into the austempering bath to complete the accelerated transformation. Minimal deformation degrees by conventional forging standards, i.e., an average strain of 25 % would be sufficient for the forming part of the processing sequence. It has been reported [10] that in situations where very severe deformation occurs, the workpiece may not need to be returned to the austempering bath to complete the transformation to ausferrite, as the latter will have been completed by the time the workpiece is extracted from the die.

The idea of creating preforms in ductile iron and then ausforming them to the final shape could be quite effective for relatively simple-shaped castings that must meet high-demanding strength and ductility requirements, e.g., connecting rods for automotive applications. It is understood that certain deviations in design elements of both the preform as well as the die set should be involved compared to the design of the conventional ADI process. The abovementioned concept has been utilized to produce tank track center guides [11] using a finite element simulation technique to match both the preform design and the die design so that a uniform equivalent strain throughout the casting averaged ~20%. No inclination to fracture or cracking has been reported.

npr. ojnice za avtomobilsko industrijo. Razume se, da je treba v primerjavi z načrtovanjem konvencionalnega postopka ADI upoštevati določena odstopanja pri konstrukcijskih elementih tako predhodne forme in kokile. Zgoraj omenjeni koncept je bil uporabljen za izdelavo središčnih vodil za rezervoarje [11] z uporabo tehnike simulacije končnih elementov, ki je ustrezala zasnovi predoblike in zasnovi kokil, tako da je bil enakomeren delež dodatkov v celotnem ulitku v povprečju ~20 %. Nagnjenosti k lomljenju ali razpokam ni bila zaznana.

Termomehanska obdelava sive litine s kroglastim grafitom in ADI

Ta raziskovalni program je potekal v sodelovanju z Inštitutom za metalurgijo Tehnološke univerze Clausthal v Nemčiji v obdobju 2011–2022, rezultati pa so bili objavljeni v različnih mednarodnih revijah in na konferencah [12–22].

V naslednjem kratkem primeru sta bili izvedeni termomehanska obdelava in dilatometrična študija z uporabo termomehanskega simulatorja Baehr Dil 805D (Slika 14), da bi potrdili učinek izpopolnjevanja ausforminga na mikrostrukturo litine ADI.

Za termomehansko obdelavo in dilatometrično študijo je bil uporabljen termomehanski simulator Baehr Dil 805D. Termomehanska simulacija je bila izvedena na valjastih vzorcih s premerom 5 mm in dolžino 10 mm. Na površino vzorcev so bili v osrednjem položaju posamično točkovno privarjeni termočleni tipa S »Pt/Pt-10 % Rh« z nazivnim premerom 0,2 mm. Vzorci so izpostavljeni dvema termomehanskima razporedoma (Slika 15). Pri teh načrtih so bili vzorci segreti na 960 °C in izpostavljeni dvema deformacijskima stopnjama pri 960 °C ter 940 °C. Glavni cilj teh deformacijskih korakov je izboljšati strukturo

Thermomechanical Treatment of Ductile Iron and ADI

This research program has been conducted in collaboration with the Institute of Metallurgy- Clausthal University of Technology-Germany over the time period of 2011-2022, and the results have been published in different international periodicals and conferences [12 - 22].

In the next short discussion, the thermomechanical processing and dilatometric study were performed using a Baehr Dil 805D thermomechanical simulator (Fig. 14) to confirm the refining effect of ausforming on the ADI microstructure.

For thermo-mechanical processing and dilatometric study, a Baehr Dil 805D thermo-mechanical simulator was used. The thermo-mechanical simulation was performed on cylindrical samples of

5 mm diameter and 10 mm length. Sheathed type S “Pt/Pt-10% Rh” thermocouples with a nominal diameter of 0.2 mm were individually spot-welded to the specimens’ surface in a central position. The specimens are subjected to two thermo-mechanical schedules (Fig. 15). In these schedules, the specimens were heated up to 960°C and subjected to two deformation steps at 960°C and 940°C. The main objective of these deformation steps is to refine the structure through work hardening, recovery and recrystallization effects in austenite.

This work highlights transformation kinetics, microstructure evolution and mechanical behavior of thermo-mechanically processed ductile irons. Two types of matrices were produced in the ductile iron, namely ausferritic and ferritic-ausferritic matrices.

Furthermore, the ductile iron is deformed applying a total true strain of 0.3 in the austenite region one time and 0.2 in the austenite region and 0.1 during s postopkom utrjevanja, obnavljanja in rekristalizacije v avstenitu.

To delo poudarja kinetiko preoblikovanja, razvoj mikrostrukture in mehansko obnašanje termomehansko obdelanih sivih litin s kroglastim grafitom. V sivi litini s kroglastim grafitom sta nastali dve vrsti matric, in sicer ausferitna in feritno-ausferitna matrica.

Poleg tega se siva litina s kroglastim grafitom enkrat deformira s skupno pravo deformacijo 0,3 v območju avstenita, drugič z 0,2 v območju avstenita in 0,1 med ustempranjem (ausforming) **(Slika 15).** Tako ausforming kot vnos ferita v matrico pospešita kinetiko pretvorbe ausferita (Slika 16). Postopek ausforminga vpliva na povečanje enakomernosti mikrostrukture in izpopolnjevanje ausferitnih ploščic. Zaradi takšnih mikrostrukturnih sprememb se trdota, trdnost in duktilnost tako oblikovane sive litine s kroglastim grafitom znatno povečajo.

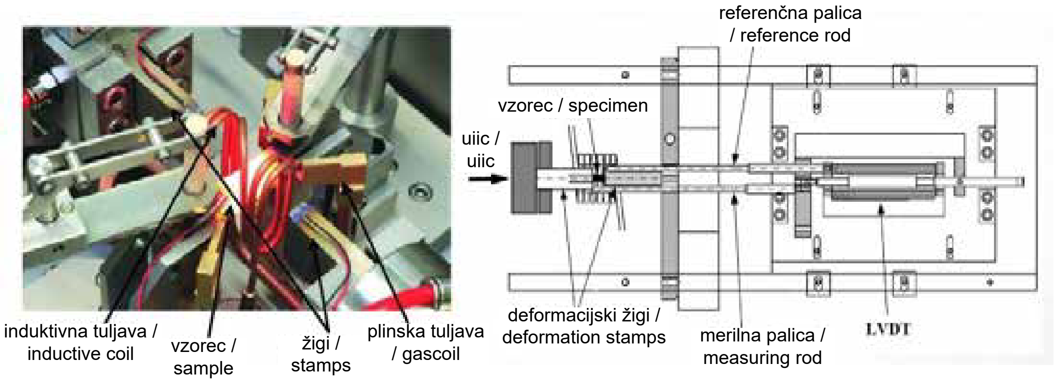
Primerjava morfologije ausformiranega ausferita z neausformiranim pri obeh uporabljenih shemah kaže na vpliv ausformiranja na povečanje mikrostrukturne enotnosti in izboljšanje ausferitnih ploščic (slika 17). Opažena izpopolnitev je

austempering (ausforming) other time (Fig. 15). Both ausforming and ferrite-introduction to the matrix accelerate the ausferrite transformation kinetics (Figure 16). The ausforming process has its impact on enhancing the microstructural uniformity and refining the ausferrite platelets. Such microstructural variations result in a remarkable increase in hardness, strength and ductility of the ausformed ductile iron.

The comparison of the ausformed ausferrite morphology with the non-ausformed one for both of the applied schedules indicate the impact of ausforming on enhancing the microstructural uniformity and refining the ausferrite platelets (Figure 17). The observed refinement is mainly a consequence of the increased nucleation sites of the ausferrite-platelets.

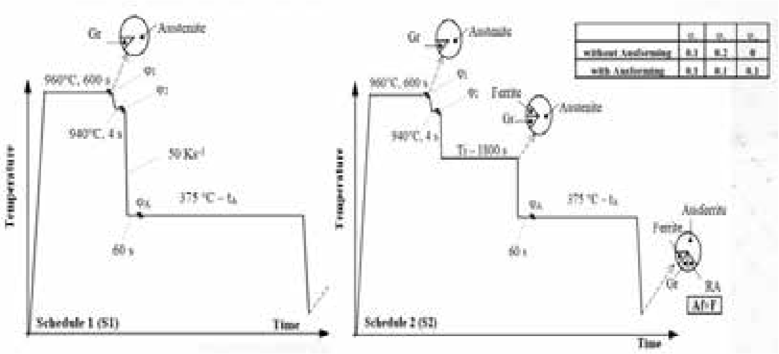
3 Machinability of ADI

When ADI first started to be used for engineering applications, there were many difficulties experienced in trying to machine it, and some of these doubtlessly persist to this day. The hardest grades of ADI reach a hardness of ~ 50 HRC, which would pose a challenge for any high-volume machining



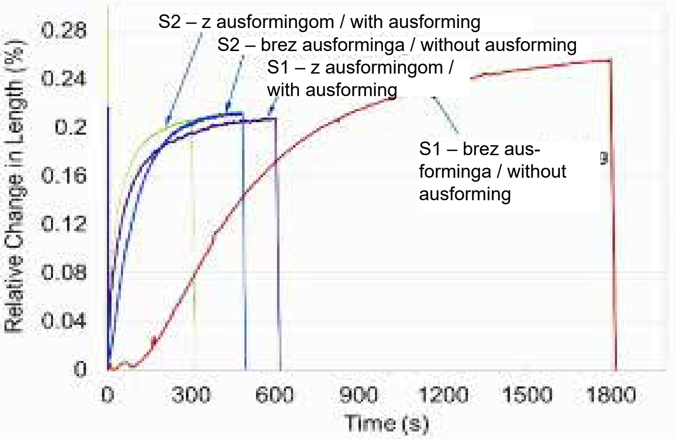
Slika 14. Termomehanski simulator Baehr Dil 805D

Figure 14. Baehr Dil 805D thermomechanical simulator



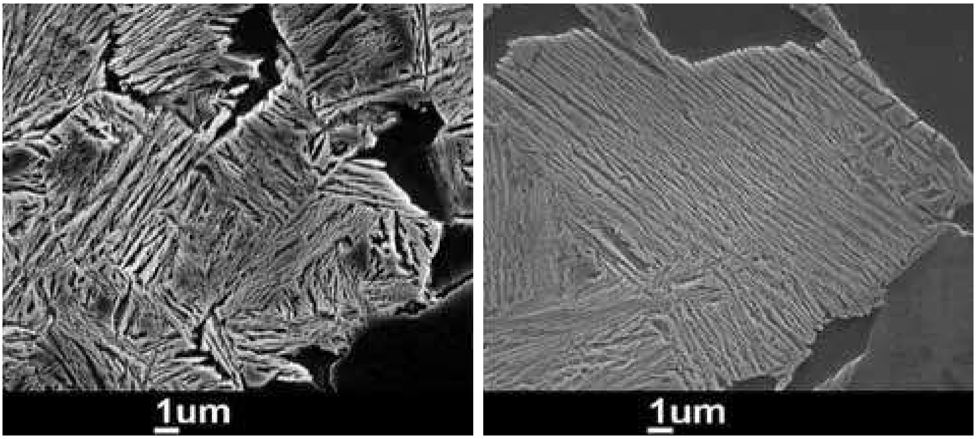
Slika 15. Termomehanski razporedi

Figure 15. The thermomechanical schedules



Slika 16. Vpliv ausforminga na pospešitev ausferitne transformacije

Figure 16. Effect of ausforming on acceleration of the ausferritic transformation



Slika 17. Vpliv ausforminga na strukturno izpopolnjevanje

Figure 17. Effect of ausforming on structural refinement

predvsem posledica povečanega števila mest nukleacije ausferitnih ploščic.

3 Obdelovalnost litine ADI

Ko se je litina ADI prvič začela uporabljati za inženirske aplikacije, so se pojavile številne težave pri njeni strojni obdelavi, in nekatere od njih nedvomno še danes niso odpravljene. Najtrše vrste ADI dosegajo trdoto ~50 HRC, kar bi predstavljalo izziv za vsako obsežno strojno obdelavo. Čeprav imajo mehkejše vrste ADI tipično trdoto 300–350 BHN, njihova matrična struktura vsebuje do 40 % zadržanega avstenita. Ko je ta faza podvržena obremenitvam med obratovanjem, se hitro strdi in se lahko spremeni v martenzit; to lahko zmanjša obdelovalnost v primerjavi z jeklom z enako trdoto.

Sestavni deli iz litine ADI se zdaj uporabljajo v zelo širokem polju uporabe z enako širokim razponom zahtev glede natančnosti in kakovosti površine. Slika 18 povzema možnosti glede vključitve postopkov strojne obdelave v proizvodno pot litine ADI. Na enem koncu lestvice velikega števila sestavnih delov iz litine ADI ni treba strojno obdelati; primeri vključujejo kmetijska orodja in orodja za zemeljska dela. Vendar je treba večino avtomobilskih sestavnih delov strojno obdelati. Večino izdelkov iz mehkejših vrst litine ADI je mogoče strojno obdelovati po toplotni obdelavi z uporabo ustreznih strojnih orodij in vložkov. To je z naraščanjem trdote vedno težje, zato je pogosto bolje, da se jih pred toplotno obdelavo strojno obdela z upoštevanjem povečevanja dimenzij, če je to predvidljivo in če ne pride do večjih deformacij. Če povečevanje dimenzij ni dovolj dosledno, je edina možnost, da se večino strojne obdelave opravi pred austempranjem in se vse kritične dimenzije dokončno obdela po kaljenju. Ta način se operation. Although the softer grades of ADI have a typical hardness of 300–350 BHN, their matrix structure contains up to 40% retained austenite. When subjected to strains in service, this phase rapidly work hardens and can transform to martensite; this can thereby reduce the machinability compared with a steel of equivalent hardness.

ADI components are now used in a very wide range of applications, having an equally wide range of requirements regarding accuracy and surface finish. Fig. 18 summarizes the options regarding the integration of the machining operations into the ADI production route. At one end of the scale, substantial numbers of ADI components do not require to be machined; examples include ground- engaging agricultural and earth-moving tools. However, most automotive components will need to be machined. Most of those made in the softer grades of ADI can be machined after heat treatment using appropriate machine tools and inserts. This becomes progressively more difficult as the hardness increases and it is often preferable to machine before heat treatment by making an allowance for the dimensional growth, assuming that this is predictable and that there is no significant distortion. If the dimensional growth is not sufficiently consistent, the only option is to do most of the machining before austempering, and to finish machining any critical dimensions after austempering. This route has been widely used for ADI gears, which must be extremely accurate for them to operate quietly and have a long life.

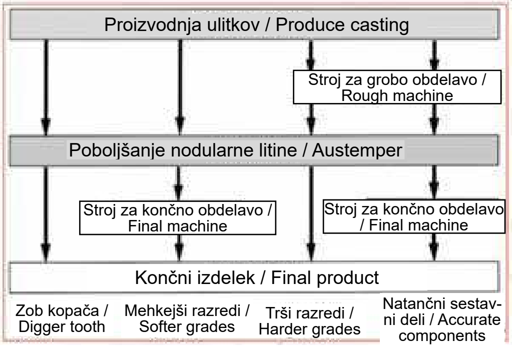
In a recent research at CMRDI [23, 24], the machinability of the different ADI-grades was determined as a function of the cutting force experienced during machining. The effect of different parameters of machining, like cutting speed as well as cutting depth, pogosto uporablja za zobnike iz litine ADI, ki morajo biti zelo natančni za tiho delovanje in dolgo življenjsko dobo.

V nedavni raziskavi na inštitutu CMRDI [23, 24] je bila obdelovalnost različnih razredov litine ADI določena v odvisnosti od rezalne sile med obdelavo. Preučen je bil vpliv različnih parametrov obdelave, kot sta hitrost in globina rezanja, na silo rezanja, ki so bili povezani z deformacijsko inducirano martenzitno pretvorbo iz ohranjenega avstenita med obdelavo. Ugotovljeno je bilo, da ima ohranjena transformacija avstenita v martenzit z učinkom TRIP pomembno vlogo pri določanju rezalne sile in obdelovalnosti vrst litin ADI.

Debelina plasti, utrjene z nastankom martenzita, je odvisna od različnih dejavnikov, med katerimi sta globina in hitrost rezanja, ter od količine in stabilnosti zadržanega avstenita v različnih litinah ADI. Očitno je, da je povečanje rezalne sile vedno povezano z ustreznim povečanjem vsebnosti martenzita pri povečanju globine rezanja od 0,5 do 2,0 mm (Slika 19). Zlitini ADI-375 in ADI-275, ki sta bili podvrženi rezanju globine 2,0 mm, sta imeli enak skupni delež martenzita (ki je vsota prvotne vsebnosti pred strojno obdelavo + martenzit, ki je nastal zaradi deformacijske pretvorbe iz ohranjenega avstenita). Dejstvo, da sta zlitini ADI-375 in ADI-275 pri globini reza 2,0 mm dosegli enako rezalno silo, je dober pokazatelj, da je martenzitna transformacija zaradi induciranih deformacij

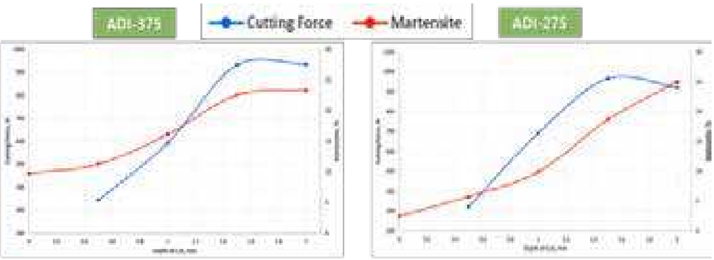
on the force of cutting was investigated and correlated to the strain-induced martensitic transformation from retained austenite during machining. Retained austenite transformation to martensite through the TRIP effect was found to play a profound role in determining the cutting force and machinability behavior of ADI grades.

The thickness of the layer hardened by martensite formation is a function of different factors, among them are the cutting depth and cutting speed, added to the amount and stability of the retained austenite in the different alloys of ADI. It is evident that the increase in cutting force is always associated with a corresponding



Slika 18. Možnosti integracije litja, strojne obdelave in toplotne obdelave komponent iz litine ADI [2]

Figure 18. Options for integrating casting, machining and heat treatment of ADI Components [2]



Slika 19. Rezalna sila kot funkcija deformacije, ki jo povzroči nastanek martenzita med strojno obdelavo vzorcev ADI, kaljenih pri 275 in 375 °C.

Figure 19. The cutting force as a function of deformation-induced martensite formation during machining os ADI specimens austempered at 275 & 375 °C

tesno povezana z možnostjo obdelave zlitin ADI.

4 Ultrafina litina ADI, strjena v ultrazvočnem polju

Ta raziskava je bila nedavno opravljena na inštitutu CMRDI v sodelovanju z inštitutom FTI v Minsku, Belorusija. V tem delu je bila uporabljena ultrazvočna obdelava taline (UST) za proizvodnjo nove ultrafine kakovosti sive litine s kroglastim grafitom (SG) in litino ADI. Shematski prikaz eksperimentalnega sistema je prikazan na Sliki 20. Ultrazvočni sistem z močjo 0,7–1,0 kW in frekvenco 20 kHz je bil uporabljen za obdelavo taline sive litine s kroglastim grafitom (SG), ki se strjuje.

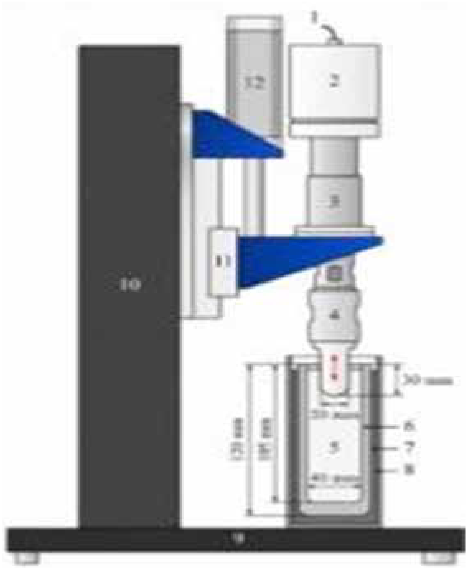
Metalografska analiza novo razvite železove zlitine SG je pokazala ultrafino strukturo grafita. Premer grafitnih krogel je bil od 6 do 19 µm, skupno število krogel pa od 900 do več kot 2000 na mm2 (Slika 21), kar v literaturi za ulitke enakega premera, tj. 40 mm, še ni bilo omenjeno. Poleg tega je bila pri vseh ultrazvočno obdelanih sivih litinah s kroglastim grafitom opažena popolnoma feritna matrica. Nadaljnja toplotna obdelava z austempranjem je bila izvedena za izdelavo različnih vrst poboljšane litine ADI z različnimi ausferitnimi morfologijami. Dilatometrične študije za razvite litine ADI so pokazale, da je bil čas, potreben za dokončanje tvorbe ausferita v ultrazvočno obdelanih litinah, štirikrat krajši od časa, potrebnega za statično strjene sive litine s kroglastim grafitom (Slika 22). mikroposnetki z vrstično elektronsko mikroskopijo za litine ADI so pokazale izjemno fino in kratko ausferitno strukturo skupaj z majhnimi avstenitnimi bloki v matrici (Slika 23). Z delno avstenitizacijsko toplotno obdelavo v interkritičnem temperaturnem območju, kjer soobstajajo faze avstenit + ferit + grafit, je bila izdelana

increase in the martensite content when the cutting depth was increased from 0.5 - 2.0 mm (Figure 19). The ADI-375 and ADI-275 alloys, being subjected to a cutting depth of 2.0 mm had the same total martensite (which is the sum of original content before machining + the martensite formed by deformation induced transformation from the retained austenite). The fact that the two alloys, ADI-375 and ADI-275, reached the same cutting force at 2.0 mm depth of cut gives a good indication that the martensitic transformation due to induced strains is closely related to the machinability behavior of the ADI-alloys.

4 Ultrafine ADI Solidified in Ultrasonic Field

This research was recently carried out at CMRDI in collaboration with the Physico-Technical Institute, Minsk, Belarus. In this work, ultrasonic melt treatment (UST) was used to produce a new ultrafine grade of spheroidal graphite (SG) cast iron as well as ADI. The schematic drawing of the experimental setup is shown in Figure 20. An ultrasonic system with 0.7-1.0 KW power and 20 kHz frequency was used for the treatment of solidifying ductile iron (SG) melt.

The metallographic analysis of the newly developed SG iron alloy showed an extremely ultrafine graphite structure. The graphite nodule’s diameter ranged between 6 to 19 µm with a total nodule count ranging between 900 to more than 2000 nodules per mm2 (Fig. 21), which has never been mentioned in the literature for castings of the same diameter, i.e., 40 mm. In addition, a fully ferritic matrix was observed in all UST SG irons. Further austempering heat treatments were performed to produce different austempered ductile iron (ADI) tudi dvofazna interkritično poboljšana siva litina s kroglastim grafitom (IADI). Pri dvofazni litini IADI je bilo ugotovljeno, da bi vnos prostega ferita v matrico zagotovil dodatno izpopolnitev ausferita [25].



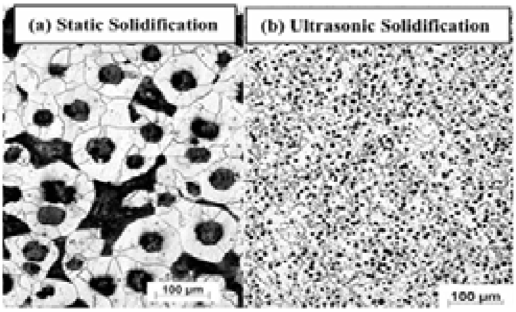
Slika 20. Eksperimentalna postavitev za ultrazvočno obdelavo sive litine s kroglastim grafitom. 1. Kabel za ultrazvočni generator, 2. Pretvornik, 3. Pospeševalnik, 4. Sonotroda, 5. Talina, 6. Grafitno orodje, 7. Polnilo, 8. Posodica, 9. Stojalo za podstavek, 10. Nosilec, 11. Mehanizem za odmik, 12. Pnevmatski cilinder.

Figure 20. The experimental setup for the ultrasonic treatment of SG iron. 1. Cable to ultrasonic generator, 2. Transducer, 3. Booster, 4. Sonotrode, 5. Molten metal, 6. Graphite mold, 7. Filling, 8. Cup, 9. Base stand, 10. Mount, 11. Displacement mechanism, 12. Pneumatic cylinder.

Očitno je, da bi 75-odstotno skrajšanje cikla toplotne obdelave litine ADI povzročilo znatno zmanjšanje proizvodnih stroškov, kar bi se zagotovo odrazilo v nadaljnjem povečanju konkurenčne prednosti materiala ADI.

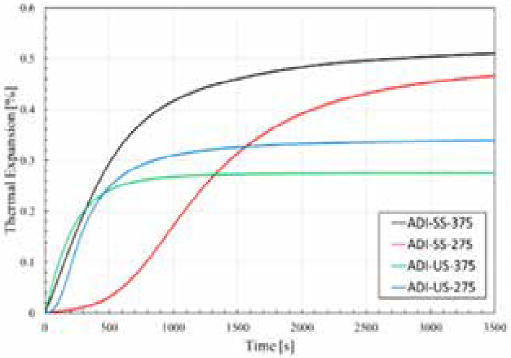
grades with different ausferrite morphologies. The dilatometry studies for the developed ADI alloys showed that the time required for the completion of the ausferrite formation in UST alloys was four times shorter than that required for statically solidified SG irons (Figure 22). SEM micrographs for the ADI alloys showed an extremely fine and short ausferrite structure together with small austenite blocks in the matrix (Figure 23). A dual-phase intercritically austempered ductile iron (IADI) alloy was also produced by applying partial austenitization heat treatment in the intercritical temperature range, where austenite + ferrite + graphite phases coexist. In a dual-phase IADI alloy, it was established that introducing free ferrite in the matrix would provide additional refinement for the ausferrite [25].

It is obvious that 75% shortening of the heat treatment cycle of ADI would result in a considerable reduction of production cost, which will certainly reflect on a further increase in the competitive edge of ADI material.



Slika 21. Mikrostruktura, pridobljena iz sive litine s kroglastim grafitom, (a) statično stanje in (b) stanje UST

Figure 21. Microstructure obtained from the SG iron, (a) static condition and (b) UST condition

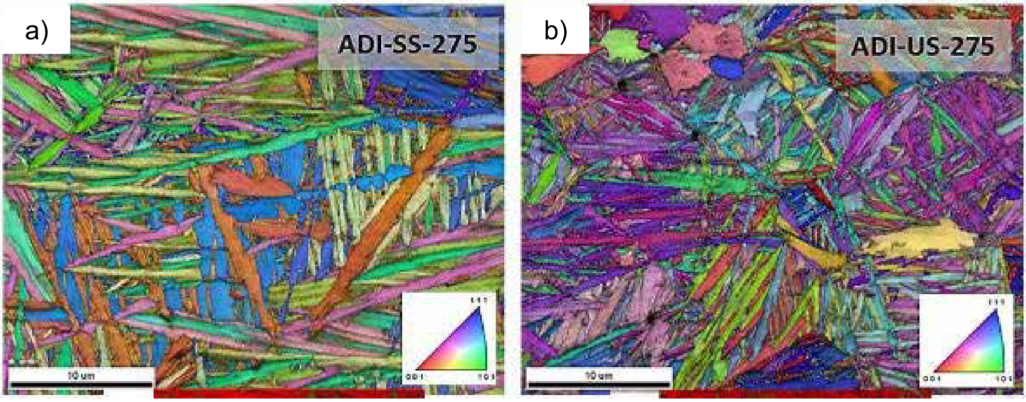


Slika 22. Dilatometrična krivulja različnih preiskovanih vzorcev, kaljenih pri 275 °C in 375 °C, SS: vzorec za konvencionalno strjevanje, US: vzorci, obdelani z ultrazvokom

Figure 22. The dilatometry curve of the different investigated samples austempered at 275°C and 375 °C, SS: conventional solidification sample, US: ultrasonically treated samples

Slika 23. Izboljšanje ausferitne matrice po ultrazvočni obdelavi

Figure 23. Refinement of ausferritic matrix after ultrasonic treatment



References:

1. A. Nofal, “Advances in the Metallurgy and Applications of ADI”, Journal of Metallurgical Engineering, 2013.
2. R. A., Harding, “The Production, Properties and Automotive Applications for Austempered Ductile Iron”, Asia-Europe Environment Forum Conference, Jakarta, Indonesia, 23-31 Nov., 2005.
3. J.R. Keough, K.I. Hayrynen, “Automotive Applications of Austempered Ductile Iron (ADI)”, A Critical review in: Design and Archiving LightWeight Vehicles (SP-1684), SEA Technical Report 200-1-0764.
4. A. Nofal, H. Nasr El-din, M. Ibrahim, and A. Ramadan, “Cold Rolling of Austempered Ductile Cast Iron”, Journal of Materials Science and Technology, Vol. 11, No. 2, pp. 86-96, 2003.
5. K.M. Ibrahim, H. Nasr El-din, A.A. Nofal and M. Ibrahim, “Wear Resistance of Cold Rolled ADI, Steel Grips”, Vol., No. 3, 278-283; 2003.

6. H.N. El-Din, A.A. Nofal, A. Ramadan and M. Ibrahim, “Structure Characteristics and Mechanical Properties of Cold-Rolled Austempered Ductile Iron Alloyed with Nickel”, Canadian Metallurgical Quarterly, vol. 43, No. 2, pp. 203-218, April 2004.
7. H. N. El-Din, A.A. Nofal, M.M. Ibrahim and A.A. Ramadan, “Ausforming of Austempered Ductile Iron Alloyed with Nickel”, The International J. of Cast Metals Research, Vol. 19, No. 3, pp. 137-150, 2006.
8. A.A. Nofal, H.N. El-Din and M.M. Ibrahim, “Thermomechanical Treatment of ADI”, Proceedings of the 8th Symposium on Science and Processing of Cast Iron SPCI-8, Beijing, China, pp. 397-402, Oct. 16-19, 2006.
9. Nofal, A.A., “Austempered Ductile Iron (ADI) – The Dynamic Benchmark Material and its New Applications”, Plenary Session of the 60th International Foundry Conference, Bengaluru, India, 2012.
10. Olson, B.N., Moore, D.J., Rundmanb, K.B. and Simula, G.R., “Potential for Practical Applications of Ausforming Austempered Ductile Iron”, AFS Trans., vol. 110, 02-118, pp. 965-980, 2002.
11. Lei, X and Lissenden, C.J., “Finite Element Simulation of Ausforming of Austempered Ductile Iron Components”, Trans. of the ASME, vol. 12, pp. 420-425, 2001.
12. M. Soliman, H. Palkowski, and A. Nofal, “Thermo-Mechanically Processed Multi-Phase Ductile Iron, Microstructure Development”, Key Engineering Materials, 457, pp. 199-204, 2011.
13. M. Soliman, H. Palkowski, A. Nofal, “Effect of Aluminum Content on Phase Transformation and Mechanical Properties of Dual Matrix, Thermo-Mechanically Processed Austempered Ductile Iron”, 70th World Foundry Congress, Monterrey, Mexico, April 2012.
14. M. Soliman, H. Palkowski and A. Nofal, “Effect of Silicon Content in Dual-Matrix Austempered Ductile Iron on Structure Development and Mechanical Properties”, OMD, Moscow, 14-17 April, 2014.
15. M. Soliman, H. Ibrahim, A. Nofal, and H. Palkowski, “Effect of Thermo-Mechanical Processing Parameters on Phase Transformation and Hardness of Dual Matrix Ductile Iron”, SPCI10, Mar del Plata, Argentina, 10-13 Nov., 2014.
16. M. Soliman, H. Ibrahim, A. Nofal, and H. Palkowski, “Effect of Intercritical Annealing on Phase Transformation and Mechanical Properties of Thermo-Mechanically Processed Dual Matrix Ductile Iron”, The Minerals, Metals & Materials Society supplementary proceeding (TMS-2014), 2014.
17. M. Soliman, H. Ibrahim, A. Nofal, and H. Palkowski, “Effect of Thermomechanical Processing Parameters on Phase Transformation and Hardness of Dual Matrix Ductile Iron”, International Journal of Cast Metals Research, Advance article, 2015.
18. M. Soliman, H. Ibrahim, A. Nofal, and H. Palkowski, “Thermo-Mechanically Processed Dual Matrix Ductile Iron Produced by Continuous Cooling Transformation”, Journal of Materials Processing Technology, Vol. 227, PP. 1:10, 2016.
19. Soliman, M., Palkowski, H., & Nofal, A., “Multiphase Ausformed (?) Austempered Ductile Iron. Archives of Metallurgy and Materials”, 62(3), pp. 1493-1498, 2017.
20. Soliman, M., Nofal, A., & Palkowski, H., “Effect of Hot Working Parameters on Microstructure Evolution and Mechanical Properties of Ausformed (?) Austempered Ductile Iron”, In Materials Science Forum (Vol. 925, pp. 218-223). Trans Tech Publications Ltd. 2018.

21. Soliman, M., Nofal, A., & Palkowski, H., “Effect of Thermo-Mechanical Processing on Structure and Properties of Dual-Phase Matrix ADI with Different Si-Contents”, International Journal of Metalcasting, 14, 853-860. 2020.
22. A Nofal, M Soliman, M Ahmed, H Palkowski, A Volochko, V Rubanik, “Ultrafine Structured Austempered Ductile Iron (ADI)”, АКТУАЛЬНЫЕ ПРОБЛЕМЫ ПРОЧНОСТИ, 400-402, 2022.
23. M. Ahmed, A. Nofal, M. Waly and A. Hussein, “Influence of Strain Induced Martensitic Transformation on The Machinability of Different Grades of ADI”, SPCI XI, 3-7 Sept., 2017.
24. Hussein, M., Ahmed, M., Soliman, M., Mohamed, L. Z., Palkowski, H., Rashad, R. M., & Nofal, A., “Influence of Austenite Stability on the Machinability of Different Grades of Austempered Ductile Iron (ADI) During Dry Turning Machining”, International Journal of Metalcasting, pp. 1-15, 2023.
25. Ahmed, M., Riedel, E., Kovalko, M., Volochko, A., Bähr, R., & Nofal, A., “Ultrafine Ductile and Austempered Ductile Irons by Solidification in Ultrasonic Field”, International Journal of Metalcasting, pp. 1-15, 2021.