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Primerjava udarne in lomne žilavosti sive litine s kroglastim grafitom in feritnega jekla

Comparison of Impact and Fracture Toughness of Ductile Iron and Ferritic Steel

Povzetek

Namen raziskave je bil določitev lomne in udarne žilavosti sive litine s kroglastim grafitom EN-GJS-400-18LT in njena primerjava z valjanim konstrukcijskim jeklom S235JR+AR pri sobni temperaturi, 0 °C, -20 °C in -40 °C. Prav tako je bil cilj določiti temperaturni interval prehoda iz duktilnega v krhek lom ter analizirati lomno obnašanje obeh zlitin.

V ta namen smo za obe zlitini izvedli preizkuse lomne žilavosti s tri-točkovnim upogibnim preizkusom in preizkuse udarne žilavosti po Charpyu pri prej omenjenih temperaturah. Izvedli smo tudi metalografsko analizo, analizo prelomnih površin na makroskopskem nivoju ter na določenih vzorcih tudi mikrofraktografijo z uporabo vrstičnega elektronskega mikroskopa (SEM).

Izkazalo se je, da je udarna žilavost jekla S235JR+AR pri sobni temperaturi bistveno večja kot udarna žilavost zlitine EN-GJS400-18LT, a z nižanjem temperature drastično pade, tako da pri -40 °C obe zlitini izkazujeta enako vrednost udarne žilavosti. Lomna žilavost zlitine EN-GJS-400-18LT je pri vseh temperaturah večja od lomne žilavosti jekla S235JR+AR in s padcem temperature celo nekoliko naraste.

Abstract

The aim of the study was to determine the fracture and impact toughness of ductile iron EN-GJS-400-18LT and to compare it with the hot-rolled structural steel S235JR+AR at room temperature, 0°C, -20°C and -40°C. Another objective was to determine the temperature interval of the transition from ductile to brittle fracture and to analyse the fracture behaviour of both alloys.

To this end, fracture toughness testing was carried out using a three-point bending test and Charpy impact toughness tests at the abovementioned temperatures for both alloys. Metallographic examination, macroscopic analysis of fracture surfaces and microfractography using a scanning electron microscope (SEM) were also carried out on certain samples.

The impact toughness of S235JR+AR at room temperature is shown to be significantly higher than that of EN-GJS400-18LT, however, drops markedly as the temperature is lowered, so that at -40°C, both alloys exhibit the same impact toughness value. The fracture toughness of EN-GJS-400-18LT is higher than that of S235JR+AR at all temperatures and even increases slightly with temperature.

1 Uvod

Železove litine srečujemo na vsakem koraku, saj so najpogosteje uporabljene zlitine na svetu. Poleg jekla, ki ima zelo široko uporabnost zaradi odličnih lastnosti, se veliko uporabljajo tudi sive litine. Od slednjih je še posebej uporabna siva litina s kroglastim grafitom. V primerjavi z jeklom ima boljšo livnost, drsne lastnosti, manjšo gostoto, postopek izdelave pa je enostaven in cenovno ugodnejši. [1] Za sive litine s kroglastim grafitom je značilna majhna udarna žilavost, ki je pri jeklu znatno večja. Žilavost se določa z udarnim preizkusom po Charpyu, ki je bil pred stotimi leti razvit za preizkušanje udarne žilavosti in za določanje temperature prehoda iz duktilnega v krhek lom. [2] Enak postopek se danes uporablja za vrsto materialov, med drugim tudi za sivo litino s kroglastim grafitom, čeprav gre za drugačno vrsto materiala. Mikrostruktura jekla je v veliko primerih feritno-perlitna, kar velja tudi za sivo litino s kroglastim grafitom, a ima le-ta med feritom in perlitom v matrici še ogljik, strjen v obliki grafitnih krogel. Tako imamo opravka s kompozitno zgradbo. Številni raziskovalci so mnenja, da siva litina vendarle nima tako nizke žilavosti, ampak je težava v preizkusu Charpy, ki ni primeren za določanje splošne žilavosti vsakega materiala pod istimi pogoji. Predlagajo določanje žilavosti s tri-točkovnim upogibnim preizkusom, pri katerem kot rezultat dobimo vrednosti J-integrala, faktor odpiranja vrha razpoke – CTOD ter lomno žilavost. Postopek temelji na eksperimentalno primerljivih situacijah situacije, saj se na preizkušancu najprej naredi ostra utrujenostna razpoka, obremenitev pa je kvazistatična in ne dinamična ter točkovno usmerjena z visoko hitrostjo, kot je to pri preizkusu Charpy. [3, 4]

1 Introduction

Cast iron is found all around us as it is the most commonly used alloy in the world. In addition to steel, which has a very wide range of applications due to its excellent properties, grey cast iron is also widely used. A particularly useful grey cast iron is ductile iron. Compared to steel, it has better casting and sliding properties, lower density, and is easier and cheaper to manufacture. [1] Ductile iron is characterised by low impact toughness, which is significantly higher in steel. The toughness is determined by the Charpy impact test, which was developed a hundred years ago to test impact toughness and to determine the temperature of transition from ductile to brittle fracture. [2] The same procedure is still in use today for a range of materials, including ductile iron, even though the material is completely different. In many cases, steel has ferrite-perlite microstructure, which is also true for ductile iron, with the different that it contains carbon in the matrix between the ferrite and perlite, solidified in the form of graphite nodules. So, what we are dealing with is a composite structure. Many researchers believe that the toughness of ductile iron is not as low and instead the problem lies with the Charpy test, which is not suitable for determining the overall toughness of any material under the same conditions. They propose to determine the toughness by means of a three-point bending test, which yields J-integral values, crack tip opening displacement (CTOD) and fracture toughness. The procedure is focused on simulating experimentally comparable conditions, as the specimen is first subjected to a sharp fatigue crack and the loading is quasistatic rather than dynamic and point-based at high speed, as is the case with the Charpy test. [3, 4]

2 Eksperimentalno delo

Jeklo S235JR+AR je bilo pridobljeno s strani zunanjega proizvajalca v obliki 25 mm debele valjane plošče. Zlitino EN-GJS-400-18LT smo pripravili v Kovis Livarni v 10-tonski indukcijski peči. Po doseženi načrtovani bazni kemijski sestavi in ustrezni temperaturi se je talina prelila v 2-tonsko ponvico, kjer je potekla reakcija z magnezijem po postopku »sandwich«. Sledilo je prelivanje v livno ponvico, dodano je bilo še cepivo na osnovi barija, sledil je transport na livni voz ter litje Y-prob tipa II v enkratne forme iz bentonitne peščene mešanice. Pri litju je potekalo še cepljenje v curek z dodatkom cerija.

Iz plošče S235JR+AR in ulitkov Y-prob zlitine EN-GJS-400-18LT smo s pomočjo tračne žage izrezali vzorce za preizkus lomne žilavosti (preizkušanci SENB), preizkus udarne žilavosti po Charpyu (preizkušanci CVN) ter vzorce za metalografsko analizo. Končne dimenzije vzorcev smo zagotovili z uporabo žične erozije, ustrezno hrapavost površine pa s ploskovnim brusilnim strojem.

2.1 Preizkus lomne žilavosti

Preizkuse lomne žilavosti smo opravili pri štirih različnih temperaturah, in sicer pri sobni temperaturi, 0 °C, -20 °C ter -40 °C. Pri vsaki temperaturi smo naredili preizkus na treh vzorcih sive litine in na enem vzorcu jekla. Preizkus lomne žilavosti je potekal v skladu s standardom ASTM E1820. [5] Vsi vzorci so bili najprej ciklično upogibno utrujani s ciljem, da iz mehansko narejene zareze nastane ostra utrujenostna razpoka. Med utrujanjem se je s pomočjo kamere nenehno nadzorovalo napredovanje razpoke. Ko je bila razpoka primerne dolžine, se je utrujanje končalo. Skupna dolžina

2 Experimental Work

S235JR+AR was obtained from an external producer in the form of 25 mm thick hot-rolled plate. EN-GJS-400-18LT was prepared at Kovis Livarna in a 10-tonne induction furnace. Once the planned base chemical composition and temperature were achieved, the melt was transferred to a 2-tonne pan where it reacted with magnesium in the „sandwich" process. This was followed by pouring into a ladle, with the addition of a barium-based inoculant. Next, it was transported to the casting carriage and the casting of type II Y-blocks into single-use sand mix moulds. The casting process also involved pouring stream inoculation with the addition of cerium.

Specimens for fracture toughness testing (SENB specimens), Charpy impact toughness testing (CVN specimens) and metallographic examination were cut from S235JR+AR and EN-GJS-400-18LT Y-block castings using a band saw. The final dimensions of the samples were achieved using wire erosion while the corresponding surface roughness was achieved using a surface grinder.

2.1 Fracture Toughness Test

The fracture toughness tests were carried out at four different temperatures, i.e. room temperature, 0°C, -20°C and -40°C. At each temperature, three samples of ductile iron and one sample of steel were tested. The fracture toughness test was conducted in line with ASTM E1820. [5] All specimens were first subjected to cyclic bending fatigue testing with the aim of producing a sharp fatigue crack from the mechanically created notch. During fatigue testing, the crack propagation was continuously monitored using a camera. When the začetne mehansko narejene razpoke in utrujenostne razpoke mora biti med 0,45 W in 0,70 W, kjer je W širina vzorca. Ko so bili vsi vzorci utrujani, je sledil preizkus lomne žilavosti. Preizkus lomne žilavosti poteka tako, da vzorec SENB z razpoko na spodnji strani namestimo v stroj na valja na razdaljo, predpisano v omenjenem standardu. Na utor na preizkušancu smo namestili tipalo, ki zaznava premik oziroma odpiranje ustja razpoke (CMOD) pri obremenjevanju. Preizkušanec je nato upogibno statično obremenjen z naraščajočo silo. Računalnik tako beleži odpiranje ustja razpoke (CMOD) v odvisnosti od sile (F). Ko računalnik zazna, da prihaja do nestabilnega širjenja razpoke (sila začne padati, razpoka pa se širi) oziroma bi prišlo do zloma, se preizkus ustavi. Slika 1 prikazuje nameščen vzorec pred začetkom preizkušanja lomne žilavosti, na spodnji strani vzorca je v utor nameščeno tipalo za zaznavanje pomika, ki je povezano z računalnikom.

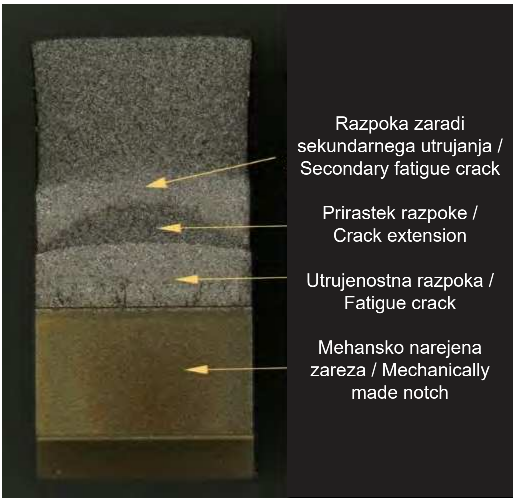
Slika 1. Merjenje lomne žilavosti s tri-točkovnim upogibnim preizkušancem (SENB).

Figure 1. Measurement of fracture toughness with a three-point bending tester (SENB).

crack was of sufficient length, the fatigue testing was concluded. The total length of the initial mechanically created crack and the fatigue crack must be between 0.45 W and 0.70 W, where W is the sample width. Once all the samples were fatigue tested, fracture toughness testing was carried out. The test is conducted by placing the SENB sample with a crack on the underside inside the machine onto beams at the distance specified in the aforementioned standard. A sensor was placed in the test piece groove in order to detect the movement or crack mouth opening displacement (CMOD) during loading. The specimen is then subjected to a static bending load with increasing force. The computer records the crack mouth opening displacement (CMOD) as a function of force (F). When the computer detects the unsteady propagation of the crack (the force begins to reduce and the crack is propagating) or an imminent fracture, the test is stopped. Figure 1 shows the mounted specimen before the start of fracture toughness testing, with a displacement sensor connected to a computer inside the groove on the bottom of the specimen.

After fracture toughness testing was completed, cyclic fatigue testing was again undertaken, this time with reduced force until the failure of the specimen. The purpose of such fatigue testing is to distinguish on the surface of the specimen after fracture the area of the crack that formed during the first fatigue test, the area of actual stable crack growth during the fracture toughness test (crack increment) and the area of the last fatigue before fracture. The latter is needed to measure the crack increment as accurately as possible, which is required to calculate the J-integral, CTOD and fracture toughness. Figure 2 shows a snapshot of the fracture surface of one of the EN-GJS-400-18LT samples.

Po končanih preizkusih lomne žilavosti je bilo spet na vrsti ciklično utrujanje, tokrat z manjšo silo, dokler ni prišlo do zloma preizkušanca. Namen tega utrujanja je, da se na površini vzorca po lomu loči področje razpoke, ki je nastalo med prvim utrujanjem, področje dejanske stabilne rasti razpoke med preizkusom lomne žilavosti (prirastek razpoke) in področje zadnjega utrujanja pred zlomom. Slednje je potrebno, da lahko čim natančneje izmerimo prirastek razpoke, ki je nujen za izračun J-integrala, CTOD in lomne žilavosti. Na Sliki 2 je prikazan posnetek prelomne površine enega izmed vzorcev iz zlitine EN-GJS-400-18LT.



Slika 2. Prelomna površina SENB vzorca iz zlitine EN-GJS-400-18LT.

Figure 2. Fracture surface of SENB sample made of EN-GJS-400-18LT.

2.2 Preizkus udarne žilavosti

Preizkus udarne žilavosti je potekal po standardu SIST EN 1563. [6] Preizkusi so prav tako potekali pri temperaturah -40 °C, -20 °C, 0 °C ter pri sobni temperaturi. Pri vsaki temperaturi smo naredili preizkus udarne žilavosti na treh vzorcih zlitine EN-GJS-400-18LT in treh vzorcih jekla S235JR+AR. Iz rezultatov smo izračunali povprečje za vsak material pri vsaki temperaturi ter naredili analizo rezultatov ter primerjavo z rezultati lomne žilavosti.

2.3 Metalografska analiza

Vzorci za analizo mikrostrukturnih sestavin so se pripravili po običajnem postopku priprave metalografskih vzorcev. Jedkanje je potekalo z 2-odstotnim NITAL-om za boljše razkritje mikrostrukturnih sestavin pod svetlobnim mikroskopom. Za opazovanje vzorcev smo uporabili svetlobni mikroskop Olympus BX61. S programsko opremo Ansys 5.0 smo določili tudi obliko, porazdelitev in velikost grafitnih krogel v skladu s standardom EN ISO 945-1.

2.2 Impact Toughness Test

The impact toughness test was carried out in line with SIST EN 1563. [6] Similarly, the testing was again carried out at temperatures of -40°C, -20°C, 0°C and at room temperature. At each temperature, impact toughness tests were completed on three EN-GJS-400-18LT samples and three S235JR+AR samples. The results were averaged for each material at every temperature and analysed and compared with the fracture toughness results.

2.3 Metallographic Analysis

The samples for the analysis of microstructural elements were prepared according to the standard metallographic sample preparation procedure. The etching was performed using 2% NITAL to better reveal the microstructural elements under

[7] Za mikrofraktografijo smo uporabili vrstični elektronski mikroskop na poljsko emisijo (FEG SEM) proizvajalca Thermo Scientific, model Quattro S. Celotna analiza mikrostrukture je potekala na Naravoslovnotehniški fakulteti Univerze v Ljubljani.

3 Rezultati in diskusija

3.1 Kemijska sestava in mehanske lastnosti

Kemijska sestava obeh zlitin je prikazana v Preglednici 1. Večja razlika med zlitinama je v deležu ogljika in silicija.

Preglednica 2 prikazuje mehanske lastnosti obeh zlitin. natezna trdnost in meja tečenja je pri jeklu S235JR+AR večja za 45 MPa oziroma 25 MPa, raztezek pa kar za 15 %.

3.2 Mikrostruktura

Na Sliki 3 je prikazana mikrostruktura zlitine EN-GJS-400-18LT. Grafitne krogle so dokaj sorazmerno razporejene, večinoma v najmanjših velikostnih razredih, njihovo povprečno število na kvadratni milimeter pa znaša 166. Delež ferita in perlita v matrici znaša 89 % oziroma 11 %.

Mikrostruktura jekla S235JR+AR na Sliki 4 je prav tako sestavljena iz 89 % ferita in 11 % perlita. Zrna so v smeri valjanja nekoliko podolgovata, opazna je rahla trakavost.

an optical microscope. An Olympus BX61 optical microscope was used for sample examination. Ansys 5.0 software was also used to determine the shape, distribution and size of graphite nodules in line with EN ISO 945-1.[7] For microfractography, the Thermo Scientific field emission gun scanning electron microscope (FEG SEM), Quattro S model, was used. The complete microstructure analysis was carried out at the Faculty of Natural Sciences and Engineering, University of Ljubljana.

3. Results and Discussion

3.1 Chemical Composition and Mechanical Properties

The chemical composition of the two alloys is shown in Table 1. The major difference between the alloys is in carbon and silicon proportions.

Table 2 shows the mechanical properties of the two alloys. The tensile strength and yield strength of S235JR+AR are higher by 45MPa and 25MPa, respectively, and elongation by 15%.

3.2 Microstructure

The microstructure of EN-GJS-400-18LT is shown in Figure 3. Graphite nodules are distributed fairly evenly, mostly in the smallest size classes, with an average number of 166 per square millimetre. The

Preglednica 1. Kemijska sestava zlitine EN-GJS-400-18LT in jekla S235JR+AR.

Table 1. Chemical composition of EN-GJS-400-18LT and S235JR+AR.

ZLITINA	CE	C	Si	Mn	P	S	Cr	Cu	Mg	Ni	Fe
EN-GJS-400-18LT	4,22	3,44*	2,33	0,17	0,019	0,01	0,04	0,05	0,04	0,02	Rest
S235JR+AR	-	0,12	0,17	0,57	0,034	0,02	0,2	0,54	0,00	0,16	Rest

Preglednica 2. Mehanske lastnosti zlitine EN-GJS-400-18LT in jekla S235JR+AR.

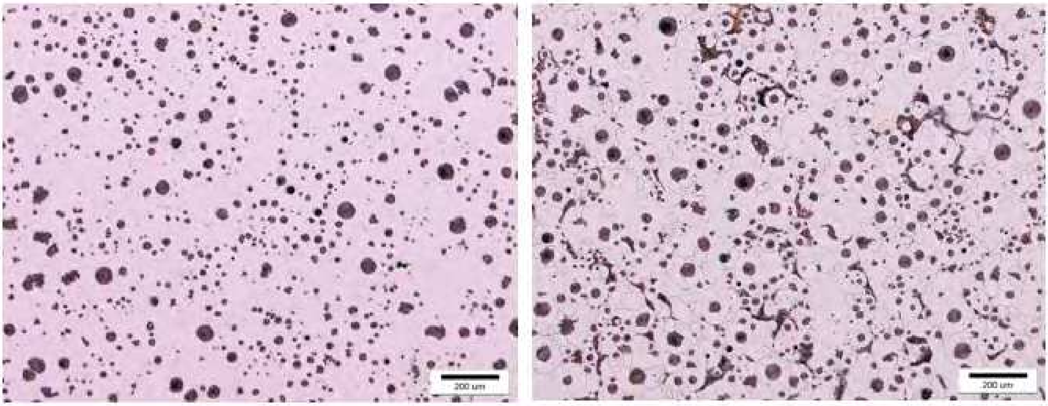
Table 2. Mechanical properties of EN-GJS-400-18LT and S235JR+AR.

ZLITINA	Rm [MPa]	$R_{p0,2}$ [MPa]	A [%]
EN-GJS-400-18LT	413	269	19,4
S235JR+AR	457	294	34,4

proportion of ferrite and pearlite in the matrix is 89% and 11%, respectively.

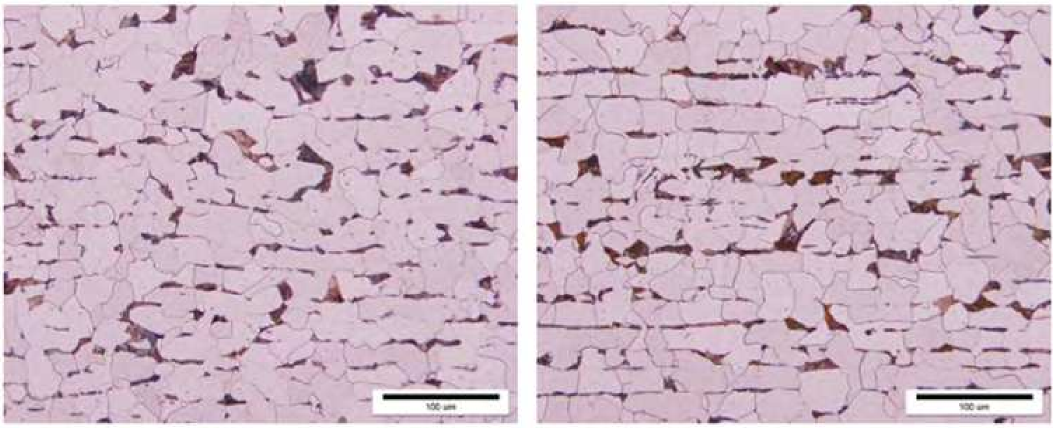
Figure 3: Microstructure of EN-GJS-400-18LT: a) In polished, unetched condition, b) After etching

The microstructure of S235JR+AR, shown in Figure 4, is also composed of 89% ferrite and 11% pearlite. The grains are slightly elongated in the rolling direction and slight banding can be observed.



Slika 3. Mikrostruktura jekla S235JR+AR: a) prečno na smer valjanja, b) v smeri valjanja.

Figure 3. Microstructure of S235JR+AR: a) Transverse to the rolling direction, b) In the rolling direction.



Slika 4. Lomna žilavost zlitine EN-GJS-400-18LT v odvisnosti od temperature.

Figure 4. Fracture toughness of EN-GJS-400-18LT as a function of temperature.

3.3 Lomna žilavost

Lomna žilavost zlitine EN-GJS-400-18LT je prikazana na Sliki 5. Na sobni temperaturi znaša približno 70 MPa na koren metra in s padcem temperature naraste kar na 86 pri -40 °C.

Pri jeklu S235 je lomna žilavost v povprečju manjša za prib. 60 % in na sobni temperaturi znaša okoli 30 MPa na koren metra. S padcem temperature je bolj ali manj konstantna in prav tako nekoliko naraste, kot je razvidno iz Slike 6.

3.3 Fracture Toughness

The fracture toughness of EN-GJS-400-18LT is shown in Figure 5. At room temperature, it measures about 70MPa·$m^{-1/2}$, increasing to as much as 86 as the temperature drops to -40 °C.

S235 has an average reduction in fracture toughness of under 60%, and at room temperature it was measured at about 30MPa·$m^{-1/2}$. As the temperature drops, it is more or less constant and even increases slightly, as can be seen in Figure 6.

3.4 Udarna žilavost

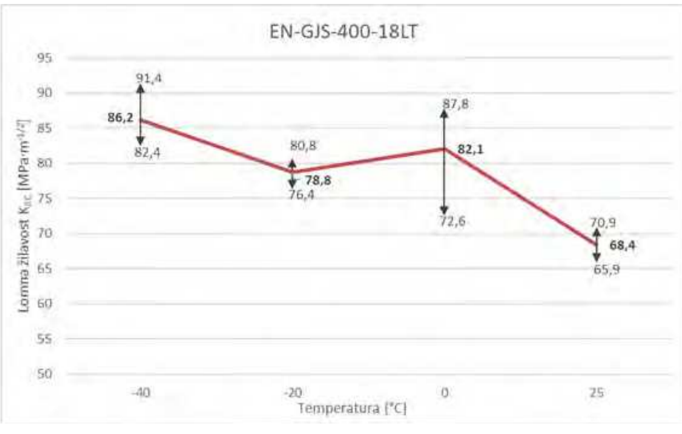
Udarna žilavost pa prikazuje popolnoma drugačno sliko. Pri zlitini EN-GJS-400-18LT je izjemno nizka že pri sobni temperaturi in nekoliko pade s 15,7 J na 12,2 J pri -40 °C, kar je prikazano na Sliki 7.

Jeklo S235 ima zelo veliko udarno žilavost pri sobni temperaturi, in sicer kar 141,5 J, a ta strmo pade z nižanjem temperature na samo 13,7 J pri -40 °C, kar je primerljivo z sivo litino. Pri 0 °C in -20 °C je prisoten velik raztros meritev, kar je

3.4 Impact Toughness

Impact toughness, however, paints a completely different picture. In the case of EN-GJS-400-18LT, it is already extremely low at room temperature, dropping even lower from 15.7J to 12.2J at -40°C, as shown in Figure 7.

At room temperature, S235 has a very high impact toughness of 141.5 J. However, as the temperature drops, it is reduced sharply to only 13.7 J at -40 °C, comparable to ductile iron. At 0°C and -20°C, the



Slika 5. Lomna žilavost jekla S235JR+AR v odvisnosti od temperature.

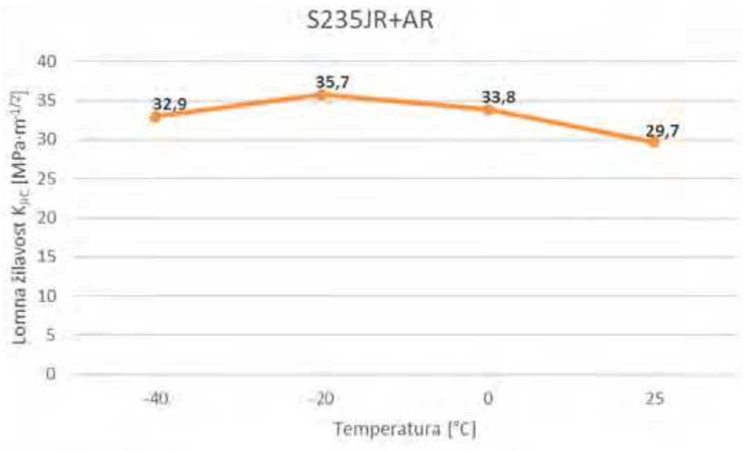
Figure 5. Fracture toughness of S235JR+AR as a function of temperature.

pokazatelj, da gre za prehodno območje med duktilnim in krhkim lomom.

Na Sliki 9 vidimo, da se pri lomu okoli grafitnih krogel pri sobni temperaturi izoblikujejo jamice. Vidijo se tudi vdolbine, iz katerih so bile izpuljene grafitne krogle, in nekaj grafitnih krogel, ki so ostale v vdolbinah. Feritna matrica okoli krogel se deformira, saj so vdolbine večje kot grafitne krogle v njih. Prelom ima duktilen značaj.

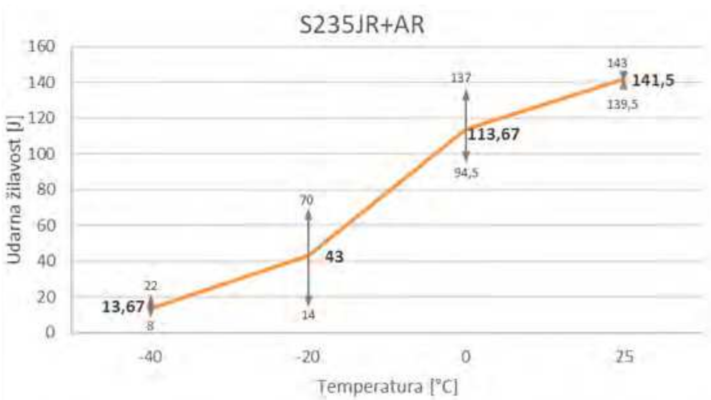
measurements are severely scattered, indicating a transition zone between ductile and brittle fracture.

In Figure 9, we can see that, in case of fracture around graphite nodules, voids are formed. Recesses are also visible from which the graphite nodules were ripped as well as some graphite nodules remaining in the recesses. The ferrite matrix around the graphite nodules deforms as the recesses



Slika 6. Udarna žilavost zlitine EN-GJS-400-18LT v odvisnosti od temperature.

Figure 6. Impact toughness of EN-GJS-400-18LT as a function of temperature.



Slika 7. Udarna žilavost jekla S235JR+AR v odvisnosti od temperature.

Figure 7. Impact toughness of S235JR+AR as a function of temperature.

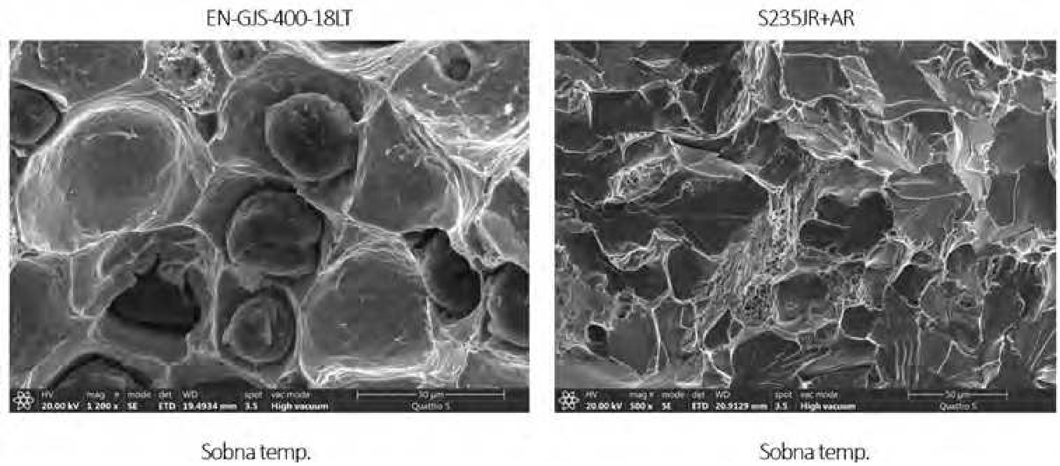
Pri jeklu so pri sobni temperaturi vidna področja duktilnega loma z značilnimi jamicami (duktilni prelom s koalescenco jamic) ter področja krhkega preloma z značilnimi gladkimi ploskvami, stopnicami in porečji (transkristalni cepilni prelom).

Pri -40 °C okoli grafitnih krogel ni znatne plastične deformacije (jamice se glede na kroglo niso povečale). Večina matrice okoli krogel je prelomljeno krhko, kar dokazujejo ravne in gladke cepilne ploskve z značilnimi

are larger than the graphite nodules inside them. The break exhibits ductile characteristics.

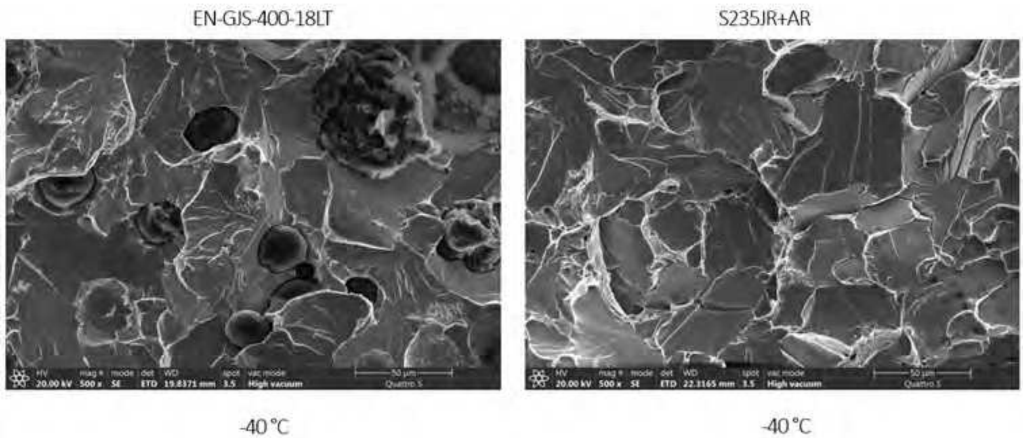
At room temperature, steel exhibits ductile fracture areas with characteristic voids (ductile fracture with coalescence of voids) and brittle fracture areas with characteristic smooth faces, gradations and basins (transcrystalline cleavage fracture).

At -40°C, no significant plastic deformation is apparent around the graphite



Slika 8. Prelomna površina CVN vzorcev obeh zlitin pri sobni temperaturi.

Figure 8. Fracture surface of CVN samples of both alloys at room temperature.



Slika 9. Prelomna površina vzorcev CVN obeh zlitin pri -40 °C.

Figure 9. Fracture surface of CVN samples of both alloys at -40 °C.

porečji. Prav tako gre za transkristalni krhek lom.

Tudi pri jeklu na -20 °C je očitno, da je lom potekal s transkristalnim cepilnim krhkim prelomom, saj so po celotni prelomni površini vidne gladke ploskve z rekami.

Z analizo prelomnih površin vzorcev CVN pod vrstičnim elektronskim mikroskopom smo potrdili, da lom v jeklu S235JR+AR poteka krhko pod temperaturo -20 °C, pri sobni temperaturi pa gre za kombinacijo duktilnega in krhkega loma. Pri posnetkih prelomne površine zlitine EN-GJS-400-18LT je vidno, da grafitne krogle močno vplivajo na izoblikovanje prelomne površine, pri čemer se krogle trgajo iz matrice, ta pa se deformira, pri čemer nastaja površina v obliki stožcev in vdolbinic.

Razlog, da je lomna žilavost sive litine s kroglastim grafitom tako dobra kljub nizkim vrednostim udarne žilavosti, leži v grafitnih kroglah, ki vplivajo na propagacijo razpoke. Pri počasnem napredovanju razpoke prihaja do otopitve konice razpoke, ko ta naleti na grafitno kroglo, zato se zmanjša intenziteta napetosti. Razpoka napreduje skozi matrico od krogle do krogle po poti, ki je energijsko najugodnejša. Ko razpoka napreduje skozi matrico in naleti na grafitne krogle, se njeno širjenje upočasni, saj se mora razpoka širiti okoli grafitne krogle. Razpoka se zato ukrivi med grafitnimi kroglami, njena dolžina pa se posledično podaljša. Tako za ločevanje na fazni meji med grafitno kroglo kot tudi za podaljšanje dolžine razpoke je potrebna dodatna energija, kar prispeva k večji žilavosti pri kvazistatični obremenitvi. Pri preizkusu udarne žilavosti je hitrost deformacije tako visoka, da se ta prednost, ki jo dajejo grafitne krogle sivi litini, izniči in so grafitne krogle dejansko ravno razlog za nizko udarno žilavost. Tretiramo jih lahko kot poroznost, ki slabša udarno žilavost materiala.

nodules (the voids have not increased in size relative to the graphite nodules). Most of the matrix around the graphite nodules features a brittle fracture, as evidenced by flat and smooth fracture surfaces with characteristic basins. Furthermore, a transcrystalline brittle fracture also occurs.

Even at -20°C, the fracture is seen to have been a transcrystalline brittle cleavage fracture, as smooth planes with basins are visible across the entire fracture surface.

By analysing the fracture surfaces of CVN samples under a scanning electron microscope, it was confirmed that the fracture in S235JR+AR is brittle below -20°C, while at room temperature, it exhibits a combination of ductile and brittle fracture. The images of the fracture surface of EN-GJS-400-18LT show that the graphite nodules have a strong influence on the formation of the fracture surface, with the nodules being ripped out of the matrix, deforming the latter and forming a cone and recess-shaped surface.

The reason why the fracture toughness of ductile iron is so favourable despite low impact toughness lies in the graphite nodules that influence crack propagation. As the crack slowly propagates, the tip becomes more obtuse as it encounters the graphite nodules, reducing the stress intensity. The crack progresses through the matrix from nodule to nodule along the most energetically favourable path. As the crack progresses through the matrix and encounters the graphite nodule, its propagation slows down as the crack must expand around the graphite nodule. The crack therefore bends between the graphite nodules, and its length is extended. Both the separation at the interface between the graphite nodule as well as crack elongation require additional energy, which contributes to the increased toughness under quasistatic loading. In the impact

4 Zaključki

Namen raziskave je bila primerjava lomne in udarne žilavosti sive litine s kroglastim grafitom EN-GJS-400-18LT pri različnih temperaturah ter primerjava z jeklom S235JR+AR. Prišli smo do naslednjih ugotovitev:

- mikrostruktura zlitine EN-GJS-400-18LT in jekla S235JR+AR je sestavljena iz povprečno 11 odstotkov perlita in 89 odstotkov ferita, z razliko, da je pri prvi v matrici še ogljik – strjen grafit v obliki krogel,
- grafitne krogle pri kvazistatični obremenitvi vplivajo na propagacijo razpoke. Konica razpoke pri grafitni krogli otopi, kar zniža faktor intenzitete napetosti, širjenje razpoke pa se upočasni. Razpoka se ukrivi med grafitnimi kroglami, kar podaljša njeno pot, za kar se porabi več energije,
- lomna žilavost sive litine s kroglastim grafitom EN-GJS-400-18LT je s padcem temperature bolj ali manj konstantna oziroma celo nekoliko naraste z 68,4 MPa·m-1/2 na 86,2 MPa·m-1/2. Lomna žilavost jekla S235JR+AR je prav tako konstantna skozi temperaturni interval in ravno tako nekoliko naraste z 29,40 MPa·m-1/2 pri sobni temperaturi na 32,93 MPa·m-1/2 pri -40 °C. Lomna žilavost zlitine EN-GJS-400-18LT je tako v celotnem temperaturnem intervalu približno dvakrat večja od lomne žilavosti jekla, kar lahko pripišemo grafitnim kroglam, ki vplivajo na propagacijo razpoke,
- pri preizkusu lomne žilavosti je prišlo pri zlitini EN-GJS-400-18LT v celotnem temperaturnem intervalu do stabilne rasti razpoke, pri jeklu S235JR+AR pa je prišlo pri temperaturah -20 °C in -40 °C do nestabilnega širjenja razpoke in nestabilnega loma v fazi otopitve

toughness test, the rate of deformation is so high that the advantage that graphite nodules impose on ductile iron is negated, and in fact, reversing the effect, resulting in extremely low impact toughness. They can be treated as porosity, which weakens the material’s impact toughness.

4 Conclusions

The purpose of the study was to compare the fracture and impact toughness of EN-GJS-400-18LT ductile iron at different temperatures, as well as to compare it to S235JR+AR steel. The following conclusions were made:

- The microstructure of EN-GJS-400-18LT and S235JR+AR consists of an average of 11% pearlite and 89% ferrite, while the matrix of the former also contains solidified graphite nodules.
- Graphite nodules under quasistatic loading affect crack propagation. The crack in spheroidal graphite becomes obtuse, which lowers the stress intensity factor and the crack propagation is made slower. The crack bends between graphite nodules, lengthening its path and resulting in increased energy consumption.
- The fracture toughness of EN-GJS-400-18LT ductile iron is more or less constant or even increases slightly from 68.4MPam$^{-1/2}$ to 86.2MPam$^{-1/2}$ as the temperature is reduced. Furthermore, the fracture toughness of S235JR+AR is also constant throughout the temperature interval and even increases slightly from 29,40MPa·m$^{-1/2}$ at room temperature to 32,93MPa·m$^{-1/2}$ at -40°C. This means that the fracture toughness of EN-GJS-400-18LT is approximately twice that of steel across the entire temperature interval, which

konice razpoke,

- povprečna udarna žilavost zlitine EN-GJS-400-18LT je zelo nizka pri vseh temperaturah in pade s 15,7 J na sobni temperaturi na 12,2 J pri -40 °C. Pri jeklu S235JR+AR je pri sobni temperaturi povprečna udarna žilavost odličnih 141,5 J, a strmo pade na 13,7 J pri -40 °C,
- pri jeklu se pri preizkusu udarne žilavosti vzpostavi ravninsko napetostno stanje, kar praviloma daje večje rezultate kot meritve v deformacijskem napetostnem stanju. Dokaz za to so velike plastične deformacije na prelomni površini in krčenje vzorca v prečni smeri. Pri zlitini EN-GJS-400-18T večjih deformacij in krčenja v prečni smeri ni,
- temperatura prehoda iz duktilnega v krhek lom je pri jeklo S235JR+AR v temperaturnem intervalu med 0 °C in -20 °C. To so dokazali rezultati udarne žilavosti in mikrofraktografije.

Zaključimo lahko, da je siva litina s kroglastim grafitom EN-GJS-400-18LT bolj odporna na kvazistatične obremenitve med sobno temperaturo in -40 °C kot jeklo S235JR+AR. Jeklo S235JR+AR je bolj primerno, kadar je komponenta izpostavljena udarnim, sunkovitim obremenitvam, saj ima precej večjo udarno žilavost kot zlitina EN-GJS-400-18LT, razen na -40 °C, kjer sta zlitini enakovredni.

can be attributed to graphite nodules influencing crack propagation.

- In the fracture toughness test, EN-GJS-400-18LT showed stable crack growth across the entire temperature interval while S235JR+AR demonstrated unstable crack propagation at -20°C and -40°C, and unstable fracture in the crack tip obtusion phase.
- The average impact toughness of EN-GJS-400-18LT is extremely low at all temperatures, dropping from 15.7J at room temperature to 12.2J at -40°C. S235JR+AR has an excellent average impact toughness of 141.5J at room temperature, but is reduced sharply to 13.7J at -40°C.
- In the case of steel, the impact toughness test establishes a plane loading state, which generally yields higher results compared to measurements in the deformation loading state. This is substantiated by the large plastic deformations at the fracture surface and the shrinkage of the sample in the transverse direction. EN-GJS-400-18T does not exhibit significant deformation and shrinkage in the transverse direction.
- The ductile-to-brittle fracture transition temperature for S235JR+AR is in the 0°C and -20°C temperature interval. This is demonstrated by impact toughness and microfractography results.

It can be concluded that EN-GJS-400-18LT ductile iron is more resistant to quasistatic loading between room temperature and -40°C than S235JR+AR. S235JR+AR is more suitable when a component is subjected to impact and sudden loads as it has a much higher impact toughness than EN-GJS-400-18LT, except at -40°C where the alloys exhibit equivalent characteristics.

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