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Kumulativni vpliv legirnih elementov na mikrostrukturo s trdno raztopino legirane nodularne litine

Accumulative impact of alloying elements on the microstructure of solid solution strengthened ductile iron

Povzetek

Odpadno železo je zaradi stroškovnih prihrankov ena najpomembnejših surovin pri izdelavi nodularne litine (DI). Količina elementov v sledovih v odpadnem železu raste. V tem prispevku se osredotočamo na elemente, ki spodbujajo nastajanje perlita in karbida, kot so krom, baker, mangan, molibden, niobij ali vanadij, ki lahko negativno vplivajo na mikrostrukturo in mehanske lastnosti nodularne litine, še posebej feritne tipe. Zato bodo stroški izdelave feritnih tipov s čistim odpadnim železom rasli. Inovativni tipi nodularnih litin, legirani s trdno raztopino (SSDI), so bolje topni v karbidotvornih elementih, kar do določene mere omogoča uporabo mešanega odpadnega železa. Vendar pa mejne koncentracije teh elementov še niso znane. V predstavljeni študiji smo proučili posamezne in skupne učinke elementov, ki spodbujajo nastajanje perlita in karbida SSDI tipa EN-GJS- 500-14 na podlagi načrtovanja dejavnikov pri preizkusu. Kvantitativna razmerja med kemijsko sestavo in mikrostrukturo so bila oblikovana z izračunom regresijskih parametrov. Rezultati predstavljajo osnovo za zanesljivo proizvodnjo SSDI ob upoštevanju prihodnjih sestav odpadnega železa z vse več elementi v sledovih.

Abstract

Steel scrap is one of the most important feedstock for manufacturing ductile iron (DI) for reasons of cost savings. The amount of tramp elements in steel scraps is on the increase. In the work presented we focus on pearlite and carbide promoting elements such as chromium, copper, manganese, molybdenum, niobium or vanadium which can have a negative impact on the microstructure and the mechanical properties of DI, especially ferritic grades. Thus, the costs for producing ferritic grades with clean steel scrap will increase. Innovative solid solution strengthened ductile iron grades (SSDI) have a larger solubility for carbide promoting elements which enables the use of mixed scraps to some extent. However, the limiting concentrations of these elements are unknown. In the study presented, the individual and combined effect of pearlite and carbide promoting elements in the SSDI grade EN-GJS- 500-14 are investigated by means of a factorial design of experiment. Quantitative relations between chemical composition and microstructure were modelled by regression calculations. The results establish a basis for the reliable production of SSDI taking into account future scrap compositions with increasing amounts of tramp elements.

1 Uvod

Nodularna litina (DI) kot livni material obstaja približno 70 let in združuje livnost ter stroškovno učinkovitost sive litine z žilavostjo jekla [1]. Zelo pogosto se uporablja v večini industrijskih panog, kot je izgradnja strojev, avtomobilska industrija ali na področju obnovljivih virov. Odpadno železo je zaradi svoje nizke cene poleg grodlja ena najpomembnejših surovin pri izdelavi nodularne litine. Delež železa v proizvodnji nodularne litine je v zadnjih desetletjih zaradi pritiska cen, s katerimi se soočajo železarne, močno porasla. Po drugi strani jeklarska industrija nenehno razvija nove vrste jekla z vse večjim številom legirnih elementov, ki spreminjajo dolgoročno kakovost in razpoložljivost odpadnega železa za proizvodnjo nodularne litine. Številni legirni elementi v jeklu, kot so krom, baker, mangan, molibden, niobij ali vanadij, v mikrostrukturi nodularne litine povzročajo nastajanje perlita in/ali karbidov. Zato je le vprašanje časa, kako dolgo bo odpadno železo brez primesi za proizvodnjo feritnih vrst jekel na voljo po razumni ceni.

Inovativne vrste nodularnih litin, utrjenih s trdnimi raztopinami (SSDI), ki vsebujejo do 4,3 mas. % silicija, predstavljajo edinstveno kombinacijo trdnosti in voljnosti [2], zanje pa je značilna tudi večja topnost za karbidotvorne elemente [3]. Visoka vsebnost Si spodbuja nastanek popolnoma feritne matrice, ki zagotavlja visoko voljnost in dobro obdelovalnost v primerjavi z enakovrednimi perlitnimi vrstami. Visoka vsebnost silicija povečuje topnost karbidotvornih elementov v avstenitu in feritu. Zato je mogoče ob predpogoju, da je mogoče količinsko opredeliti vpliv na mikrostrukturo, uporabiti cenejše odpadno železo, ki bo na voljo v prihodnosti. Posledično je treba preučiti in količinsko opredeliti posamezne in kombinirane vplive

1 Introduction

The casting material ductile iron (DI) exists since approximately 70 years and combines the castability and cost-efficiency of grey iron with the toughness of steel [1]. It is widely used in the most sectors of industry, such as machine building, automotive industry or renewable energy. Steel scrap is, apart from pig iron, the most important feedstock for the production of DI because of its low cost. The percentage of steel scrap in ductile iron production has increased considerably during the last decades because of the cost pressure cast iron foundries are facing. On the other hand, steel industry constantly develops new steel grades with increasing numbers of alloying elements which changes the long-term quality and availability of steel scrap for the production of DI. Many alloying elements in steel, such as chromium, copper, manganese, molybdenum, niobium or vanadium cause the formation of pearlite and/or carbides in the microstructure of DI. Thus, it is a question of time how long clean steel scrap is available for reasonable costs to produce ferritic grades.

Innovative solid solution strengthened ductile iron (SSDI) grades, which contain up to 4.3 wt. % of silicon, exhibit a unique combination of strength and ductility [2] and furthermore an increased solubility for carbide promoting elements [3]. The high Si content promotes the formation of a fully ferritic matrix, which ensures high ductility and good machinability in comparison with equivalent pearlitic grades. The high silicon content increases the solubility of carbide promoting elements in austenite and ferrite. Thus, less expensive and in future available steel scrap can be used under the precondition that the impact on the microstructure can be quantified. Therefore, the individual and combined impact of these elements on the microstructure has to be teh elementov na mikrostrukturo. V ta namen je vrsta SSDI EN- GJS-500-14 na podlagi načrtovanja faktorjev pri preizkusu legirana s Cr, Cu, Mn, Mo, Nb in V, prav tako je opravljena analiza mikrostrukture pri vzorcev, proizvedenih pod različnimi pogoji ohlajanja. Kvantitativna razmerja med kemijsko sestavo, pogoji ohlajanja in mikrostrukturo se razvijajo z regresijsko analizo.

2 Pregled virov

Vplivi elementov, ki tvorijo perlit in karbide, na mikrostrukturo in mehanske lastnosti nodularne litine so že nekaj desetletij predmet raziskav. Pregled vpliva različnih elementov v nodularnih litinah podaja Hasse [4], druge objave pa se osredotočajo na vplive posameznih elementov. Učinek dodatka vanadija do 0,5 mas. % na lastnosti feritne nodularne litine je preučil Nechtelberger [5] leta 1969 na vzorcih klinaste oblike Y_2 z debelino stene 25 mm. Odkril je, da se vsebnost perlita z vanadijem povečuje in da cementit tvori dodatke V pri vsebnosti nad 0,3 mas. %. Približno 30 let pozneje so Rezvani et al. proučili učinek podobnih dodatkov V nodularnih litinah, a z bistveno večjo vsebnostjo Si. Niso našli evtektičnih karbidov, temveč karbidne delce, bogate z vanadijem, ki so jih analizirali z mikroanalizami SEM-EDX in TEM. Glede na obe deli vanadij povečuje natezno trdnost in trdnost teženja, zmanjšuje pa raztezek pri zlomu. Učinek niobija so proučili Riviera et al. [6], pa tudi Souza et al. [7]. Niobij slabo spodbuja tvorbo perlita v nodularni litini in botruje zmernemu zvečanju natezne trdnosti in zmanjšanju raztezka. Niobijevi karbidi se v mikrostrukturi pojavljajo kot majhni poligonalni delci. Manganovi karbidi se zaradi segregacije tega elementa tvorijo na kristalnih mejah, kar so dokazali

investigated and quantified. To achieve this, the SSDI grade EN- GJS-500-14 is alloyed with Cr, Cu, Mn, Mo, Nb and V in a factorial design of experiment and the microstructure is analyzed in samples produced with different cooling conditions. Quantitative relations between chemical composition, cooling conditions and microstructure are developed via regression analysis.

2 Literature review

The impact of pearlite and carbide promoting elements on the microstructure and the mechanical properties of DI have been investigated for several decades. An overview of the impact of different elements in DI is given by Hasse [4], whereas other publications focus on the individual impact of one element. The effect of vanadium additions up to 0.5 wt. % on the properties of ferritic DI was investigated by Nechtelberger [5] in 1969 for Y_2 wedges with a wall thickness of 25 mm. He found that the pearlite content increases with vanadium and that cementite forms for V-additions above 0.3 wt. %. Nearly 30 years later, Rezvani et al. investigated the effect of similar additions of V in DI, but with a considerably higher Si- content. Here no eutectic carbides were found, but vanadium rich carbide particles, which were analyzed via SEM-EDX and TEM. According to both works, vanadium increases tensile and yield strength and decreases the elongation at fracture. The effect of niobium was analyzed by Rivera et al. [6] and also by Souza et al. [7]. Niobium is a weak pearlite promoter in DI and leads to a moderate increase of tensile strength and a decrease of elongation. Niobium carbides appear as small polygonal particles in the microstructure. Manganese carbides form at the grain boundaries due to the segregation of this

Ahmadabadi et al. [8] za nodularne litine z 1 mas. % Mn. Drugi karbidotvorni elementi, kot sta Mo in Cr, kažejo podobno segregacijsko vedenje. Učinek Cr, Cu, Mo in Ni na mikrostrukturo in mehanske lastnosti nodularne litine pri vzorcih klinaste oblike Y_4 (debelina stene 75 mm) so proučili Cho et al. [9], rezultati pa kažejo, da Cr in Cu močno spodbujata tvorbo perlita, Mo pa zgolj malo poveča količino perlita. Cr in Mo spodbujata tudi tvorbo karbidov na kristalnih mejah. Tako perlit kot medcelični karbidi negativno vplivajo na raztezek. O slabi tendenci Mo k spodbujanju tvorbe perlita so poročali tudi Hernandez-Avila et al. [10] pri nodularnih litinah z do 0,38 mas. % Mo.

Za preiskavo kombiniranega učinka več karbidotvornih elementov na lastnosti nodularne litine je potrebno obsežno načrtovanje pri preizkusu. Campomanes in Goller [11] sta v 32 preizkusih litja uporabila načrtovanje faktorjev, da bi proučila učinek Si, Mn, Cr, Ti in V na mikrostrukturo. Rezultate sta uporabila za izračun regresijskih parametrov. Za Cr in Mn sta ugotovila, da močno spodbujata tvorbo perlita, medtem kot Ti in V vplivata predvsem na tvorbo karbida. Večjo vsebnost Si je mogoče uporabiti kot protiučinek negativnemu vplivu drugih elementov. To vodi do večje tolerance proti karbidotvornim elementom pri SSDI [12]. Wolf et al. [13] so uporabili podobni virtualni preizkus litja (DOE) za proučevanje vpliva B, Cr, Mn, Nb in V na feritno železo EN-GJS-400-15. Pri tem so upoštevali tudi vpliv hitrosti ohlajanja, saj so uporabili lite dele različnih debelin. Čas strjevanja močno vpliva na morfologijo grafita in segregacijo elementov, ki spodbujajo tvorbo karbidov, zato je ta dejavnik zajet tudi v tej študiji.

element, as it was shown by Ahmadabadi et al. [8] for DI with 1 wt. % Mn. Other carbide promoting elements, such as Mo and Cr, are showing a similar segregation behaviour. The effect of Cr, Cu, Mo and Ni on the microstructure and the mechanical properties of DI in Y_4 wedges (wall thickness 75 mm) was examined by Cho et al. [9] and their results indicated that Cr and Cu are strong pearlite promoters, whereas Mo only slightly increases the amount of pearlite. Cr and Mo further promote the formation of carbides at the grain boundaries. Both pearlite and intercellular carbides have a negative impact on the elongation. The weak tendency of Mo to promote pearlite formation was also reported by Hernandez-Avila et al. [10] for DI with up to 0.38 wt. % Mo.

To investigate the combined effect of several carbide promoting elements on the properties of DI, an extensive design of experiment is required. Campomanes and Goller [11] used a factorial design of experiment with 32 casting trials to study the effect of the Elements Si, Mn, Cr, Ti and V on the microstructure. The results were used for regression calculations. Cr and Mn were identified as strong pearlite promoters, whereas Ti and V mainly influence the carbide content. An increased Si-content can be used to counteract the negative impact of the other elements. This leads to an increased tolerance against carbide promoters in SSDI [12]. Wolf et al. [13] used a similar DOE to study the impact of B, Cr, Mn, Nb and V on ferritic EN-GJS-400-15. Here the influence of the cooling rate was also taken into account by using cast parts with various thicknesses. The solidification time greatly affects the graphite morphology and the segregation of elements that promotes carbide formation, which is the reason, why this factor is also included in the present study.

3 Preizkusne metode

Zasnova preizkusa

V tej študiji je bila skoraj evtektična EN-GJS-500-14, legirana s trdno raztopino s ciljno vsebnostjo Si v višini 3,8 mas. %, legirana, z različnimi kombinacijami elementov Cr, Cu, Mn, Mo, Nb in V. Za vsak element sta bili na voljo dve različici z najmanjšo in največjo vsebnostjo, kar je prikazano v Preglednici 1. Najmanjše vsebnosti ustrezajo kemijski sestavi referenčne taline brez posebnih dodatkov legirnih elementov.

Preglednica 1: Ciljna najmanjša in največja vsebnost vsake legirne komponente

Table 1: Targeted minimum and maximum content of each alloy component

Element	Min [wt%]	Max [wt%]
Cr	0,045	0,600
Cu	0,060	0,300
Mn	0,170	0,500
Mo	0,005	0,500
Nb	0,003	0,200
V	0,006	0,200

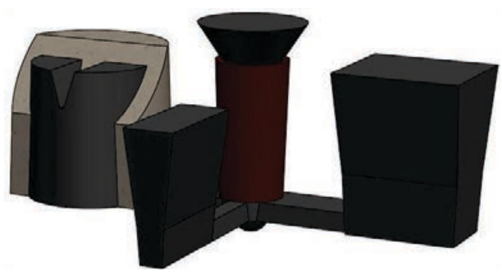
Geometrija ulitka, ki je prikazana v Sl. 1, zajema tri lite dele: en vzorec klinaste Y_2 oblike (debelina stene 25 mm), en vzorec klinaste Y_4 oblike (debelina stene 75 mm) in en valj (premera 140 mm). Valj je bil izoliran z izolacijsko razdelilno oblogo za podaljšanje časa strjevanja. Peščena forma je izdelana iz kremenčevega peska in s furansko smolo. Čas strjevanja vseh treh delov je določen s termoelektričnimi pirometri, ki smo jih pred litjem namestili v livne votline. Čas strjevanja je določen na pribl. 4, 15 in 45 minut za Y_2 element, Y_4 element in valjasti ulitek.

3 Experimental Methods

Design of Experiment

In this study, near-eutectic solid solution strengthened EN-GJS-500-14 with a targeted Si- content of 3.8 wt. % was alloyed with various combinations of the Elements Cr, Cu, Mn, Mo, Nb and V. Each element was varied in a two-stage manner with a minimum and a maximum content, which are listed in table 1. The minimum contents correspond to the chemical composition of the reference melt without extra additions of alloying elements.

The casting geometry, which is shown in fig. 1, includes three cast parts: one Y_2 wedge (wall thickness 25mm), one Y_4 wedge (wall thickness 75 mm) and one cylinder (diameter 140 mm). The cylinder was isolated with an insulating riser sleeve to further increase its solidification time. The sand mold is made of silica sand and furan resin. The solidification time in the three parts is determined with thermocouples that were placed in the mold cavities before casting. The solidification time is determined to be approx. 4, 15 and 45 minutes for the Y_2, Y_4 and cylindrical casting, respectively.



Sl. 1: Geometrija ulitka

Fig. 1: Casting geometry

Postopek litja

Material smo stopili v grafitnem lončku v srednjefrekvenčni indukcijski talilni peči. Za material za izdelavo taline smo uporabili reciklirano lito železo EN-GJS-400-15 in čisto železo z vsebnostjo 99,7 mas. % in dobili referenčno talino z minimalno vsebnostjo vsake komponente, navedene v Preglednici 1. Vsebnost Si in drugih legirnih elementov smo prilagodili z dodajanjem posebnih ferozlitin v talino, z izjemo bakra, ki je legiran kot čisti material. Talino smo pregreli na temperaturo 1500 °C in jo pri tej temperaturi zadrževali pribl. 5 minut. Žlindro smo odstranili pred obdelavo taline z magnezijem, in sicer s predzlitino FeSiMg brez cerija v zvonu, sledilo je dodatno odstranjevanje žlindre. Talino smo modificirali z 0,2 mas. % modifikatorja na osnovi ferosilicija. Po modifikaciji smo odvzeli vzorce za termalno analizo in proizvodnjo ohlajenega vzorca za kemično analizo s pomočjo iskrne emisijske spektrometrije. Nato smo talino prelili v formo iz peska z livno temperaturo pribl. 1350 °C. Ulitke smo pred odstranitvijo hladili 24 ur.

Priprava vzorca in analiza

Za metalografsko analizo smo za pridobitev vzorcev iz toplotnega središča vsakega ulitka velikosti pribl. 10 × 10 × 10 mm ulitke zrezali z ločno žago in vodno hlajenim rezalnikom. Po vgradnji smo vsak metalografski vzorec obdelali v avtomatiziranem brusilnem stroju najprej s kremenovim brusnim papirjem (velikost zrn: 180, 320, 500 in 1.000), nato pa še z diamantno polirno pasto (9, 3 in 0,25 µm) in polirno krpo. Za metalografske fotografije smo uporabili digitalni mikroskop z ločljivostjo 2.600 × 2.060 slikovnih pik in povečavo 1.000. Za slikovno analizo smo

Casting procedure

The material is melted in a graphite crucible via a medium frequency induction furnace. Recycled cast iron EN-GJS-400-15 and 99.7 wt. % pure iron is used as charging materials to produce the melt, which results in the reference melt with the respective minimum content of each component listed in table 1. The Si-content and the content of the other alloying elements are adjusted by adding particular ferroalloys into the melt, except for copper, which is alloyed as pure metal. The melt is superheated to 1500 °C and held at that temperature for approx. 5 min. Slag is removed before the magnesium treatment of the melt was performed with a cerium-free FeSiMg master alloy in a plunging bell, followed by a second slag removal. Then the melt is inoculated with 0.2 wt. % of a ferrosilicon-based inoculant. After inoculation, specimens are taken for thermal analysis and the production of a chilled sample for chemical analysis via spark emission spectrometry. The melt is poured into the sand mold with a casting temperature of approx. 1350 °C. The castings cooled down for 24 h before unpacking.

Sample preparation and analysis

For metallographic analysis, the cast parts are cut with a bow saw and a water-cooled disk cutter to obtain specimens from the thermal center of each cast parts with approx. 10 x 10 x 10 mm size. After embedding, each metallographic specimen is prepared in an automated buffing machine, first with silica sand paper (respective grain size: 180, 320, 500 and 1000) and then with diamond polish (9, 3 and 0.25 µm, respectively) and a polishing cloth. A digital microscope with a resolution of 2600 x uporabili sliko, ustvarjeno s programsko opremo Axiovision KS 400. Fotografije za analizo grafitne faze so posnetki poliranega vzorca s 100-kratno povečavo za vzorca klinaste oblike Y_2 in oblike Y_4 oz. s 50-kratno povečavo za valj zaradi večjih kristalnih zrn in manjšega števila vozlov. Enake prilagoditve smo uporabili pri fotografijah s HNO_3 jedkanih vzorcev, ki smo jih posneli za oceno vsebnosti perlita. Za oceno količine karbidov smo vzorce zjedkali s Klemmovim jedkalom, fotografije pa posneli pri 200-kratni povečavi. Posneli smo pet fotografij vsakega vzorca na različnih mestih.

Fotografije grafitne faze smo uporabili za določitev števila grafitnih vozlov na mm², površinskega odstotka grafita in nodularnosti, ki opisuje razmerje okroglih grafitnih delcev glede na skupno število grafitnih delcev. Za razvrstitev opazovanih grafitnih delcev v grafitne oblike I–IV skladno s standardom DIN-EN-ISO-945-1 smo uporabili koeficient sferičnosti in kompaktnosti brezdimenzijskih oblik. Te faktorje smo uporabili za razvrstitev vsakega delca na podlagi omejitev, ki jih je določila Velichkova [14]. Te omejitve razvrstitev so odvisne od velikosti delcev. Po razvrstitvi vsakega delca smo izračunali nodularnost N na površini grafitnih delcev A z naslednjo formulo:

$$N = \frac{\sum_{VI} A_i + \frac{1}{2}\sum_{IV}^{V} A_i}{\sum_{I}^{VI} A_i} \qquad (1)$$

Površino vseh grafitnih delcev oblike VI (okrogli delci) smo sešteli s polovico površine grafitnih oblik IV in V (nepravilni okrogli delci) ter delili s skupno površino grafita. Odstotek površine grafita %G je potreben za izračun odstotka perlita %P s posnetkov jedkanega HNO_3 z določeno celotno površino grafita in perlita. Odstotek perlita se torej izračuna po formuli:

2060 pixels and a maximum magnification factor of 1000 is used for the metallographic pictures. The image software Axiovision KS 400 is used for image analysis. Pictures for the observation of the graphite phase are taken from the polished specimen with a magnification factor of 100 for the Y_2 and Y_4 wedge and with a factor of 50 for the cylinder because of the larger grains and the lower number of nodules. The same adjustments are applied for the pictures of the HNO_3-etched specimens, which were taken to estimate the pearlite content. For determining the amount of carbides, the samples are etched with Klemm´s reagent and pictures are taken with a magnification factor of 200. Five pictures are taken from each specimen at different locations.

The pictures of the graphite phase are used for determining the number of graphite nodules per mm², the area percentage of graphite and the nodularity, which describes the ratio of round graphite particles to all graphite particles. To group the observed graphite particles into graphite forms I - VI according to DIN-EN-ISO-945-1, the dimensionless shape factors roundness and compactness are used. These factors are used for classification of each particle according to the limits defined by Velichko [14]. These classification limits depend on the particle size. After the classification of each particle, the nodularity N is calculated from the area A of graphite particles according to the following formula:

$$N = \frac{\sum_{VI} A_i + \frac{1}{2}\sum_{IV}^{V} A_i}{\sum_{I}^{VI} A_i} \qquad (1)$$

The area of all graphite particles of the shape VI (round particles) is added together with half of the area of the graphite shapes IV and V (irregular round particles) and divided by the total area of graphite. The area percentage of graphite %G is required

$$\%P = (\%G + \%P)_{HNO_3} - \%G_{polirano} \quad (2)$$

Odstotek površine karbidov smo določili ročno na podlagi mreže, ki smo jo položili prek barvno jedkane mikrostrukture.

4 Rezultati

Preglednica 2 prikazuje kemijsko sestavo vsake taline. Lite so bile kombinacije do treh elementov.

Morfologija grafita

Morfologija grafita kaže jasne razlike med tremi analiziranimi ulitki. Na Sliki 2 je

to calculate the percentage of pearlite %P from the HNO_3-etched pictures, where the total area of graphite and pearlite is determined. The pearlite percentage is thus calculated as:

$$\%P = (\%G + \%P)_{HNO_3} - \%G_{polished} \quad (2)$$

The area percentage of carbides is determined manually via a grid overlaid on the color- etched microstructure.

4 Results

Table 2 shows the chemical composition of each respective melt. Combinations of up to three elements are cast.

Cast no.	Si	Cr	Cu	Mn	Mo	Nb	V	Mg
1	4.04	0.04	0.06	0.17	0.002	0.003	0.004	0.028
2	3.88	0.04	0.07	0.19	0.004	0.180	0.007	0.040
3	4.06	0.62	0.06	0.18	0.005	0.003	0.001	0.032
4	3.96	0.05	0.07	0.18	0.535	0.003	0.006	0.028
5	4.23	0.04	0.07	0.18	0.007	0.003	0.200	0.032
6	3.82	0.04	0.07	0.52	0.003	0.004	0.007	0.045
7	4.14	0.04	0.30	0.16	0.002	0.003	0.004	0.031
8	3.98	0.04	0.07	0.53	0.003	0.237	0.006	0.034
9	4.11	0.61	0.07	0.53	0.004	0.003	0.007	0.043
10	4.00	0.05	0.07	0.54	0.528	0.003	0.006	0.023
11	4.20	0.05	0.07	0.52	0.004	0.003	0.207	0.032
12	3.94	0.62	0.07	0.18	0.005	0.211	0.008	0.025
13	4.24	0.05	0.32	0.19	0.007	0.216	0.017	0.038
14	4.18	0.04	0.31	0.18	0.004	0.003	0.180	0.035
15	4.15	0.05	0.07	0.18	0.503	0.220	0.006	0.029
16	3.95	0.57	0.06	0.16	0.007	0.003	0.199	0.030
17	4.00	0.04	0.07	0.51	0.002	0.217	0.213	0.032
18	4.15	0.60	0.31	0.55	0.002	0.003	0.005	0.038
19	4.14	0.61	0.32	0.19	0.004	0.214	0.007	0.033
20	4.06	0.61	0.40	0.18	0.005	0.003	0.188	0.027
21	4.02	0.05	0.07	0.51	0.482	0.003	0.185	0.030

Preglednica 2: Kemijske sestave v mas. %, izmerjena z iskrno emisijsko spektrometrijo

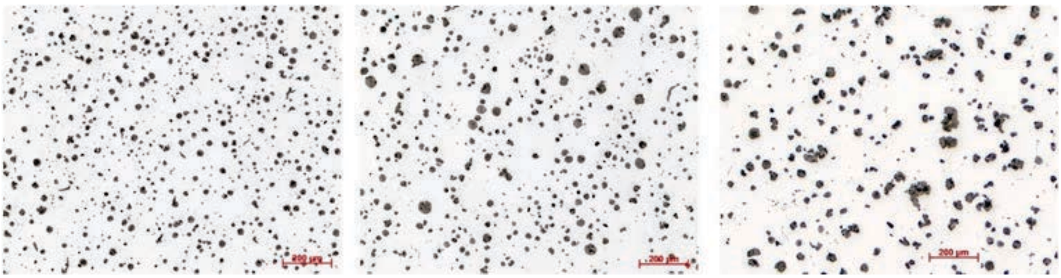
Table 2: Chemical compositions in wt. % measured via spark emission spectrometry

predstavljena morfologija grafita vsakega litja ulitka št. 1, v katerem ni bilo dodanih elementov. Večja kot je debelina, manjše je število vozlov. Z večanjem grafitnih delcev pa oblika postaja bolj nepravilna, zlasti pri valju. Število vozlov na mm² znaša 526, 344 oz. 136, nodularnost pa 87, 85 oz. 69 %.

Število grafitnih delcev in nodularnost pri vseh preizkusih litja sta prikazani v grafu raztrosa na Sliki 3 kot funkcija ostanka Mg. V enem je opazen velik odklon obeh parametrov v okviru analize preizkusov litja. Vendar pa se oblaki točk vseh treh delov

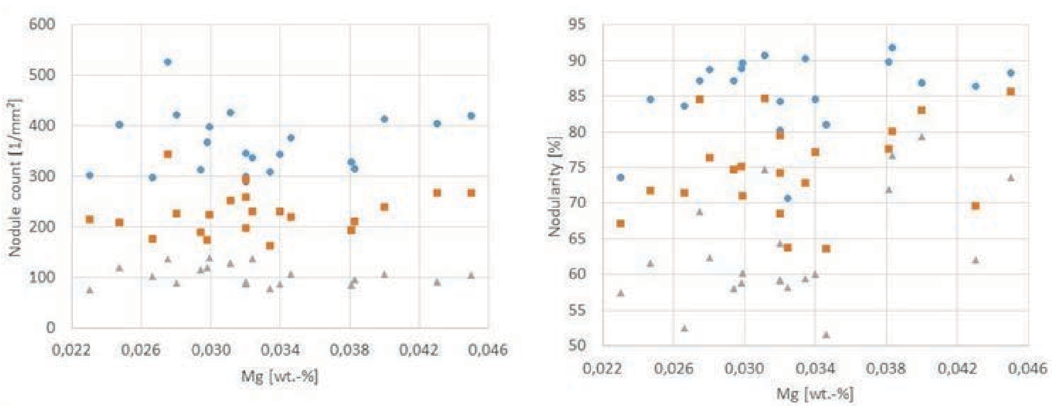
Graphite morphology

The graphite morphology shows distinct differences between the three cast parts that were analyzed. Figure 2 represents the graphite morphology in each casting for cast no. 1, where no element was added. The number of nodules decreases with increasing thickness. At the same time, the average size of the graphite particles increases while the shape becomes more irregular, especially in the cylinder. The nodule count is 526, 344 and 136 per



Sl. 2: Reprezentativna struktura grafita vseh treh ulitkov: Y_2, Y_4 in valj (od leve proti desni)

Fig. 2: Representative graphite structure in the three cast parts: Y_2, Y_4 and cylinder (from left to right)



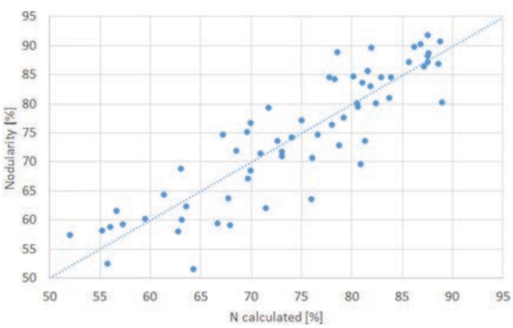
Sl. 3: Število vozlov in nodularnost vseh treh ulitkov kot posledica prostega Mg
(● vzorec klinaste oblike Y_2 ■ vzorec klinaste oblike Y_4 ▲ valj)

Fig. 3: Nodule count and nodularity in the three cast parts as a function of residual Mg- content
(● Y_2 wedge ■ Y_4 wedge ▲ cylinder).

komajda medsebojno prekrivajo. Pri vseh treh ulitkih se zlasti razlikuje število vozlov.

Število vozlov pri vzorcu klinaste oblike Y_2 navadno znaša med 300 in 450 mm^{-2}, pri vzorcu klinaste oblike Y_4 pa med 150 in 350 mm^{-2}. Pri valju je število vozlov med 75 in 150 mm^{-2}. Iz grafa raztrosa je razvidno, da vsebnost Mg nima bistvenega vpliva na število vozlov. Nodularnost se z večanjem vsebnosti Mg izboljšuje. Najslabša nodularnost je prisotna pri valju. Spremembe v nodularnosti so zelo močne pri valju, kajti nodularnost je dovzetnejša na preostalo vsebnost Mg pri daljšem času strjevanja. Tudi nekateri legirni elementi zmanjšujejo nodularnost. Iz zadevne regresijske analize so razvidna naslednja razmerja med nodularnostjo N, časom strjevanja t^{sol}, ostankom Mg in vsebnostjo karbidotvornih elementov:

$$N\,[\%] = 99.4 - 0.141\frac{\sqrt{t^{sol[min]}}}{Mg} - 32.5V - 10.5Mn - 10.1Nb \qquad (3)$$



Sl. 4: Vrednosti nodularnosti v preizkusu v primerjavi z na podlagi regresijske formule izračunano nodularnostjo

Fig. 4: Experimental nodularity values vs. nodularity calculated by regression formula (3)

mm² and the nodularity 87, 85 and 69 %, respectively.

Graphite nodule count and nodularity for all casting trials are shown in a scatter diagram in figure 3 as a function of the residual Mg-content. A large variation of the two parameters within the analyzed casting trials can be observed. However, the point clouds of the three parts hardly overlap with each other. Especially the nodule count is very different in the three castings.

The nodule count in the Y_2 wedge is usually between 300 and 450 mm^{-2}, whereas in the Y_4 wedge between 150 and 350 nodules per mm^{-2} are present. The cylinder has a nodule count between 75 and 150 mm^{-2}. From the scatter diagram, it can be seen that the Mg-content does not have a significant impact on the nodule count. The nodularity improves with increasing Mg-content. The lowest nodularity is found in the cylinder. The variation in nodularity is also very large in the cylinder because the nodularity is more sensitive to the residual Mg-content when the solidification time is higher. Also some of the elements alloyed tend to decrease the nodularity. A respective regression analysis yields the following relationship between nodularity N, solidification time t^{sol}, the residual Mg-content and the content of carbide promoters:

$$N\,[\%] = 99.4 - 0.141\frac{\sqrt{t^{sol[min]}}}{Mg} - 32.5V - 10.5Mn - 10.1Nb \qquad (3)$$

R^2 = 78,8 %

The intercept value is 99.4 % and thus very close to 100 %, which corresponds to the highest nodularity that can theoretically be achieved in DI. Vanadium has the highest negative impact on nodularity. Figure 4 shows the nodularity calculated

$R^2 = 78{,}8\ \%$

Vrednost odseka je 99,4 % in torej zelo blizu 100 %, kar ustreza najvišji stopnji nodularnosti, ki jo je teoretično mogoče doseči pri nodularni litini. Vanadij najbolj negativno vpliva na nodularnost. Slika 4 prikazuje izračunano in izmerjeno nodularnost. Točke so enakomerno razporejene okrog diagonale in nakazujejo linearno vedenje, kar pomeni, da je predvidena odvisnost pravilna.

Perlit in karbidi

Posledica dodajanja številnih elementov, ki spodbujajo tvorbo perlita in karbidov, so različne mikrostrukture, od popolnoma feritnih matričnih struktur do popolnoma perlitnih matričnih struktur. Na Sliki 5 je prikazana mikrostruktura, jedkana s HNO_3, vzorca klinaste oblike Y_4 pri različnih dodatkih legirnih elementov. Ko je Mn legiran brez dodatnih elementov, ostane matrica feritna. Količina perlita se pri dodatku Cr in Cu močno poveča. Odstotkovna vrednost perlita znaša 5, 49 in 72 %.

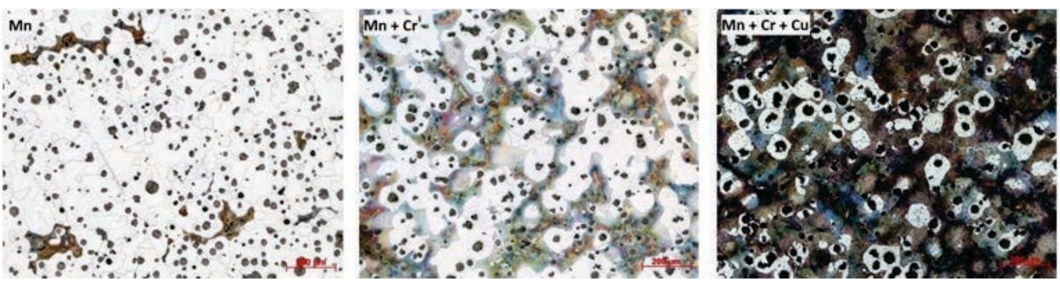
Uporabljeni legirni elementi različno vplivajo na spodbujanje tvorbe perlita, njihov posamezni vpliv na mikrostrukturo pa

and measured. The points are equally distributed around the diagonal and show a linear behaviour, which means that the dependency assumed is correct.

Pearlite and carbides

The addition of multiple pearlite and carbide promoting elements results in a variety of observed microstructures ranging from fully ferritic matrix structures to fully perlitic matrix structures. Figure 5 shows the HNO_3-etched microstructure in the Y_4 wedge for different additions of alloying elements. When Mn is alloyed without additional elements, the matrix stays ferritic. The amount of pearlite increases significantly as Cr and Cu are added. The pearlite percentage is 5, 49 and 72 %, respectively.

The alloying elements used vary in their tendency to promote the formation of pearlite and their individual impact on the microstructure accumulates when multiple elements are added. This tendency is quantified for SSDI via the following regression analysis for the pearlite percentage P. This analysis takes account for the weight percentage of each element and the solidification time, which yields:



Sl. 5: Spreminjanje količine perlita v mikrostrukturi vzorca klinaste Y_4 oblike z vse večjimi dodatki elementov (ulitki št. 6, 9 in 18)

Fig. 5: Evolution of the amount of pearlite in the microstructure of the Y_4 wedge with increasing addition of elements (cast no. 6, 9 and 18)

se pri dodajanju več elementov akumulira. Ta tendenca je pri SSDI določena s pomočjo naslednje regresijske analize za odstotkovno vrednost perlita P. Ta analiza upošteva odstotek teže vsakega elementa in čas strjevanja:

$$P[\%] = 82.2\,Cr + 88.7\,Cu + 15.4\,Mn + 18.2\,Mo + 17.6\,Nb + 10.2\,V + 0.0368\,t_{sol}[\mathrm{min}] - 14.5 \quad (4)$$

$R^2 =$ 98.3 %

Na podlagi regresijske formule (4) krom in baker najbolj spodbujata tvorbo perlita, preostali štirje elementi pa na matrično strukturo vplivajo minimalno. Osno razmerje je izraženo z negativno vrednostjo, kajti popolnoma feritno strukturo je mogoče doseči že z dodajanjem zelo majhnih koncentracij teh elementov. Čas strjevanja skorajda nima vpliva na odstotek perlita. Vsebnost perlita se zveča za pribl. 1 %, ko se čas strjevanja podaljša za 27 minut. Zato imajo različni pogoji hlajenja, predstavljeni v študiji, zanemarljiv vpliv na količino perlita. Primerjava med izračunanimi in izmerjenimi vsebnosti perlita je prikazana v Sliki 7(a) in nakazuje zelo dobro soodnosnost.

Karbidi, oborjeni zaradi dodanih elementov, se močno razlikujejo tako po velikosti kot obliki. V Sliki 6 so prikazani karbidi v mikrostrukturi valjastega ulitka po jedkanju s Klemmovim jedkalom za ulitka št. 15 in 16. V s Cr in V legirani SSDI so veliki razvejani karbidi zaradi segregacije Cr oborjeni. Ti karbidi so prisotni na kristalnih mejah in obkroženi s perlitom. Vanadijevi karbidi so mnogo manjši in kompaktnejši. V zlitini z dodatkom Mo in Nb najdemo značilno oblikovane Mo-karbide, obkrožene z majhnimi območji perlita. Nb-karbidi so mnogo manjši in bolj homogeno porazdeljeni v mikrostrukturi. Večina Nb-karbidov je prisotnih na kristalnih mejah; vendar pa so nekateri ugnezdeni v feritnih

$$P[\%] = 82.2\,Cr + 88.7\,Cu + 15.4\,Mn + 18.2\,Mo + 17.6\,Nb + 10.2\,V + 0.0368\,t_{sol}[\mathrm{min}] - 14.5 \quad (4)$$

$R^2 =$ 98.3 %

According to regression formula (4), chromium and copper are the strongest pearlite promoters, while the other four elements have a minor impact on the matrix structure. The axis intercept is a negative number because a fully ferritic structure can even be achieved when low concentrations of these elements are added. The solidification time has almost no impact on the pearlite percentage. The pearlite content increases by approx. 1 % as the solidification time increases by 27 minutes. Thus, the different cooling conditions in the study presented have a negligible impact on the amount of pearlite. The pearlite contents calculated and measured are compared in figure 7 (a) and show a very good correlation.

The carbides precipitated by the elements added vary significantly in both size and shape. Figure 6 shows the carbides in the microstructure of the cylindrical cast part after etching with Klemm´s reagent for cast no. 15 and 16. In the Cr and V alloyed SSDI, large branched carbides are precipitated due to the segregation of Cr. These carbides are located at the grain boundaries, surrounded by pearlite. The vanadium carbides are much smaller and compacted. In the alloy with Mo and Nb additions, characteristically shaped Mo-carbides are found, surrounded by small regions of pearlite. The Nb-carbides are much smaller and more homogeneously distributed in the microstructure. Most Nb-carbides are located at grain boundaries; however, some are embedded in ferrite grains because they were formed at earlier stages of solidification.

kristalnih zrnih, ker so nastali v zgodnejših fazah strjevanja.

Površina frakcije karbidov v mikrostrukturi je ocenjena tudi z regresijsko analizo z dodatnimi interakcijami. Te interakcije opisujejo dejstvo, da se lahko ob prisotnosti več karbidotvornih elementov tvorijo mešani karbidi. Cu ni zajet v regresijski izračun, kajti ne spodbuja tvorbe karbidov. Mn je bil zajet, vendar pa nismo našli bistvenega vpliva na količino karbidov. Rezultat regresijske formula pri frakciji karbidov C:

$$C\,[\%] = 0.365\,Cr + 0.434\,Mo + 0.852\,Nb + 5.973\,Nb \times V + 0.76\,V + 0.00253\,t_{sol}[\text{min}] - 0.053 \qquad (5)$$

$$R^2 = 73.6\,\%$$

Niobij in vanadij imata največji vpliv na količino karbidov. Nadalje ta elementa nakazujeta pomembno interakcijo, izraženo z ustrezno formulo. Čas strjevanja kaže minimalno zvečanje odstotkovne vrednosti karbidov. Soodnosnost med izmerjeno in izračunano vsebnostjo karbida je prikazana na Sliki 7(b). Raztros točk pri karbidu je izrazito večji kot pri perlitu. Vendar pa večina točk nakazuje dobro soodnosnost med regresijo in meritvijo.

5 Razprava

V predstavljeni študiji je ocenjen vpliv dodajanja več legirnih elementov litini EN-GJS-500-14 (SSDI) na mikrostrukturo in kvantificiran z regresijsko analizo. Upoštevan je čas strjevanja na podlagi geometrije ulitkov za tri različne ulitke. Nakazuje, da čas strjevanja močno vpliva na morfologijo grafita, tj. števil vozlov in nodularnost. Z daljšanjem časa strjevanja se oba parametra zmanjšujeta, kar je skladno z rezultati iz literature [15–17]. Vpliv časa

The area fraction of carbides in the microstructure is also evaluated via a regression analysis applying additional interaction terms. These interaction terms describe the fact that mixed carbides can be formed when multiple carbide promoters are present. Cu is not included in the regression calculation since it does not promote carbide formation. Mn was included, however, no significant impact on the amount of carbides was found. The regression formula for the fraction of carbides C yields:

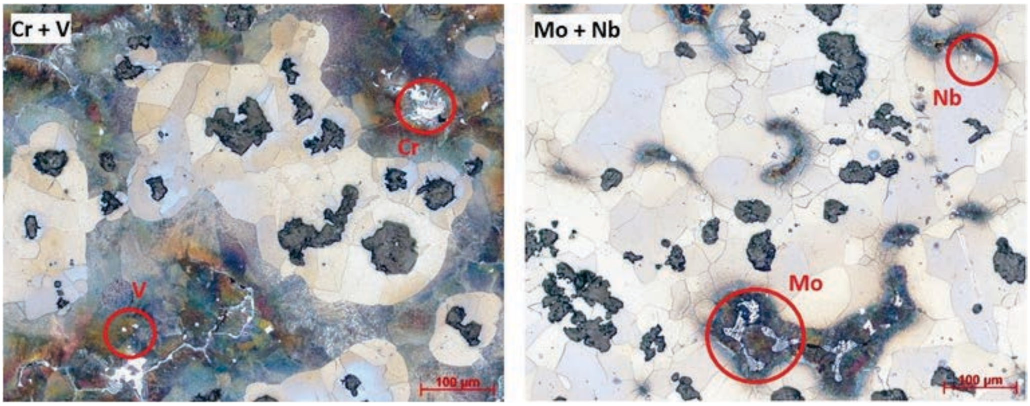
$$C\,[\%] = 0.365\,Cr + 0.434\,Mo + 0.852\,Nb + 5.973\,Nb \times V + 0.76\,V + 0.00253\,t_{sol}[\text{min}] - 0.053 \qquad (5)$$

$$R^2 = 73.6\,\%$$

Niobium and vanadium have the highest individual impact on the amount of carbides. Furthermore, these elements show significant interaction quantified by the corresponding interaction term. The solidification time shows a minor increasing impact on the percentage of carbides. The correlation between the carbide content measured and calculated is shown in figure 7(b). The scattering of the points is clearly higher for the carbides compared to pearlite. Nevertheless, most points indicate a good correlation between regression and measurement.

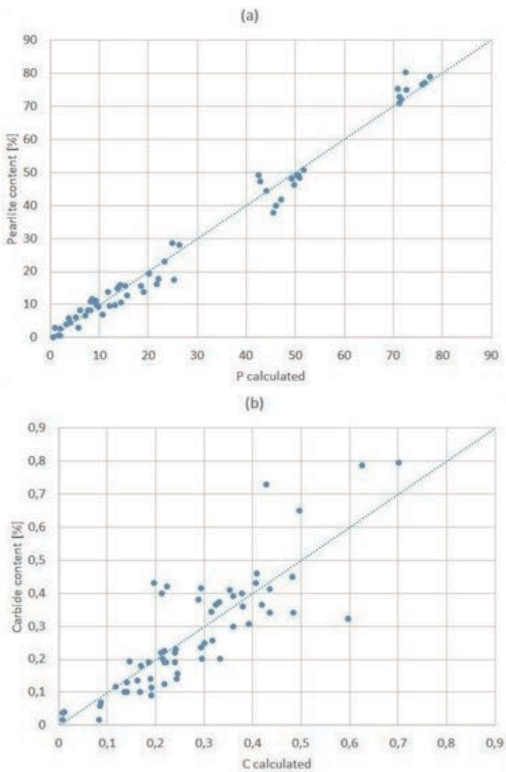
5 Discussion

In the study presented multiple alloying elements are added to EN-GJS-500-14 (SSDI) and their impact on the microstructure is evaluated and quantified via regression analysis. The solidification time is taken into account using a casting geometry with three different cast parts. It is shown that the solidification time has a high impact on the graphite morphology, i.e. the nodule



Sl. 6: Karbidi v mikrostrukturi za ulitka št. 15 (desno) in 16 (levo)

Fig. 6: Carbides in the microstructure for cast no. 15 (right) and 16 (left)



Sl. 7: Soodnosnost med izračunanim in izmerjenim odstotkom površine perlita (a) in karbidov (b)

Fig. 7: Correlation between calculated and measured area percentage of pearlite (a) and carbides (b).

count and the nodularity. Both parameters decrease with increasing solidification time, which is in agreement with results reported in literature [15-17]. The influence of solidification time, residual Mg-content and alloying elements on the nodularity was quantified via regression analysis. These results indicate that the impact of increasing solidification time can be compensated with a higher Mg-content. A large solidification time goes along with fading of the Mg-treatment and the inoculation, that results in poor nodularity, that has been reported earlier for conventional DI by [18, 19]. When the Mg- content after the treatment is at elevated levels, more residual Mg is present when the eutectic solidification starts. The negative impact of individual elements, especially vanadium, is quantified by the regression analysis. The negative impact of V on the spherical shape of graphite has been reported by Nechtelberger [5] for conventional DI. According to his work, the addition of V increases the irregularity of graphite nodules. For Nb and Mn, no quantitative information about the impact on nodularity in DI is found in literature.

The quantification of the pearlite content in terms of a regression analysis shows a very good correlation in the study strjevanja, ostanka Mg in legirnih elementov na nodularnost je opredeljen z regresijsko analizo. Ti rezultati nakazujejo, da je mogoče vpliv vse daljšega časa strjevanja izravnavati z večjo vsebnostjo Mg. Daljši čas strjevanja se ujema z zmanjševanjem obdelave in modifikacije Mg, posledica česar je slaba nodularnost, o kateri so avtorji [18, 19] že poročali v povezavi s klasičnimi nodularnimi litinami. Pri višji vsebnosti Mg po obdelavi je na začetku evtektičnega strjevanja prisotnega več ostanka Mg. Negativni vpliv posameznih elementov, zlasti vanadija, je določen z regresijsko analizo. O negativnem vplivu V na sferično obliko grafita je poročal Nechtelberger [5] za klasično nodularno litino. Na podlagi njegovega dela dodatek V povečuje nepravilnost grafitnih vozlov. Literatura ne navaja nobenih kvantitativnih informacij v zvezi z vplivom Nb in Mn na nodularnost nodularne litine.

Količinska opredelitev vsebnosti perlita pri regresijski analizi v tej študiji kaže zelo dobro soodnosnost. Cu in Cr sta opredeljena kot elementa, ki močno spodbujata tvorbo perlita pri SSDI, drugi elementi pa zelo malo vplivajo na količino perlita. To je skladno z rezultati, predstavljenimi v literaturi. Čas strjevanja nima bistvenega vpliva na vsebnost perlita, kajti daljši čas strjevanja izravnava padajoče število vozlov. To velja tudi za reakcijo ferita/perlita. Ko število vozlov raste, se difuzijska razdalja za prenos ogljika zmanjšuje, kar spodbuja pretvorbo iz avstenita v ferit, kot poroča [20]. Hitrosti ohlajanja pri vseh treh ulitkih, uporabljene v predstavljenem delu, so najverjetneje prenizke, da bi bilo mogoče zaznati njihov vpliv na število vozlov. Vendar pa zamenjava časa strjevanja s številom vozlov v regresijski analizi nakazuje tudi pomemben vpliv na vsebnost perlita. Prevladujoči vpliv v tej študiji predstavlja segregacija litih komponent in njihov vpliv na evtektoidno transformacijsko presented. Cu and Cr are identified as strong pearlite promoters in SSDI, whereas other elements have a minor impact on the amount of pearlite. This is in agreement with the results presented in literature. The solidification time has no significant impact on the pearlite content since increasing solidification time compensates for the decreasing nodule count. This is also true for the ferritic / perlitic reaction. When the nodule count increases, the diffusion distance for carbon transport decreases, which favours the transformation from austenite to ferrite as reported by [20]. The cooling rates in the three cast parts used in the work presented are probably too low to see an impact of the number of nodules. Thus, replacing the solidification time by the nodule count in the regression analysis shows also insignificant impact on the pearlite content. The predominant impact in the study presented is given by the segregation of components alloyed and their impact on the eutectoid transformation temperature, which has already been described by Lacaze et al. [21]. In this context elements such as Cr and Mn decrease both, the eutectoid transformation temperature and the temperature range for the ferritic transformation to take place, which promotes the formation of pearlite. Due to the segregation of these elements, their impact increases at the grain boundaries where the perlitic transformation is initiated.

The carbides investigated in the microstructures originate from the segregation of carbide promoting elements and are thus located at grain boundaries. The area percentage of carbides is modelled via regression analysis. It is found that niobium and vanadium have the highest impact on carbide formation. No significant contribution of Mn on the area percentage of carbides was found in SSDI, even though Mn is described as temperaturo, ki so opisali že Lacaze et al. [21]. Tukaj elementa, kot sta Cr in Mn, zmanjšata tako evtektoidno transformacijsko temperaturo kot temperaturni razpon feritne transformacije, ki spodbuja tvorbo perlita. Zaradi segregacije teh elementov se povečuje njihov vpliv na kristalnih mejah, kjer se začne perlitna transformacija.

Karbidi v preiskovanih mikrostrukturah izvirajo iz segregacije karbidotvornih elementov in so zato prisotni na kristalnih mejah. Odstotek površine karbidov je modeliran z regresijsko analizo. Odkrili smo, da imata niobij in vanadij največji vpliv na tvorbo karbidov. Pri SSDI nismo ugotovili bistvenega vpliva Mn na odstotek površine karbidov, čeprav je Mn v literaturi o klasični nodularni litini opisan kot karbidotvorni element. Posledično lahko sklepamo, da visoka vsebnost silicija v SSDI preprečuje tvorbo Mn-karbidov. Za razliko od Cr ali V ima mangan manj izražen segregacijski profil. Vrednosti segregacijskih faktorjev teh in drugih elementov navaja Hasse [4]. Lahko sklepamo, da obogatitev z Mn v preostali talini med strjevanjem ni zadostna za precipitacijo Mn-karbidov.

Izvedena regresijska analiza v bistvu opisuje kvantitativno odvisnost mikrostrukturnih parametrov od kemijske sestave in časa strjevanja. Najboljša soodvisnost med izračunanimi in izmerjenimi vrednostmi je pri vsebnosti perlita z determinacijskim koeficientom R^2 = 98,3 %. Pri nodularnosti je dosežen mnogo nižji koeficient 78.8 % zaradi večjih razlik med samimi podatki. Kljub temu pa so podatki enakomerno razporejeni okoli koordinate na Sliki 4, ki kaže pravilno regresijsko analizo. Količina karbidov nakazuje dobro soodvisnost med izračunanimi in izmerjenimi podatki v večini primerov, vendar pa so nekatere točke zunaj koordinate, prikazane na Sliki 7(b). Ta odstopanja so posebej pomembna pri visokih vsebnostih karbidov.

a carbide promoting element in literature for conventional DI. As a result, it can be concluded that the high silicon content in SSDI prevents the formation of Mn-carbides. In contrast to Cr or V, manganese has a less pronounced segregation profile. Values for the segregation factors of these and other elements are given by Hasse [4]. It can be concluded that the enrichment of Mn in the residual melt during solidification insufficient to precipitate Mn-carbides.

The regression analysis performed essentially describes the quantitative dependence of microstructure parameters on the chemical composition and solidification time. The best correlation between the values calculated and measured is found for the pearlite content with a coefficient of determination of R^2 = 98.3 %. For nodularity, a much lower coefficient of 78.9 % is reached because of the larger variation of data itself. Nevertheless, the data are homogeneously distributed around the trend line in Figure 4 which indicates a correct regression analysis. For the amount of carbides a good correlation between calculated and measured data is found in most cases, however some points are located far away from the trend line in Figure 7 b. These discrepancies are especially significant for high carbide contents. Maybe additional interaction terms are required to describe these data points, however no clear trend is evident. In future work this issue is analyzed in detail with the help of microsegregation simulation as performed by Pustal et al. [22].

6 Conclusions

The aim of this work is to analyse and quantify the impact of multiple pearlite and carbide promoting elements on the

Morda so za opis teh podatkovnih točk potrebne dodatne interakcije, vendar jasen trend ni razviden. V prihodnjem delu to vprašanje podrobno obravnavano skozi analizo s pomočjo mikrosegregacijske simulacije, kot so jo izvedli Pustal et al. [22].

6 Sklepi

Cilj tega dela je analizirati in količinsko ovrednotiti vpliv elementov, ki spodbujajo tvorbo perlita in karbida, na mikrostrukturo SSDI EN-GJS-500-14 pri različnih pogojih hlajenja. V tem smislu smo dognali naslednje:

1. Čas strjevanja vpliva predvsem na število vozlov. Nodularnost je odvisna od časa strjevanja in ostanka Mg. Koncentracija karbidotvornih elementov dodatno zmanjšuje nodularnost. Na nodularnost močno negativno vpliva vanadij.
2. Krom in baker močno spodbujata tvorbo perlita v SSDI, molibden, mangan, niobij in vanadij pa so šibki spodbujevalci tvorbe perlita. Pri različnih pogojih ohlajanja nismo opredelili bistvenega vpliva časa strjevanja ali števila vozlov na količino perlita, kajti učinek časa in učinek razdalje se medsebojno izenačujeta. Učinek spodbujanja tvorbe perlita pri proučevanih legirnih elementih se veča na enostaven in linearen način.
3. Vanadij in niobij močno vplivata na količino karbidov, prav tako pa medsebojno močno reagirata. Tudi krom in molibden precej vplivata na količino karbidov, nobenega zvečanja pri vsebnosti karbidov pa nismo zaznali pri dodatku 0,5 mas. % mangana. Zaključimo lahko, da karbidotvorni učinek Mn do neke mere kompenzira visoka vsebnost Si.

microstructure of SSDI EN-GJS-500-14 for different cooling conditions. With respect to this, the following conclusions can be outlined.

1. The solidification time chiefly impacts the nodule count. The nodularity depends on solidification time and the residual Mg-content. The concentration of carbide promoting elements additionally decreases the nodularity. Especially vanadium has a distinct negative impact on nodularity.
2. Chromium and copper are strong pearlite promoters in SSDI, whereas molybdenum, manganese, niobium and vanadium are weak pearlite promoters. For different cooling conditions, no significant impact of the solidification time or the nodule count on the amount of pearlite was found, because the time effect and the distance effect compensate for each other. The pearlite promoting effect of the alloying elements investigated adds up in a simple linear manner.
3. Vanadium and niobium have a strong impact on the amount of carbides and their interaction is significant. Chromium and molybdenum also have a distinct influence on the amount of carbides, whereas no increase of carbide content is found when 0.5 wt. % manganese is added. In conclusion, to some extent the carbide promoting effect of Mn is compensated by the high Si-content.

The regression formulas calculated allow the forecast of microstructure parameters from a given chemical composition, at least within the analyzed ranges. The scattering results of the carbide content at elevated levels of carbide promoting elements as well as the influence on the mechanical properties of SSDI will be presented in future publications.

Izračunane regresijske formule omogočajo napoved mikrostrukturnih elementov na podlagi kemijske sestave, vsaj v okviru analiziranih razponov. Rezultati raztrosa vsebnosti karbidov pri visokih količinah karbidotvornih elementov, pa tudi vpliv na mehanske lastnosti SSDI, bodo predstavljeni v prihodnjih objavah.

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