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Kontinuirno litje visokoogljičnega nanostrukturnega bainitnega jekla

Continuous Casting of High Carbon Nanostructured Bainitic Steel

Povzetek

V prispevku smo obravnavali strjevanje in razvoj mikrostrukture med navpičnim kontinuirnim litjem v laboratorijskem okolju. Izbrana zlitina je visokoogljično nanostrukturno bainitno jeklo s kemijsko sestavo (0,7C-5,5Mn-1Cr-1,5Al-0,6Mo).

Nanostrukturna bainitna jekla dosegajo izjemne kombinacije mehanskih lastnosti, ki hkrati povezujejo visoko trdnost in žilavost. To omogoča izjemno fina mikrostruktura, kjer znaša debelina plošč bainitnega ferita zgolj okrog 10 nm. Fina mikrostruktura se doseže z baininto transformacijo jekla pri zelo nizkih temperaturah od 200 °C pa vse do sobne temperature. Da bi zagotovili tako nizke transformacijske temperature, je treba znižati temperaturo začetka tvorbe martenzita Ms pod sobno raven. Posledično imajo ta jekla visoko vsebnost ogljika in so hkrati legirana z Mn, Cr, Ni in Mo. Dodatno se za zakasnitev oz. zavrtje izločanja karbidov tem jeklom posamezno ali v kombinaciji dodajajo visoke količine Si in Al. Zaradi kompleksne kemijske sestave predstavljajo ta jekla tehnološki izziv za izdelavo s tehnologijo kontinuirnega litja.

Trenutna preiskava je pokazala, da je novo razvito jeklo primerno za izdelavo s kontinuirnim litjem, kadar je mogoče zagotoviti stabilne razmere strjevanja.

Ključe besede: nanostrukturno bainitno jeklo, kontinuirno litje, segregacije

Abstract

The current research work describes the solidification and microstructure formation during vertical continuous casting of a high carbon nanostructured bainitic steel (0.7C-5.5Mn-1Cr-1.5Al-0.6Mo) in laboratory conditions.

Nanostructured bainitic steels achieve exceptional combinations of mechanical properties due to their very fine microstructure where the bainitic ferrite plate thickness is only about 10 nm. This very fine structure is obtained by bainite formation at very low temperatures below 200 °C and down to ambient level. To ensure such low transformation temperatures and suppress the formation of martensite below room temperature these steels have a high carbon content and are also alloyed with Mn, Cr, Ni, and Mo. Additionally, in order to suppress the precipitation of carbides during bainite formation, they contain high amounts of Si and Al either separately or in combination. Such a complex composition is challenging from the viewpoint of production using continuous casting.

It was observed that the newly developed steel can be successfully continuously cast, provided stable solidification conditions can be maintained during the casting process.

Keywords: Nanostructured bainitic steel, continuous casting, segregations

1 Uvod

Na letni ravni se s tehnologijo kontinuirnega litja izdela 1,2 milijarde ton jekla. Povečano povpraševanje po naprednih materialih zahteva nenehne izboljšave in dvig produktivnosti. Zagotavljanje potreb trga posledično vodi v različne izzive za proizvajalce in kontinuirno litje jekel z vedno bolj zahtevnimi kemijskimi sestavami [1]. Med ta jekla sodijo tudi visoko trdnostna jekla s transformacijsko podprto plastičnostjo (TRIP); te vrste jekel vsebujejo visok delež Al za stabilizacijo določenega deleža zadržanega avstenita [2]. S povišanjem vsebnosti ogljika in drugih legirnih elementov se zniža temperatura martenzitne premene pod sobno temperaturo in tako omogoči tvorbo nizkotemperaturnega bainita. Kadar poteka tvorba bainita pri temperaturah pod 250 °C, se debelina plošč bainitnega ferita giblje v nano območju.

Visoka vsebnost Al povzroči povišanje viskoznosti jekla, kar otežuje litje in lahko privede do neenakomerne površine ali celo površinskih napak [3], zato je potrebna visoka hitrost litja. Hkrati pa visoka vsebnost ogljika zniža toplotno prevodnost jekla [4], kar praviloma zahteva nižjo hitrost litja, da se tvori zadostno debela skorja. Višja vsebnost ogljika poviša tudi tendenco jekla k tvorbi mikro segregacij [5] in hkrati poviša trdoto po litju kot tudi občutljivost jekla na zarezni učinek. Razpoke, nastale iz površinskih napak, tako lažje napredujejo v notranjost. Namen trenutnega prispevka je ovrednotenje potenciala za nova visokoogljična nanostrukturna bainitna jekla z visoko vsebnostjo aluminija.

2 Materiali in tehnologije

Jeklo s kemijsko sestavo 0,7C-5,5Mn-1,5Cr-1,5Al-0,6Mo je bilo vertikalno kontinuirno lito na laboratorijski napravi. Visoka vsebnost

1 Introduction

Each year about 1.2 billion tons of steel are produced into semi-finished shapes using a continuous casting process. The demand for producing high-performance steel has increased which requires manufacturing via continuous casting to increase productivity and reduce production costs. These factors force steel producers to face different challenges to meet the customers' demands by producing steels of high quality with ever more demanding chemical compositions [1]. One such steel group is high strength transformation induced plasticity steels (TRIP), grades contain high Al to achieve the desired amount of retained austenite [2]. At increasing carbon content the transformation temperatures are decreased allowing for the formation of bainite at low temperatures. When bainite is formed at temperatures below 250 °C the plate thickness is in the nanostructured range.

The high Al content is known to increase the steels viscosity during pouring thereby leading to the formation of surface depressions [3] therefore requiring a high casting speed. Whereas the high carbon content decreases the steel thermal conductivity [4] and it is, therefore, necessary to cast slowly to obtain a sufficiently thick outer shell. Additionally, a higher carbon content makes the steel more susceptible to micro and macro segregations [5] as well as increases the cast hardness and notch sensitivity of the cast billet thereby cracks can easily propagate from depressed regions. The current work aims to evaluate the potential for successful continuous casting of a novel high carbon, high aluminium TRIP steel.

Al poviša viskoznost taline, medtem ko je po strjevanju jeklo nagnjeno k nastanku razpok zaradi visoke vsebnosti ogljika, kar predstavlja izziv za uspešno izvedbo kontinuirnega litja. Poskus je bil izveden na napravi za laboratorijsko vertikalno kontinuirno litje Technica-Guss GMBH 30 E. Sklop sestoji iz okrogle šobe premera 10 mm, kokile, vhodne šobe, vodno hlajene bakrene kokile in potisne palice, kot je shematsko prikazano na Sliki 1. Jeklo je bilo indukcijsko pretaljeno v vakuumu, pred litjem je bila komora napolnjena z argonom, in sicer za zmanjšanje poroznosti. Pred litjem je bila temperatura taline 1560 °C. Postopek kontinuirnega litja poteka po korakih, pri čemer se potisna palica odmakne za določeno razdaljo-korak, kar talini omogoča, da steče v šobo in vodno hlajeno kokilo, kjer se zadrži za določen čas in pri tem strdi. Ključni parametri hitrosti litja so dolžina koraka in čas zadrževanja, saj določajo stabilnost procesa in kakovost površine lite gredice. Stabilni parametri so bili doseženi pri dolžini koraka 2 mm in času zadrževanja 6 s. Iz gredice smo izrezali vzorce v vzdolžni in prečni smeri vzdolž srednje ravnine gredice. Vzorci so bili zaliti v bakelitno maso in metalografsko pripravljeni ter jedkani z barvnim jedkalom LePera. Mehanske lastnosti gredice v litem stanju so bile določene z nateznim preskusom v vzdolžni smeri.

3 Rezultati in diskusija

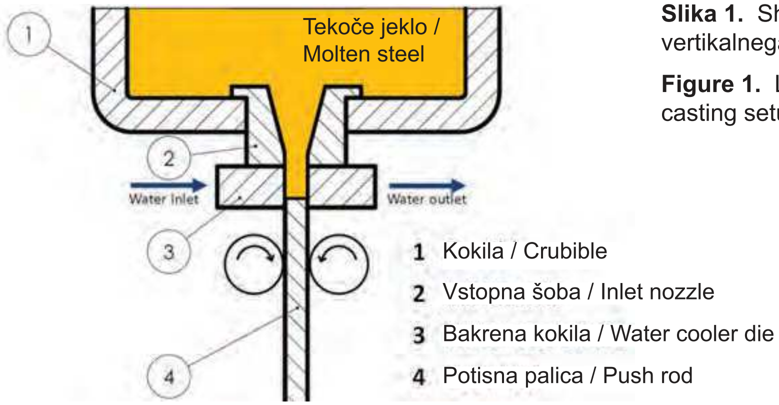
Znotraj stabilnih parametrov litja je strjena mikrostruktura, sestavljena iz globulitne cone na robu, ki preide v usmerjeno dendritno strjevanje proti sredini palice. Vidni so pasovi pozitivne in negativne segregacije, kot prikazujeta Slika 2 na prečnem prerezu in Slika 3 na vzdolžnem prerezu. Kot prikazuje Slika 2, je mikrostruktura znotraj pozitivno segregiranih območij sestavljena

2 Materials and methods

The steel of composition 0.7C-5.5Mn-1.5Cr-1.5Al-0.6Mo, was continuously cast in a laboratory setup. Due to the high Al content, the steel has reduced fluidity whereas the high carbon content increases the as cast hardness and the tendency for cracking, making this steel challenging for the continuous casting process. The laboratory setup on continuous casting machine Technica-Guss GMBH 30 E, consists of a crucible, inlet nozzle, water-cooled Cu die, and push rod as shown schematically in Fig. 1. The steel was induction melted in vacuum, before casting the chamber was filled with pure argon to reduce porosity. Before casting the melt temperature was 1560 °C. The continuous casting process is stepwise whereby the pushrod is withdrawn a certain length (step) allowing molten steel to flow into the inlet nozzle and water cooled crucible where it is held for a period of time to solidify. The parameters of holding time casting speed and step length are the most crucial in determining the stability of the cast billet. The casting step was 2 mm with a 6 s holding time. Samples for metallography were taken in the transverse and longitudinal direction along the midsection of the bar, mounted in resin and metallographically prepared, followed by tint etching using LePera reagent. The as cast ductility was determined using tensile testing in the longitudinal direction.

3 Results and Discussion

Within stable casting parameters, the solidification structure consists of positive and negative segregation bands visible in both the transverse and longitudinal directions in Fig. 2 and Fig. 3. Within regions of positive segregation an austenitic dendritic structure forms,



Slika 1. Shematični prikaz vertikalnega kontinuirnega litja

Figure 1. Laboratory continuous casting setup

Slika 2. Mikrostruktura kontinuirno lite gredice v prečnem prerezu. Vidni so potek strjevanja, segregacije in osrednja poroznost (jedkano z reagentom Le Perra)

Figure 2. Microstructure of continuously cast bar in the transverse direction, showing solidification pattern and segregation as well as porosity in the central region (etched with LePera)

Slika 3. Mikrostruktura kontinuirno lite gredice v vzdolžnem prerezu. Vidni so kot strjevanja in segregacije (jedkano z reagentom Le Perra)

Figure 3. Microstructure of continuously cast bar in the longitudinal direction, showing solidification pattern based on orientation at the angle of the melt pool (etched with LePera)

iz dendritov avstenita, znotraj območij negativne segregacije pa se tvori martenzit. Dodatno je na Sliki 2 vidna lokalna

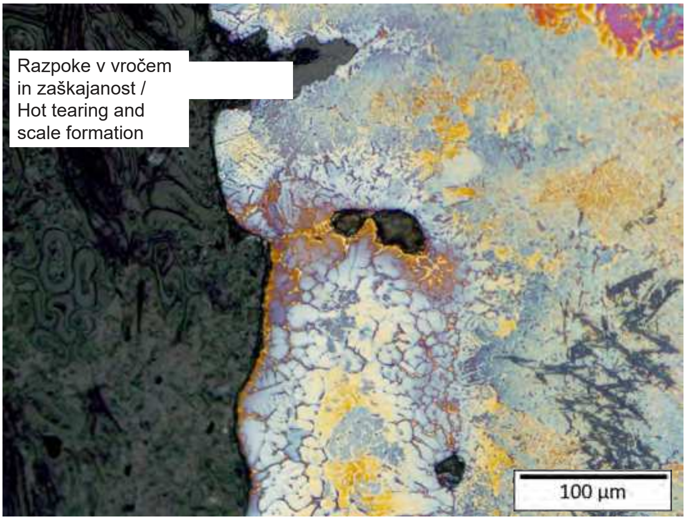
whereas in regions of negative segregation martensite is formed with inter-dendritic retained austenite as shown in Fig. 2.

poroznost v osrednjem delu gredice, kar je bilo pričakovati glede na slabo fluidnost taline. Smer strjevanja je pod kotom, kot je razvidno iz Slike 3. To nakazuje, da se gredica prične strjevati na stični površini s kokilo, medtem ko je osrednji del segret zaradi stika z zgornjo talino, ki bo ulita v naslednjem koraku.

Na površini gredice so prisotne vdolbine, ki so deloma zalite in zato vidne

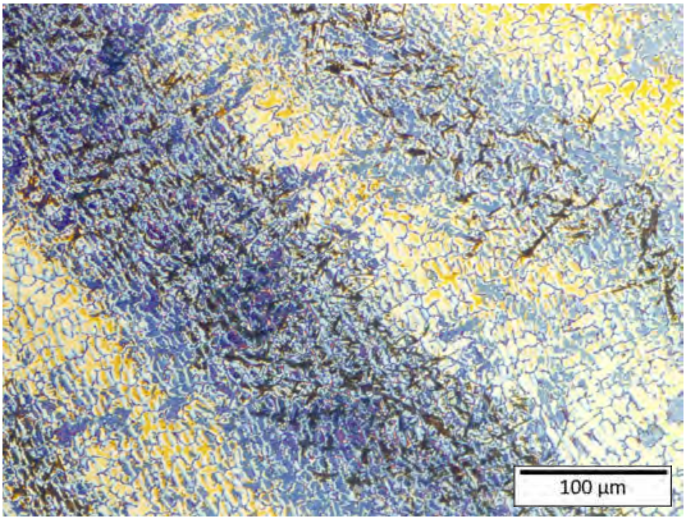
Additionally, Fig. 2 shows some centreline porosity, which is to be expected with this production process in steel with low fluidity. The solidification direction is at an angle as clearly visible in Fig. 3, this occurs as the steel solidifies first at the die surface whereas the central region is heated by the molten metal cast in the next step.

As can be expected depressions and subsurface porosity occur at the junction



Slika 4. Površinske napake in podpovršinska poroznost, (jedkano z reagentom Le Perra)

Figure 4. Surface depression and subsurface porosity, etched with Le Perra reagent



Slika 5. Trakasta mikrostruktura v notranjosti kontinuirno lite gredice. Martenzit je obarvan temno, dendriti avstenita pa rumeno/modro (jedkano z Le Perra reagentom)

Figure 5. Banded microstructure within the continuously cast bar, Positive segregation bands contain martensite (dark) and negative segregation bands consist of austenitic dendrite structure (yellow), etched with Le Perra reagent

kot podpovršinska poroznost kot prikazuje Slika 4. Ta pojav je posledica slabe fluidnosti taline, je pa znano, da se lahko v praksi v veliki meri prepreči z uporabo ustreznih livnih praškov [6]–[8]. To pomeni, da se kljub visoki vsebnosti Al lahko izdelajo gredice z ustrezno površino za nadaljnje valjanje.

Notranjost kontinuirno lite gredice ima trakasto mikrostrukturo, sestavljeno iz martenzita, ki se tvori znotraj območij negativne segregacije, na Sliki 5 je obarvana temno. Predpostavlja se, da je prišlo do segregacije predvsem C in Mn. Izračunana temperatura začetka martenzitne premene Ms za to jeklo znaša -58 °C, kar je pod sobno temperaturo, zato je pričakovati moč avstenitno/bainitno mikrostrukturo.

Jekla, ki imajo srednje vsebnosti Mn (okoli 5 %) in visok delež ogljika, so podvržena tvorbi izrazito trakaste mikrostrukture [9], ki je posledica hkratne segregacije C in Mn [10]. Ta elementa imata visoko medsebojno afiniteto in sta visoko mobilna med potekom strjevanja.

Kljub visoki vsebnosti C je trdota jekla v litem stanju samo 52 HRC. Na liti gredici so bile določene mehanske lastnosti z nateznim preskusom, kjer so bili izmerjeni natezna trdnost 1476 MPa in raztezek A5 13 % ter kontrakcija Z 32 %. Deformacija je najverjetneje lokalizirana znotraj avstenitnih območij, visok delež avstenita in deloma tudi poroznost pa sta glavna vzroka relativno nizke trdote, še posebej pa nizke trdnosti v primerjavi s trdoto.

4 Zaključki

Novo razvito jeklo je primerno za proizvodnjo s tehnologijo vertikalnega kontinuirnega litja, pri čemer je treba zagotoviti stabilne razmere litja. Segregacije in osrednja poroznost so znotraj pričakovanih okvirjev za takšno vrsto jekla in se lahko v veliki meri odpravijo

point of the stepwise casting process as shown in Fig. 4. However, these have been shown to be successfully mitigated using appropriate mold powders[6]–[8] resulting in billets of good surface quality for further processing by rolling.

The interior of the continuously cast bar exhibits a banded microstructure with martensite forming within bands of negative segregation as these contain less Mn and C. The calculated Martensite start (Ms) temperature for this steel composition is -58 °C, which is below room temperature therefore in the absence of segregation an austenitic/bainitic microstructure could be expected.

Steels containing medium manganese and high carbon content are known to be prone to banding [9], due to co-segregation of Mn and C [10], which have a high affinity towards each other and are both highly mobile during solidification.

Despite the high carbon content the as cast microstructure achieves a hardness of 52 HRC, During tensile testing we obtained a UTS of 1476 MPa and an elongation A5 13% and 32% contraction. The discrepancy between hardness and obtained UTS is likely due to casting defects most notably porosity.

4 Conclusions

The steel can be successfully vertically continuously cast provided stable conditions can be maintained, segregation and porosity content are within expected regions, and likely to homogenize during high-temperature annealing treatment before hot rolling. No coarse precipitates or large inclusions were observed within the microstructure. It would seem that the surface depressions cannot be entirely mitigated using vertical continuous casting z visokotemperaturno homogenizacijo pred nadaljnjo plastično predelavo. Znotraj mikrostrukture gredice ni bilo prisotnih grobih izločkov ali velikih nekovinskih vključkov. Zdi se, da površinskih napak brez uporabe livnih praškov ni mogoče preprečiti med vertikalnim kontinuirnim litjem. Znotraj območij negativne segregacije se tvori martenzit, ki pa ne zniža celotne duktilnosti gredice, saj deformacija poteče predvsem znotraj avstenitnih območij, nastalih znotraj območij pozitivne segregacije.

without applying a suitable mold powder, the formation of martensite within negative segregation bands does not impair the overall ductility of the continuous cast bar due to the high austenite content within positive segregation bands which provide sufficient overall plasticity.

Viri / References

[1] E. Commission, *Continuous casting of high-carbon steels in billet and bloom sections at sub-liquidus temperatures*.

[2] B. C. De Cooman, "Structure-properties relationship in TRIP steels containing carbide-free bainite," *Curr. Opin. Solid State Mater. Sci.*, vol. 8, no. 3–4, pp. 285–303, 2004, doi: 10.1016/j.cossms.2004.10.002.

[3] H. Cui *et al.*, "Formation of surface depression during continuous casting of high-Al TRIP steel," *Metals (Basel).*, vol. 9, no. 2, pp. 1–9, 2019, doi: 10.3390/met9020204.

[4] K. Kinoshita, Y. Yoshii, H. Kitaoka, A. Kawaharada, K. Nishikawa, and O. Tanigawa, "Continuous Casting of High Alloy Steels.," *Metall. Soc. AIME, TMS Pap. Sel.*, vol. 60, pp. 429–444, 1983.

[5] A. Nicholas Grundy, S. Münch, S. Feldhaus, and J. Bratberg, "Continuous Casting of High Carbon Steel: How Does Hard Cooling Influence Solidification, Micro - And Macro Segregation?," *IOP Conf. Ser. Mater. Sci. Eng.*, vol. 529, no. 1, 2019, doi: 10.1088/1757-899X/529/1/012069.

[6] W. Yan, A. McLean, Y. Yang, W. Chen, and M. Barati, "Evaluation of mold flux for continuous casting of high-aluminum steel," *Adv. Molten Slags, Fluxes, Salts Proc. 10th Int. Conf. Molten Slags, Fluxes Salts 2016*, pp. 279–289, 2017, doi: 10.1007/978-3-319-48769-4_30.

[7] K. Zhang, J. Liu, and H. Cui, "Investigation on the slag-steel reaction of mold fluxes used for casting al-trip steel," *Metals (Basel).*, vol. 9, no. 4, 2019, doi: 10.3390/met9040398.

[8] H. Steel, "Advances in Molten Slags, Fluxes, and Salts: Proceedings of the 10th International Conference on Molten Slags, Fluxes and Salts 2016," *Adv. Molten Slags, Fluxes, Salts Proc. 10th Int. Conf. Molten Slags, Fluxes Salts 2016*, no. January, 2016, doi: 10.1007/978-3-319-48769-4.

[9] S. a. Khan and H. K. D. H. Bhadeshia, "The bainite transformation in chemically heterogeneous 300M high-strength steel," *Metall. Trans. A*, vol. 21, no. 3, pp. 859–875, 1990, doi: 10.1007/BF02656570.

[10] Y. N. Dastur and W. C. Leslie, "Mechanism of work hardening in Hadfield manganese steel," *Metall. Trans. A*, vol. 12, no. 5, pp. 749–759, 1981, doi: 10.1007/BF02648339.