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Podaljšanje življenjske dobe kokil iz jekla za delo v vročem za tlačno litje s popravljalnim varjenjem z elektronskim curkom ob integrirani lokalni toplotni obdelavi

Life extension of high-pressure die casting molds made of hot-work steels by regenerative electron-beam welding with local process-integrated heat treatment

Izvleček

Na ekonomsko učinkovitost celotnega procesa tlačnega litja bistveno vpliva življenjska doba uporabljene kokile. Takšne kokile so med postopkom litja stalno izpostavljene velikim toplotnim, mehanskim, kemičnim in tribološkim cikličnim obremenitvam. Te obremenitve lahko povzročajo različne napake na kokili ali v kokili, zato se občutno skrajša njihova življenjska doba. Če se proizvodnja nenačrtovano ustavi zaradi kritične napake v kokili, je popravljalno varjenje pogosto edini način med proizvodnjo za njeno ponovno uporabo. Sedaj se za takšna rutinska popravila največ uporablja TIG-varjenje ali plazemsko varjenje. Vendar so te standardne tehnike popravljalnega varjenja nezadostne za zanesljivost in zato se z njimi ne doseže zanesljivo podaljšanje življenjske dobe. Proces popravljalnega varjenja namesto ponovne izdelave kokile je vsekakor ekonomsko in tehnično izvedljiv, če se varjenje uporabi takoj, in zanesljiv, s čemer se v zadostni meri podaljša življenjska doba.

Glavni cilj tega prispevka je razvitje tehnologije za popravo lokalno poškodovanih orodij za litje s poudarkom na metalurških lastnostih, da se s tem dosežejo boljše lastnosti v primerjavi s standardnimi tehnikami popravljalnega varjenja, kot je TIG-varjenje ali plazemsko varjenje. Tehnika varjenja z elektronskim curkom dovoljuje spremenljivo, potrebam prilagojeno načrtovanje toplotne bilance in uporabo dodajnih materialov. Zato se jo lahko imenuje popravljalno varjenje za jekla, ki se industrijsko uporabljajo za delo v vročem. Prispevek se začenja s pregledom značilnih vrst poškodb kokil. Poleg tega bodo pojasnjene metode navadnega popravljalnega varjenja kokil, kot sta TIG-varjenje ali plazemsko varjenje, v primerjavi z varjenjem z elektronskim curkom. Prispevek tudi pojasnjuje tehniko in možnosti varjenja z elektronskim curkom kot način popravljalnega varjenja. Za zaključek bodo prikazani trenutni doseženi rezultati in predstavljene nadaljnje raziskave.

Abstract

The economic efficiency of the whole high-pressure die-casting process is essentially influenced by the lifetime of the used die casting die. Such dies are constantly exposed by high thermal, mechanical, chemical, and tribological cyclic loads during the operation. These loads might cause different defects on or in the mould and thereby reduce the die lifetime significantly. In the case of an unexpected production stop caused by a critical defect in the mould, repair welding is often the only way of reinstating the casting tool during the production. Currently, the TIG or plasma welding processes are mainly used for such repair welding routines. Nevertheless these conventional repair welding techniques constitute

an insufficient process reliability and therefore achieve an insufficient life extension. A repair welding process instead of a remanufacture of a die is, however, economically and technically feasible, if the welding is done immediately and reliably and results in a sufficient lifetime.

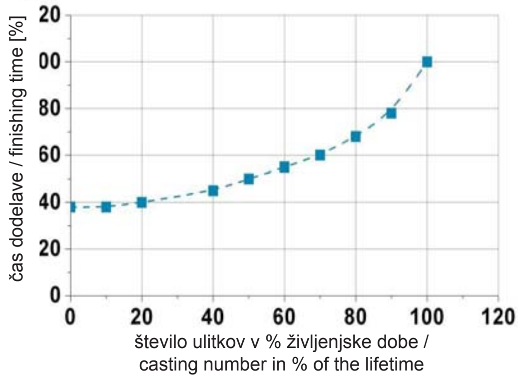
The primary objective is thus the development of a technology for an economic regeneration of locally damaged die casting tools, focusing on the metallurgical properties with improved properties compared to conventional repair welding techniques such as TIG or plasma welding. The electron-beam welding technique allows a variable, needs-adapted design of the overall heat balance and the use of filler material; therefore it is going to be qualified as a repair welding technology for industrially used hot-work steels. This article starts with an overview of the typical types of damages to die casting moulds. Furthermore, common repair welding methods for die casting moulds, like TIG- or plasma welding will be explained for a comparison to the electron-beam welding. The article also explains the technique and potential of the electron-beam welding as a repair welding method. To sum up this article, the current achieved results and the following researches will be presented.

1 Uvod

Trajne forme za tlačno litje se imenujejo kokile. To pomeni, da se te forme lahko vedno znova uporabijo pri litju, ne da bi bilo potrebno ponovno formanje s trajnim modelom. To dejstvo dovoljuje cenovno učinkovit proizvodni proces z velikim številom enot, ki se uvršča med postopke tlačnega litja in je idealna metoda za izdelavo velikih serij [1]. V tem procesu ima vsaka kokila bistveno vlogo. To pomeni, da je ekonomičnost vsakega procesa tlačnega litja bistveno odvisna od dosežene življenjske dobe kokile. Do 50 % stroškov za uliti sestavni del predstavlja izdelava in vzdrževanje orodja za tlačno litje. Zato se zahteva v vsakem primeru najdaljša možna življenjska doba kokile F2G. Kakovost površine ulitka je tudi neposredno povezana s kakovostjo površine kokile. Poškodbe zaradi procesa in propadanja materiala, ki se stalno povečujejo z vsakim ulitkom in se kažejo na t.i. funkcionalnih površinah ulitka, je treba obdelati ročno, kar je časovno zamudno in zahteva velike napore. Trud pri strojni dodelavi bo vse večji z naraščajočo stopnjo propadanja materiala. To korelacijo

1 Introduction

The moulds used in high-pressure die casting are so-called permanent moulds. This means that these moulds can be reused constantly after each casting without requiring them to be moulded again by a permanent pattern. This fact allows a cost-effective production process with a high number of units and classifies the high-pressure die casting as being the ideal manufacturing method for the production of large series [1]. In this process each mould plays a decisive role. This means that the profitability of each die casting process is significantly influenced by the achievable lifetime of the form. Up to 50 % of the cost for one cast component might be applied to the production and maintenance of die casting tools. Hence, a maximum lifetime of the form is to be demanded in each case [2]. The surface quality of the cast component, too, is directly correlated with the surface quality of the permanent mould. The process-related damages and deteriorations increasing constantly with every cast component and map onto to the so-called functional surfaces of the cast component,



Slika 1: Vpliv števila ulitkov na čas dodelave [3]

Figure 1: Influence of the cast number on the finishing time [3]

kaže diagram na sliki 1 kot čas, potreben za dodelavo vsakega ulitka [3]. To je ali postopek popravljalnega varjenja ali celo izdelava nove kokile ali kokilnega vložka, če so napori in s tem stroški strojne dodelave neekonomični [2].

Zaradi velikih izdelovalnih stroškov novega kokilnega vložka, ki lahko dosegajo do 50 % začetnih stroškov novega kokilnega vložka in stalnega stroškovnega pritiska na livarne, se raje uporablja popravljalno varjenje namesto izdelave novega vložka ali kokile [4]. Zato je časovno ugodno in zanesljivo popravljalno varjenje poškodovane kokile še bolj pomembno.

2 Vrste poškodb kokil

Na osnovi izkušenj pri tlačnem litju aluminija v zadnjih desetletjih lahko danes livarne ugotovijo in pojasnijo značilne poškodbe, ki pripeljejo do zloma kokile za tlačno litje. Osnovno poznavanje poškodb, ki nastajajo na kokilah in mehanizma njihovega nastanka je zelo pomembno pri popravljalnem varjenju. Podaljšanje življenjske dobe s popravljalnim varjenjem je možno le s tem znanjem. Zato bomo v

must be reworked manually, which is time-intensive and requires a great effort. The effort of the machine finishing will be more and more complex with the increasing degree of degeneration. This correlation is shown in the diagram in Figure 1 as a the finishing time for each cast component [3]. There is either a repair process by means of welding or even the new production of a mould or a mould insert, if the effort and thus costs for the machine finishing will be uneconomical[2].

Due to the high costs for the production of a new mould insert, which can amount to at least 50 % of the initial cost of a new mould insert, and the continuous cost pressure on the foundries, repair welding instead of new manufacturing is to be preferred [4]. Thus, a timely and reliably conducted repair welding process of a damaged die casting mould takes on even more importance.

2 Types of damage to die-casting molds

Based on the experiences collected over the last decades in the field of aluminum die casting, the foundries are nowadays able to identify and explain the characteristic damages which lead to a breakdown of die casting moulds. The fundamental knowledge of the damages occurring on the molds and their formation mechanism is very important for the application of the repair welding. An increase of the lifetime by using repair welding is only possible with that knowledge. In the following, therefore, the three typical types of damage are explained in detail.

Stress cracks occur sporadically and preferably in areas where, due to the engraving geometric and thermal stress concentrations can occur. This can happen after a few hundred casts and is nadaljevanju prispevka podrobno opisali tri značilne vrste poškodb.

Napetostne razpoke se pojavljajo občasno in predvsem na območjih, kjer se te lahko pojavljajo zaradi geometrije poglobitev v kokili in toplotno vplivanih koncentracij napetosti. To se lahko zgodi po nekaj sto ulivanjih in je posledica lokalnega utrujanja materiala zaradi cikličnih temperaturnih sprememb v kokili. Značilne za to vrsto poškodbe so široke in globoke razpoke, zaradi katerih se lahko odlomijo posamezni kosi kokile. Zareze, robovi in spremembe prerezov z zelo majhnim polmerom ukrivljenosti so s stališča geometrije kokile območja velikega tveganja za nastanek napetostnih razpok. Z vidika vpliva toplote predstavljajo veliko tveganje mesta, kjer se pojavlja dvodimenzijski prenos toplote [2,5].

Pokanje zaradi toplotne utrujenosti je glavni vzrok za zlom kokil za tlačno litje in se lahko pojavi po več kot okoli 2000 ulivanjih. Ta vrsta razpok se pojavlja za razliko od napetostnih razpok predvsem na ravnih delih, kjer ni makroskopskih koncentracij napetosti. Za pokanje zaradi toplotne utrujenosti je značilno mrežasto pojavljanje drobnih razpok na površini. Posamezna razpoka lahko sega le nekaj mm globoko v material. Če se razpoke zaradi toplotne utrujenosti pojavijo na površini kokile, jih bo le po nekaj novih nastalo med nadaljnjimi ulivnimi cikli. To se lahko razloži z zmanjšanjem notranjih napetosti, kar je posledica plastičnega obnašanja ustij razpok. Čeprav pokanje zaradi toplotnega utrujanja nima podobnih posledic kot napetostne razpoke, lahko vseeno vodi do poslabšanja kakovosti površine ulitka. Od določene stopnje naprej, kar je odvisno od zahtev, da je površina ulitka funkcionalna in dobra na otip, se te napake ne morejo tolerirati in lahko tudi vplivajo na doseganje želene življenjske dobe delovanja [2].

the result of a local material fatigue due to the cyclic temperature changes within the die. Characteristic of this type of damage is often a strong and deep crack growth, which can even lead to the individual mould pieces breaking away. Notches, edges, and cross-sectional transitions with very small radii are the areas with a high risk for stress cracks, from the geometrical point of view. From the thermal point of view radii, where the heat transfer takes place in two dimensions, are a big risk [2,5].

Heat checkings are considered to be the main reason for the breakdown of die casting molds and can occur after about 2000 casting cycles. This crack type appears unlike the stress cracks predominantly in the form of flat areas in which no macroscopic stress concentrations exist. The appearance of the heat checkings is characterized by a net-like surface structure plan. One single crack can thereby extend only a few millimeters into the material. If heat checkings occur on the surface of a mould, only a few will be developed during the following casting cycles. This fact can be explained by the reduction of the internal stress, which is a consequence of the plastic behaviour of the crack opening. Although the heat checkings do not have similar consequences as the stress cracks, they still lead to a significant deterioration of the surface quality of the cast component. To a certain degree, which depends on the requirements of the surface to function and feel, these defects cannot be tolerated and might also lead to the achievement of the service life [2].

Erosion is traced back to the mechanism of the abrasion and caused by the rapid and relative movement between the molten aluminum and the mould surface. In this case, the melt can be considered as a viscous liquid containing abrasive particles such as silicon, oxides or

Erozija lahko spremlja mehanizem obrabe, povzročajo pa jo hitra relativna gibanja med staljenim aluminijem in površino kokile. V tem primeru se talina lahko smatra kot viskozna tekočina, ki vsebuje abrazivne delce, kot so silicij, oksidi ali intermetalne faze. Če se pojavlja turbuletno gibanje v profilu toka, ki ga povzroča oblika kokile, nastajajo vrtinci in abrazivni delci so potisnjeni k steni kokile. Sile, ki pri tem delujejo na steno kokile, povzročajo odnašanje delcev materiala s površine kokile. Rezultat tega je žlebasta površina. Poškodbe se pojavljajo predvsem na območjih odnašanja in nanašanja materiala, kjer so največje hitrosti tokov in tlakov taline. Predvsem območja, kjer se spreminja smer toka taline, in robovi so najbolj nevarni za erozijo [6,7].

Tri značilne vrste poškodb prikazuje slika 2.

3 Standardne metode popravljalnega varjenja kokil za tlačno litje

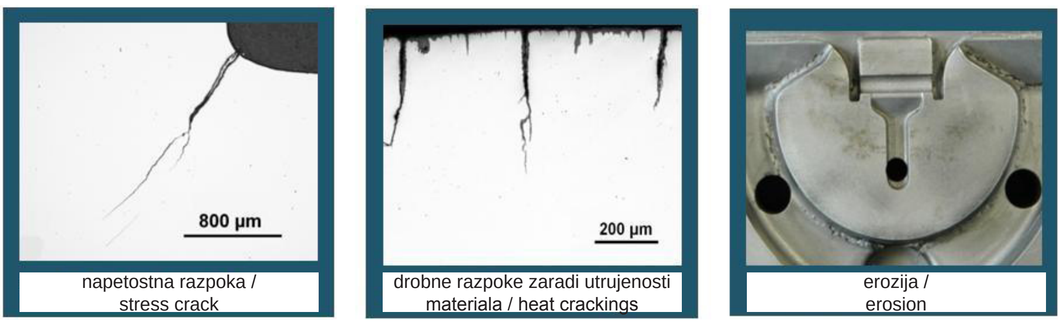
Popravljalno varjenje kokil za tlačno litje je že več desetletij uveljavljen in učinkovit način za podaljšanje uporabe poškodovanih kokil. Za to se uporabljajo različni varilni postopki, med drugim TIG-varjenje ali plazemsko

intermetallic phases. If there are turbulent flows in the flow profile caused by the shape of the mould, vortexes will be formed and the abrasive particles thrown against the mould surface. The forces, which affect thereby onto the mould surface, cause the material particles to be separated from the surface. Trough-like formed contours are the result. The damage occurs mainly in the excavating and filling areas,where the highest flow velocities and melt pressures are reached. Especially melt deflections and edges represent erosion hazard areas [6,7].

The three typical types of damage are shown in the figure 2.

3 Conventional repair welding methods for pressure casting moulds

The repair welding of die casting moulds has been established over the decades as an effective means for the continued use of damaged forms. For this purpose, various welding processes are used, although the manual TIG or plasma welding processes are used, due to the relatively low-cost system technology. Repair welding are also increasingly performed by using the semi-automated laser surface cladding [8].



Slika 2: Značilne napake na kokilah za tlačno litje.

Figure 2: Typical damages on high pressure die casting molds

varjenje, ker predstavljajo sorazmerno ceneno tehnologijo. Popravljalno varjenje se tudi vse več uporablja s postopkom polavtomatiziranega laserskega navarjanja [8].

3.1 TIG-varjenje in plazemsko varjenje

Poleg primerne izbire varilnega postopka je za doseganje dolge življenjske dobe pomembno tudi celotno vodenje popravljalnega varjenja. To pomeni, da so predvsem priprava vara, izbira dodajnega materiala in temperaturni profil med postopkom obnove kokile pomembni za trajnostno popravljalno varjenje [9].

Material kokile, ki se največ uporablja pri tlačnem litju aluminija, je jeklo 1.2343 (X38CrMov5-1) za delo v vročem. Zaradi sorazmerno velikih deležev ogljika, molibdena, vanadija in kroma to jeklo ni zelo dobro varivo. Ravno ti zlitinski elementi, ki prispevajo k dobri kaljivosti, predstavljajo pri varjenju veliko tveganje za utrjevanje materiala s kaljenjem in za pokanje. Da se pri varjenju izognemo tem napakam, je pomembno, da se pri varjenju segreje kokilni vložek nad temperaturo začetka tvorbe martenzita pri okoli 320 ^{o}C. Vendar se je treba izogniti predgrevanju nad 450 ^{o}C, ker to lahko to pripelje do pojava krhkosti osnovnega materiala [9]. Predvsem popravljalno varjenje velikih kokilnih vložkov predstavlja težave pri TIG-varjenju ali plazemskem varjenju. Poleg velike porabe časa in energije pri predgrevanju kokilnih vložkov se pojavlja tudi zapleten nadzor temperature. To pomeni, da je težko doseči ponovljivost.

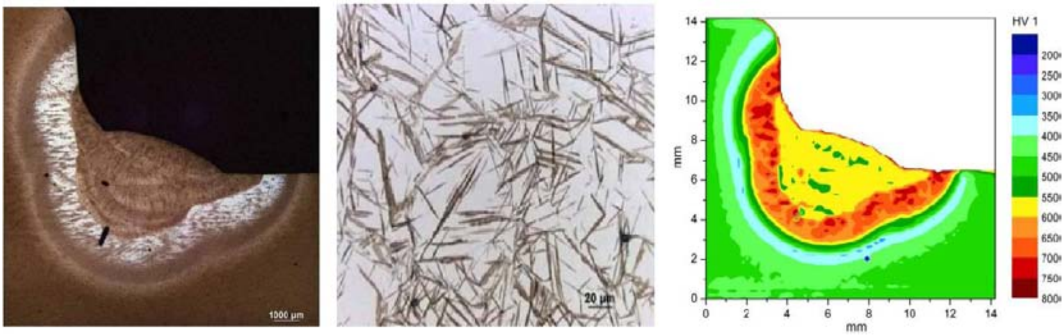
Kot posledica nezadostnega predgretja kokile ali predolgega ohlajanja pred začetkom popravljalnega varjenja se pojavlja zelo velika trdota mikrostrukture vara, kot se lahko vidi na sliki 3. To lahko tudi pripelje do makrorazpok v navaru.

3.1 TIG-/Plasma welding

In addition to the appropriate welding process, however, the whole process management of the repair welding is also an important factor for achieving a high lifetime. That means that especially the preparation of the weld, the choice of filler material and the temperature profile during the regeneration process may cause a sustainable repair welding [9].

The mould material mostly used in aluminium die casting is the hot-work steel 1.2343 (X38CrMoV5-1). Due to its relatively high carbon, molybdenum, vanadium and chromium contents, this steel is not very well weldable. Just these alloying elements that contribute to a good hardenability of the hot-work steel, constitute a high risk of hardening and cracking during welding. To avoid these welding failures it is essential to heat the mould insert before welding to above the martensite start temperature of about 320 °C. However, preheating temperatures should be avoided above 450 °C, as this may lead to embrittlement of the base material [9]. Particularly the repair welding of large mould inserts shows the difficulties in TIG or plasma welding. In addition to the high time and energy consumption during preheating of the mould inserts there is the complex handling of the temperature control. This means that the reproducibility is difficult to achieve.

As a consequence, insufficient preheating of the die or a too long cooling prior to performing the repair welding cause a very high hardness in the weld microstructure, which can be seen in Figure 3 left. This may also lead to macro cracks in the weld deposit. An absolutely necessary downstream heat treatment may reduce the hardness in the weld structure within certain limits, by welding martensitic materials. Apart from the outstanding hardness peaks,



Slika 3: Poliran prerez vzorca, varjenega po TIG-postopku z jasno vidnimi martenzitnimi iglami in razporeditvijo trdote

Figure 3: Cross-section polish with clearly identified martensite needles and a hardness allocation of a TIG-welded sample

Absolutno potrebno je, da toplotna obdelava, ki sledi, v določenih mejah zmanjša trdoto mikrostrukture vara pri varjenju martenzitnih materialov. Poleg izrazitih konic trdote je opaziti tudi območja, kjer so vrednosti trdote v toplotno vplivani coni manjše od trdote osnovnega materiala. To povzročajo učinki segrevanja zaradi dovajanja toplote med varjenjem. Omejitveni faktor pri tem je zahteva, da toplotna obdelava ne sme vplivati na osnovni material. Zaradi velike trdote se pojavlja še metalurška zareza v toplotno vplivani coni. Kljub končni strojni obdelavi površine lahko ta zareza med litjem hitro pripelje do ponovne razpoke in zloma kokile v okolici popravljelnega varjenja. Slika 3 kaže primer poliranega makroobrusa in ustrezno dvodimenzijsko porazdelitev trdote pri popravljalnem plazemskem varjenju.

3.2 Lasersko navarjanje

Med laserskim navarjanjem se dodajni material v obliki prahu ali žice vloži v interakcijsko cono med laserskim snopom in osnovnim materialom, da se stali in z metalurško vezjo veže s podlago. V primerjavi s TIG-varjenjem ali plazemskim varjenjem je za lasersko navarjanje značilna

also areas with hardness values in the heat-affected zone below the base material are noted. These are caused by annealing effects due to the heat input during the welding process. The limiting factor here is the requirement that the base material must not be influenced by the heat treatment. Because of the high hardness there is still a metallurgical notch in the heat-affected zone. Despite the final machining of the the surface, this notch might quickly lead to a renewed crack and a failure of the permanent mould in the environment of the repair weld during the casting process. Figure 3 shows an exemplary macro cross-section polish and the corresponding two dimensional hardness distributions of a plasma weld repair.

3.2 Laser surface cladding

During the laser surface cladding process a filler material composed of powder or wire is placed into the interaction zone of the laser beam with the base material, melted and bonded to the substrate via a metallurgical bond. Compared to the TIG or plasma welding the laser surface cladding is characterized by a low and precisely majhna in natančno krmiljena količina dovedene toplote. To lahko povzroči majhno izveganje, manjši prenos toplote na osnovni material in skoraj končno obliko varjenca ter majhno porabo dodajnega materiala.

S prilagoditvijo parametrov procesa je možno uporabiti plast debeline 1 – 2 mm kot tudi zelo tanke plasti od 0,05 do 0,1 mm. Sočasno dodajanje različnih prahov, ki se lahko dodajajo neodvisno drug od drugega, omogoča mešanje materialov tako, da se lahko uporabi npr. karbide v kovinski osnovi ali gradirane plasti. Postopek se lahko uporabi tako za navarjanje z enakim materialom 1.2343, kot tudi za navarjanja z različnimi materiali [10].

Tvorba laserskega curka je drugačna kot pri selektivnem laserskem taljenju (SLM – selective laser melting), kjer laserske plasti določajo laserska polja posteljic prahu, ki se talijo. V industrijski tehnologiji tlačnega kokilnega litja se uporablja proces SLM z nikljevim martenzitnim materialom 1.2709 [11,12]. Uporabnost martenzitnega jekla za delo v vročem, kot je jeklo 1.2343, se trenutno še raziskuje [13]. Tu se pojavlja težava z nastajanjem razpok v strojnem delu zaradi lokalnih temperaturnih gradientov in s tem povezanih napetosti. Težave se stalno poskuša reševati s predgrevanjem kopeli, nastale iz prahu.

Ročno ali polavtomatsko varjenje z laserskim snopom predstavlja sodoben način popravljalnega varjenja pri tlačnem litju. Vendar je treba tu narediti kompromis pri izbiri dodajnega materiala, da se zagotovi varivost. Navadno se uporablja dodajni material z deležem ogljika manjšim od deleža v osnovnem materialu. Da bi se preprečila zmanjšana trdnost in kaljivost, se dodajnemu materialu npr. dodaja molibden. Ta element je karbidotvorec in povečuje tudi kaljivost in varivost.

Bistvena pomanjkljivost varjenja z laserskim snopom je optična odbojnost

controlled amount of heat contribution. This might cause a low shape distortion, a lower heat transfer to the base material and a near net shape and resource-conserving application of the filler matieral.

By adjusting the process parameters it is possible to apply layer thicknesses of 1-2 mm as well as very thin layers of 0.05-0.1 mm. A simultaneous feeding of several powders, which are charged independently of each other, allows the mixing of materials so that, for example, carbides in a metallic matrix or graded layers can be applied. The process can be used for both, conspecific surfacing from 1.2343 as well as different types of surfacing [10].

The laser beam generation distinguishes itself from the SLM (Selective Laser Melting), in which layers defined by a laser fields of a powder bed are melted. The state of industrial technology for high-pressure die casting applications is the SLM process with the nickel-martensitic material 1.2709 [11,12]. The use of a martensitic hot-work steel such as 1.2343 is currently subject of research [13]. The problem here are cracks in the component due to high local temperature gradients and associated stresses. Consequently, an attempt is made to address the problem through a preheating of the powder bath.

The manual or semi-automatic welding with the laser beam is state of the art in the repair welding of die-casting. However, a compromise must be made here when selecting the welding filler material to ensure weldability. Usually, a filler material is used with carbon contents lower than the base material. In order to counteract a reduced strength and hardenability, for example, molybdenum is alloyed to the filler material. This element acts as a carbide former and also has a positive effect on the hardenability and weldability.

osnovnega materiala. Zaradi optične odbojnosti materialov in površin obdelovanca se del monokromatske svetlobe odbije. To obnašanje materiala vodi na eni strani do zmanjšanja učinkovitosti dovedene energije, na drugi strani pa do občutno bolj zapletenega krmiljenja te energije.

4 Tehnologija in možnosti varjenja z elektronskim curkom

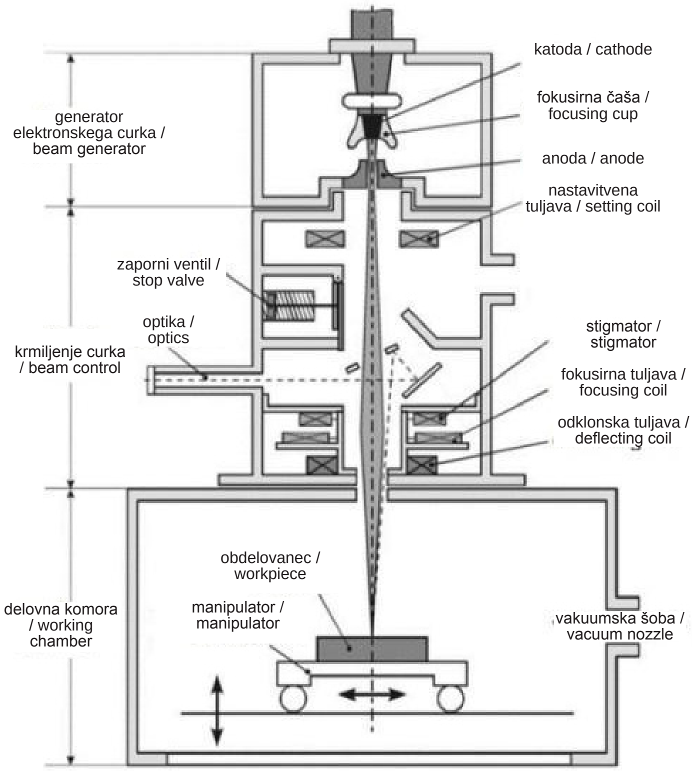
Poleg metode z laserskim snopom predstavlja metoda z elektronskim curkom drugo tehnologijo za obdelavo toplotnih materialov s snopom ali curkom.

Pri tej tehnologiji za obdelavo toplotnega materiala se elektroni, ki so skoraj brez mase in zato na njih ne delujejo vztrajnostne sile,

An essential disadvantage of the laser beam welding is the reflectivity of the base material. Because of the optically reflective light properties of materials and work piece surfaces, a part of the monochromatic light is reflected. This material behaviour leads on the one hand to a reduction in the efficiency and on the other hand to a considerably more complex controllability of the power input.

4 Technology and Potential of the Electron-Beam Welding

In addition to the laser beam method, electron beam technology represents the second beam technology for the processing of thermal materials.



Slika 4: Shematični prikaz naprave za varjenje z elektronskim curkom

Figure 4: Schematic setting of the electron-beam welding machine

s pospeševalno napetostjo deloma večjo od 150 KV pospešijo iz elektronskega oblaka pred katodo na 2/3 svetlobne hitrosti: če ti elektroni udarijo ob površino obdelovanca, se zavrejo. Pri tem procesu zmanjšanja hitrosti se kinetična energija elektronov pretvori v toplotno energijo in tako ustvari možnost stalitve osnovne kovine ali dodajnega materiala [14].

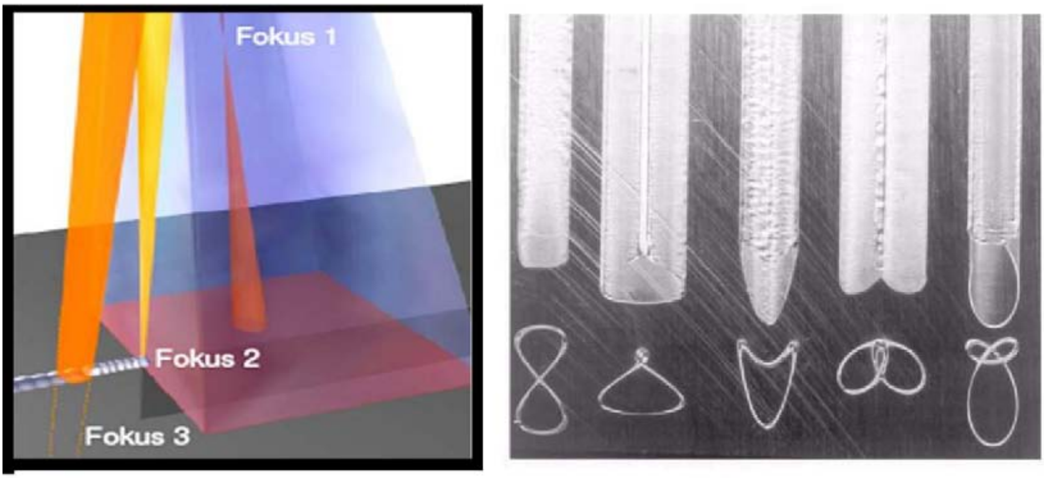
Na splošno je sistem z elektronskim curkom sestavljen iz generatorja curka, sistema za vodenje in oblikovanje curka ter delovne komore. Naloga generatorja je, da z visoko napetostjo ustvarja stalen, fokusiran curek elektronov med katodo in anodo. Fokusiranje in zelo dinamično odklanjanje elektronov se dosega s številnimi elektromagnetnimi lečami v generatorju, kot kaže slika 4, npr. z nastavitveno tuljavo, stigmatorjem, fokusirno in odklonsko tuljavo. Celoten proces poteka v visokem vakuumu, zato se pojavljajo določene omejitve v primerjavi z drugimi varilnimi postopki. V delovni komori so naprave za premikanje in vpenjanje, s katerimi se varjenec in potrošni material postavita v določen položaj. Uporaba porabljivih materialov za varjenje, kot so žice, predstavlja osnovo nastanek zgradbe navara.

Posebna tehnična lastnost sistema z elektronskim curkom je sposobnost odklanjanja curkov tako, da se navidezno cepijo v več curkov, kot kaže slika 5 levo. Ta tehnika odklanjanja omogoča sočasno izvedbo več operacij curka na površini varjenca pri veliki in bolj fleksibilno nastavljivi gostoti energije. Zato se lahko istočasno varijo različni spoji. V nekaterih primerih se ta tehnika z več snopi uporablja za ciljano krmiljenje toplotne bilance na območju spoja. Cilj tega je npr. varjenje ogljikovih jekel brez pokanja [15] ali ciljana nastavitev razmer hlajenja pri dupleksnih jeklih. Poleg tega periodično odklanjanje curka iz njegove začetne smeri omogoča

Here, almost massless and thus inertia-less electrons for the thermal material processing are accelerated up to 2/3 of the speed of light by means of an acceleration voltage of partially > 150 kV from an electron cloud in front of the cathode. If these electrons impact on the workpiece surface, they will be braked. At this deceleration process, the kinetic energy of the electrons is converted into thermal energy and thus creates the possibility of melting the metal base or filler material [14].

In general, an electron-beam system is composed of the beam generator, the beam guidance and shaping as well as the working chamber. The beam generator has thereby the task of generating a constant, focused beam of electrons by a high voltage and is applied between a cathode and anode. The focusing and highly dynamic deflection of the electron beam is effected by a number of electromagnetic lenses in the generator, shown in Figure 4 as setting coil, stigmator, focusing and deflection coil. The entire process takes place in a high vacuum, which is why particular constraints arise compared to other welding processes. Within the working chamber moving and clamping devices are available by means of which the weld metal and welding consumables can be positioned. The use of welding consumables in the form of wires represents the basis for a generative structure.

A special technical feature of the electron-beam system is the ability to deflect the beams so that they seemingly split into multiple beams, shown in Figure 5 on the left. This deflecting technique allows a simultaneous realization of several actions of the beam on the component surface at high and more variably adjustable power density. Hence, several joints could be welded at the same time. In some cases, these multi-beam technique is used for



Slika 5: Shematičen prikaz tehnike z več curki (levo) in možnosti nihanja curka (desno) [16]

Figure 5: Schematic image of the multi-beam technique (left) and possibilities of beam oscillation (right) [16]

natančno spreminjanje tvorbe varkov in njihove geometrije, kot se to lahko vidi na sliki 5 desno. To odklanje curka lahko posebej vpliva na proces taljenja in strjevanja med varjenjem in s tem se občutno izboljša razplinjevanje. Druga - in verjetno najbolj pomembna prednost varjenja z elektronskim curkom v primerjavi s standardnimi tehnikami varjenja - je velika gostota energije. Ta velika gostota energije omogoča zelo ozko toplotno vplivano cono, ki na najmanjšo mero zmanjša možne deformacije.

5 Navarjanje s sistemom za varjenje z elektronskim curkom

Glavni del raziskav za podaljšanje življenjske dobe kokil za tlačno litje, narejenih iz jekel za delo v vročem z varjenjem z elektronskim curkom se lahko pripiše popravljalnemu varjenju, ker se izrabljajo možnosti za spremenljivo, potrebam prilagojeno načrtovanje celotne toplotne bilance ter uporabljajo dodajni materiali. Da se to

the targeted control of the heat balance in the joint region. The aim is, for example, a crack-free welding of carbon steels [15] or a targeted adjustment of cooling conditions on duplex steels. Furthermore, a periodic deflecting of the beam from its initial position enables the specific alteration of the seam formation and geometry, as can be seen on the right in Figure 5. This can influence specifically the melting and solidification processes during welding and thus significantly improve the degassing. Another and probably the most important advantage of the electron-beam welding technique compared to the conventional welding techniques is the high power density. This high power density enables a quiet slim heat affected zone, which minimizes a potential deformation.

5 Deposit Welding by an Electron Beam Welding System

As the main part of the research to extend the lifetime of die casting moulds made of doseže, morajo biti izpolnjene dodatne zahteve:

- prepoznavanje in razvrščanje primernih porabljivih materialov za varjenje,
- razvoj primernega lokalnega krmiljenja toplote, vključenega v proces (pregrevanje in naknadno segrevanje), da se dosežejo navari s funkcionalno pravilnimi značilnostmi materiala,
- določanje parametrov prilagojenega procesa in razvoj strategij načrtovanja (prilagoditev položaja in zaporedja osnovnih oblik ter poti zapolnjevanja),
- razvoj strategij za zapleteno navarjanje in tridimenzijske osnovne oblike orodij.

V prvem delu načrtovanja preiskav so bili narejeni poskusi na ravnih površinah in na globelih, nastalih pri brušenju. Z brušenjem narejena globel bi lahko simulirala realno stanje pri popravljalnem varjenju, ker so vse možne razpoke v kokili pobrušene in potem ponovno zapolnjene z dodajnim materialom. Osnovni material je bilo jeklo z oznako S255, za dodajni material z oznako G3Si1 (1.5125) se je uporabila jeklena žica premera 1,2 mm. Privarjena je bila tako, da je bil gorilnik neposredno usmerjen na že izdelan del varka, pri čemer se je vzorec z vpenjanjalno napravo zasukal za 180^{o}. Vzrok za to je bil, da se je lahko na koncu vsake poteze pri varjenju oblikovala višina kapljice pri varku. Omenjeni zasuk je nadomestil razmere pri varjenju. V celoti je bilo potrebnih pet plasti, da se je zapolnila globel globine 10 mm.

Na osnovi poskusov se je ugotovilo, da je v osnovi možno izdelati napravo, ki uporablja sistem z elektronskim curkom in sistem za dodajanje materiala. Vzrok za našo izbiro osnovnega materiala in dodajnega materiala je bilo zelo dobro upravljanje z materialom. Za oba materiala so obstajale dovolj dobre izkušnje, material S255 je v splošnem zelo primeren za varjenje. Na sliki 6 levo se jasno vidi

hot-work steels the electron beam welding technique is to be qualified as a repair welding process because of its possibilities for the variable, needs-adapted design of the overall heat balance and the use of filler material. To achieve this, the following sub-objectives must be achieved:

- Identification and qualification of suitable welding consumables
- Development of a suitable process-integrated local heat control (pre-hiting and post-heating) to achieve a functionally correct material characteristic of the surfacing
- Determination of adapted process parameters and development of construction strategies (adaptation of position and sequence of the contour and fill-up path)
- Development of strategies for building complex, three-dimensional tool contours

In the first part of the investigations construction tests were performed on flat surfaces and in extra pre-milled swales. The milled swale should simulate the real situation in the repair welding process in this connection, since any possible cracks in the die are milled and then back-filled with the filler material. The basic material is a steel served with the designation S255, using G3Si1 (1.5125) as filler material, with a diameter of 1.2 mm in the form of wire. It was welded with a torch directed toward the finished part of the weld, at which the sample was rotated to 180° by means of clamping. This was the reason that at the end of each track, a drop height of the weld took shape. Said rotation compensated this condition. A total of five layers is required to fill the 10 mm depth of recess.

Based on the experiments, it was found that a generative structure using the electron-beam system and an additional material is generally possible. The reason

Slika 6: Poskus navarjanja v izbrušeni globeli (levo) in ustrezen prerez poliranega prereza navara (desno)

Figure 6: Trial of the generative build-up in a milled swale (left) and the appropriate cross-section polish of the generated deposit welding (right)

enakomerna mikrostruktura varka. Dobra povezanost med dodajno in osnovno kovino je prikazana na polirani površini na desnem delu slike 6. Varilskih napak, kot je pokanje v hladnem ali vročem, ni bilo pri nobenem navaru.

Z ugotovitvami strategije grajenja plasti ali možnimi spremenljivi hitrostmi varjenja, ki smo jih dosegli pri poskusih z materialoma S255 in G3Si1, bo sedaj možno navarjati na orodno jeklo za delo v vročem s standardno oznako 1.2343 ob uporabi primernih porabljivih varilnih materialov.

Orodno jeklo za delo v vročem kakovosti ESR (postopek električnega pretaljevanja pod žlindro) in popuščeno na trdoto okoli 43 HRC je dobavilo podjetje *Böhler-Uddeholm*. Kot dodajni material za varjenje smo uporabili material, ki je bil legiran manj, enako ali bolj kot osnovni material. Kot možnost pufernih plasti je bilo treba preiskati dodatni dodajni material na osnovi materiala Coblat in na osnovi jekel za martenzitno staranje s standardno oznako 1.2709. Vsak dodajni material se je dodajal kot žica premera 1,6 mm v staljeno kopel z dodajalnikom žice v sistem varjenja

for the selection of the base material and the filler material was the very good handling of the materials. For both materials sufficient experiences are available, the S255 is generally considered as very suitable for welding. In Figure 6, left, a uniform structure of the weld beads can clearly be seen. A good connection of the welding filler metal to the base metal in the cross-section polish in the right picture of Figure 6 is visible. Welding defects such as hot or cold cracking did not occur at all surfacings.

With the help of the findings for the strategy of the layer structure or the possible mobile welding speeds, which were obtained from the experiments with the S255 and the G3Si1, surfacing should now be carried out with the hot-work tool steel with the standard designation 1.2343 as the base material and suitable welding consumables.

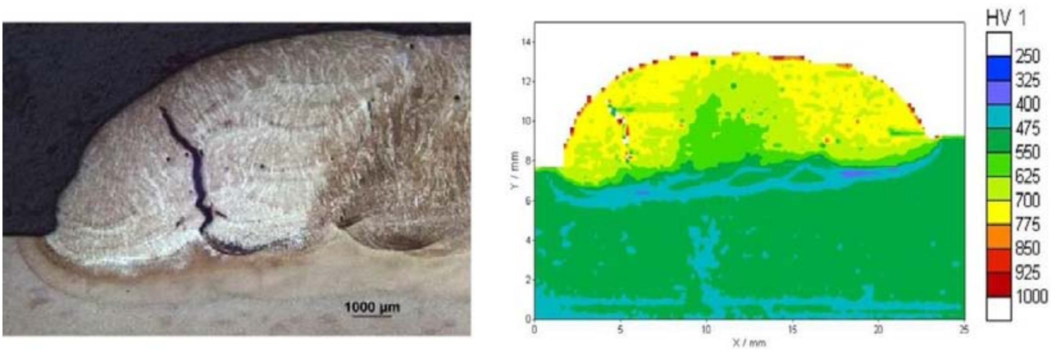
The hot-work tool steel was supplied by the company *Böhler-Uddeholm* in ESR (Electro-Slac-Remelting) quality and tempered to a hardness of about 43 HRC. As filler material for the welding an under-alloyed, a similar and an over-alloyed z elektronskim curkom, žice je dobavljalo podjetje *Welding Alloys Group*.

Pretekle študije so do danes vključevale sorazmerno enostavno navarjanje posamezne plasti jekla 1.2343 in podobnega dodajnega materiala. To pomeni, da so bili posamezni varki narejeni neurejeno eden poleg drugega. V splošnem bi bilo treba preiskati pet porabljivih varilnih materialov za uporabo pri varjenju z elektronskim curkom. To je potrebno, ker se lahko v vakuumu spremeni varivost dodajnega materiala. Čeprav prvi rezultati kažejo enakomerno mikrostrukturo nastalih varkov, kar se vidi na naslednji sliki, je bilo opaziti rahlo povečanje trdote varjene kovine pri meritvah trdote na sliki levo. Zaradi občasnih pojavov je bil osnovni material rahlo zmehčan. Pojava razpoke v vročem na levi sliki je rezultat hitrega ohlajanja dodajnega in osnovnega materiala. To varjenje je potekalo brez predgrevanja in naknadnega žarjenja. Vidi se, kako pomembni sta obe obdelavi za uspešno popravljalno varjenje jekla za delo v vročem z oznako 1.2343 tudi pri varjenju z elektronskim curkom.

Treba bo raziskati še toplotne obdelave in uporabo drugih dodajnih materialov.

material were used. For possible buffer layers an additional filler material should be examined for Coblat basis and on the basis of a maraging steel with the standard designation 1.2709. Each filler material is fed as a filler wire with a diameter of 1.6 mm into the molten bath with an in the electron-beam system built-in wire conveyor and were supplied by the *Welding Alloys Group*.

Up to this time, past studies have included relatively simple single-layer surfacing with the 1.2343 and the similar filler metal. This means that several weld beads only placed side by side and not in accordance. In general, the overall applicability of the five welding consumables should be investigated for use in the electron-beam method. This is neccesary, because the filler materials might change their weldability in a vacuum atmosphere. Although the first results during the weld show the uniform structure of the generated beads in the Figure 7, a slight increase in hardness of the weld metal can be seen in the hardness measurement in the left picture. The base material is, however, slightly softened by occasional effects. The occured hot crack in the left figure is a result



Slika 7: Poliran prerez z jasno vidno razpoko v vročem (levo) in z izmerjenimi trdotami vzorca varka, narejenega z varjenjem z elektronskim curkom (desno)

Figure 7: Cross-section polish with clearly identified hot crack (left) and a hardness allocation of an EB-welded sample (right)

6 Sklepi in prihodnje delo

Raziskave do sedaj so pokazale, da je varjenje z elektronskim curkom metoda, ki je primerna za navarjanje kovinskih materialov. Zato smo delali večplastne navare z jekli in dodajnimi materiali, s katerimi je bilo delo sorazmerno lahko. Možno je bilo tudi uresničiti strategijo izdelave tridimenzijskih teles, katerih oblike so osnova za varjenje z elektronskim curkom kot načinom popravljalnega varjenja kokil za tlačno litje, z navarjanjem.

Pri varjenju jekla za delo v vročem z oznako 1.2343 in podobnega dodajnega materiala je bilo ugotovljeno, da se pojavljajo težave pri izdelavi varov brez napak. Zato je predgrevanje in naknadno segrevanje navara bistveno v vsakem primeru. Varjenje z elektronskim curkom je tehnika, ki omogoča s tehnologijo z več curki v primerjavi s klasičnim varjenjem, da se vključi tudi predgrevanje in naknadno segrevanje v proces varjenja.

7 Zahvala

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of the fast cooling velocity of the filler and base material. This welding was executed without a pre-heating and downstreamed annealing treatment. Here you can see, how important these both treatments are for a succesful conducted repair welding process of the hot work steel 1.2343, also at the electron-beam welding.

Researches with the heat treatments and the other selected filler materials have to be done.

6 Conclusion and Prospect

The up to this moment executed studies have shown that the electron beam welding method is suitable for a generative development of metallic materials. For this purpose, multi-layer deposit weldings were realized with comparatively easy to handle steels and filler materials. It also could hence derived possible construction strategies of three-dimensional bodies, which forms the basis for the use of the electron beam welding process as repair welding of die casting moulds.

In applying the findings to the welding of hot-work steel 1.2343 and the similar filler material difficulties have been occurred focusing on the production of defect-free welds. A pre-and post-heating of the weld metal is hence essential in this or any case. The electron-beam welding technique allows with his multi-beam technology compared to the conventional welding methods a possible process-integrated pre-heating and post-heating.

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