Rok Markežič[1], Nikolaj Mole[1], Iztok Naglič[2], Boštjan Markoli[2], Roman Šturm[1]
1 Fakulteta za strojništvo, Univerza v Ljubljani, Slovenija / Faculty of Mechanical Engineering, University of Ljubljana, Slovenia
2 Naravoslovnotehniška fakulteta, Univerza v Ljubljani, Slovenija / Faculty of Natural Sciences and Engineering, University of Ljubljana, Slovenia

Napovedovanje spreminjanja trdote orodij med procesom tlačnega litja

Tool hardness change prediction during high pressure die casting process

Povzetek

Orodja za tlačno litje so med obratovanjem izpostavljena cikličnim toplotnim in mehanskim obremenitvam, ki postopno vodijo do obrabe in nastanka poškodb na orodjih. Za zagotavljanje primerne trdote, trdnosti, žilavosti in mikrostrukturne stabilnosti orodij so ta pred začetkom uporabe ustrezno toplotno obdelana. Kljub temu pa prihaja med obratovanjem do neprestanega spreminjanja-razvoja mikrostrukture materiala, kar je posledica visokih obratovalnih temperatur in toplotnega utrujanja. Spreminjanje mikrostrukture vpliva na toplotno mehčanje in s tem na padec v trdoti materiala ter posledično zmanjšanje odpornosti orodij na obrabo in poškodbe. Poznavanje spreminjanja trdote orodij med procesom tlačnega litja je ključnega pomena za natančno napovedovanje obratovalne dobe in lokalizacije kritičnih mest že v fazi razvoja orodij. V članku je predstavljena novo razvita metoda za napovedovanje spreminjanja trdote orodij med procesom tlačnega litja. Metoda sloni na kinetičnem zakonu popuščanja, ki omogoča napovedovanje spreminjanja trdote na podlagi znanih toplotnih obremenitev. Uporaba metode je prikazana na primeru uporabe orodnega jekla za delo v vročem stanju Böhler W400 VMR (AISI H11), iz katerega je izdelano orodje, in tipičnega toplotnega obremenitvenega cikla pri tlačnem litju.

Ključne besede: tlačno litje, orodna jekla za delo v vročem stanju, toplotno mehčanje, kinetični zakon popuščanja, trdota

Abstract

High pressure die casting dies are during operation exposed to cyclic thermal and mechanical loads, which gradually lead to wear and damage of dies. To provide the needed hardness, strength, toughness and microstructural stability, dies are adequately heat treated prior to service. However, continuous microstructure evolution of die material occurs during service due to high operational temperatures and thermal fatigue conditions. Microstructure evolution causes thermal softening, loss of hardness and consequently reduction in damage and wear resistance. Understanding the loss of hardness of dies during die casting process is crucial for precise die lifetime predictions and localization of critical areas during die design phase. In this paper, a newly developed method for die hardness change predictions during die casting process is presented. The method is based on a tempering kinetic law, which allows the prediction of change in hardness based on known thermal loadings. The application of the method is explained in case of use of the hot-work tool steel Böhler W400 VMR (AISI H11) as die material and a typical die casting thermal loading cycle.

Keywords: high pressure die casting, hot work tool steels, thermal softening, tempering kinetic law, hardness

1 Uvod

Orodja so zaradi visokih temperature, tlakov in hitrosti taline med procesom tlačnega litja izpostavljena cikličnim toplotnim in mehanskim obremenitvam. Posledično prihaja do obrabe in poškodbe površin toplih delov orodij, kar povzroča zaplete v procesu tlačnega litja, v najhujših primerih pa lahko vodi do porušitve in odpovedi orodja [1].

Obrabne in poškodbene mehanizme na orodjih med tlačnim litjem v splošnem delimo v štiri skupine: (1) nalepljanje, (2) korozija, (3) erozija, (4) toplotno utrujanje in nastanek razpok. Pri nalepljanju prihaja do adhezije materiala ulitka na površino orodja [2], [3]. Pojavlja se med fazo polnjenja orodja in strjevanja ulitka, vzrok za pojav nalepljanja pa je v kombinaciji metalurških in mehanskih učinkov [4]. Korozija orodij med tlačnim litjem je tesno povezana z mehanizmom nalepljanja, kaže pa se kot izguba materiala orodja s površine le-tega. Korozija je mehanizem metalurške narave in se pogosto pojavlja v kombinaciji z nalepljanjem na specifičnih mestih orodja [5]. Za razliko od nalepljanja in korozije pa je erozija izključno mehanske narave, prav tako pa se kaže kot izguba materiala orodja z njegove površine [6]. Intenzivnost nalepljanja, korozije in erozije je močno odvisna od temperature površine orodja. Višja kot je temperatura orodja, pogostejše in intenzivnejše je njihovo pojavljanje [5], [7], [8]. Temeljni vzrok za toplotno utrujanje in nastanek razpok na orodjih je v hitrih spremembah temperature in tlakov med procesom tlačnega litja. Visoke temperature ter visoke hitrosti segrevanja in ohlajanja površine orodja pospešujejo stopnjo tvorbe in rasti razpok na orodjih [9], [10].

Pred začetkom uporabe so orodja ustrezno toplotno obdelana z namenom zmanjšanja obrabe in poškodb orodij. Z

1 Introduction

Dies are due to high temperatures, pressures and melt velocities during high pressure die casting process exposed to cyclic thermal and mechanical loading. Consequently, wear and damage gradually occur on dies, causing problems in the casting process and in worst cases, failures on dies [1].

Die wear and damage mechanisms are generally divided in four groups: (1) soldering, (2) corrosion, (3) erosion, (4) thermal fatigue and cracking. Soldering or die sticking appears as adhesion of cast material to the die surface [2], [3]. It occurs during filling and solidification phase and is caused by a combination of metallurgical and mechanical effects [4]. Corrosion of dies in die casting is related to soldering and is characterized by loss of die material from the die surface. It is a metallurgically driven process and it often occurs simultaneously with soldering on a particular region of a die [5]. Erosion, on the other hand, is a mechanically driven process, also characterized by loss of die material from the die surface [6]. Die soldering, corrosion and erosion are strongly dependent on die surface temperature. Their occurrence increases with increasing die surface temperature [5], [7], [8]. The main cause for thermal fatigue and cracking of dies are high temperature and pressure gradients. Crack initiation and propagation are accelerated by higher temperatures and higher heating/cooling rates of dies [9], [10].

To reduce damage and wear and to avoid failures, dies are adequately heat treated prior to service. In this way, the desired combination of strength, hardness and fracture toughness can be achieved [11]– [13]. However, due to high operating temperatures during the die casting process, evolution of the microstructure ustrezno toplotno obdelavo zagotovimo optimalno trdnost, trdoto in žilavost [11]–[13]. Kljub temu pa prihaja zaradi visokih obratovalnih temperature med procesom tlačnega litja do dodatnega spreminjanja mikrostrukture ter mehčanja materiala orodij [10]. Mehčanje se kaže kot padec v trdoti in obratovalni trdnosti materiala orodja, vzrok za to pa je v rasti drobnih karbidov in zmanjšanju gostote dislokacij v materialu pri visokih temperaturah [14]. Za uspešno zaviranje nastanka obrabe in poškodb ter za uspešno nadziranje obratovalne dobe je torej ključnega pomena dobro razumevanje razvoja mikrostrukture materiala orodij med obratovanjem.

Za popis pojava mehčanja jekel so bili razviti številni matematično-fizikalni modeli, ki slonijo na določenih fizikalnih zakonitostih. Eden od nedavno razvitih modelov je kinetični zakon popuščanja, predlagan s strani raziskovalca Caliskanogla in sodelavcev [15]. Predlagani zakon popuščanja popisuje časovno in temperaturno odvisno mehčanje materiala na osnovi srednje velikosti razvoja sekundarnih karbidnih izločkov v materialu, ki rastejo po principu Ostwaldovega mehanizma rasti.

V članku je predstavljena uporaba metode za napovedovanje spreminjanja trdote orodij med procesom tlačnega litja. Uporaba metode je prikazana na primeru orodnega jekla za delo v vročem stanju Böhler W400 VMR (AISI H11), iz katerega je izdelano orodje, in tipičnega toplotnega obremenitvenega cikla pri tlačnem litju.

2 Materiali in metode

V poglavju 2.1 je predstavljen kinetični zakon popuščanja, predlagan s strani raziskovalca Caliskanogla in sodelavcev [15], ki temelji na delu Lifshitza, Slyozova in

continues and softening of the die material occurs [10]. Softening appears as loss of hardness and high temperature fatigue strength and is driven by progressive coarsening of fine carbides and reduction of the dislocation density in the die material at elevated temperatures [14]. Therefore, to reduce wear and damage and to successfully control the die lifetime, it is of great importance to understand the evolution of the microstructure of the die material during service.

For the description of the softening behaviour of steels, many mechanism-based models have been developed. One of the most recent is the tempering kinetic law proposed by Caliskanoglu et al. [15], which relates time and temperature dependent softening to the evolution of the mean size of secondary carbide precipitates, based on the Ostwald ripening mechanism.

In this paper, the application of a method for die hardness change prediction during die casting process is presented. The application of the method is explained in case of use of the hot work tool steel Böhler W400 VMR (AISI H11) as die material and a typical die casting thermal loading cycle.

2 Materials and Methods

In section 2.1, the tempering kinetic law, proposed by Caliskanoglu et al. [15] and based on the work of Lifshitz, Slyozov and Wagner, is presented. The tempering kinetic law was described in more detail by Jilg and Seifert [16]. In section 2.2, the die temperature field calculation with use of the commercial software Magmasoft version 5.3, module MAGMAhpdc, is explained.

Wagnerja. Obravnavani zakon popuščanja je podrobneje opisan v delu Jilga in Seiferta [16]. V poglavju 2.2 je opisan postopek izračuna temperaturnih polj na orodju med procesom tlačnega litja z uporabo komercialnega programskega paketa Magmasoft, različica 5.3, modul MAGMAhpdc.

2.1 Kinetični zakon popuščanja

Kot že omenjeno, zakon popuščanja, predlagan s strani Caliskanogla in sodelavcev [15], povezuje proces mehčanja materiala z razvojem srednje velikosti sekundarnih karbidnih izločkov v materialu pri povišanih temperaturah. Model za napovedovanje spreminjanja trdote materiala med procesom izotermnega popuščanja je predstavljen v enačbi (1), kjer *H* predstavlja trdoto materiala po času *t* pri konstantni temperaturi *T*, H_i trdoto materiala v mehkem stanju, B_H materialno lastnost utrjevanja, *k* konstanto rasti izločkov, r_0 pa začetni srednji polmer sekundarnih karbidnih izločkov. H_i in B_H sta materialni lastnosti, odvisni od trdote materiala v mehkem stanju in trdote materiala po začetni toplotni obdelavi. Konstanta rasti izločkov *k* je definirana v enačbi (2), kjer k_I predstavlja temperaturno odvisno materialno lastnost, *Q* aktivacijsko energijo popuščanja in *R* plinsko konstanto idealnega plina (8,13143 J mol^{-1} K^{-1}).

$$\boldsymbol{H = H_i + \frac{B_H}{\sqrt[3]{3kt + r_0^3}}} \tag{1}$$

$$\boldsymbol{k = k_I \frac{\exp\left(-\frac{Q}{RT}\right)}{T}} \tag{2}$$

2.1 Tempering Kinetics

Like already mentioned, the tempering kinetic law, proposed by Caliskanoglu et al. [15], relates the softening of the material to the evolution of the mean size of secondary carbide precipitates at elevated temperature. The relation for hardness change prediction due to isothermal softening is presented in Eq. (1), where *H* represents the hardness of the material after time *t* at constant temperature *T*, Hi the intrinsic hardness, BH the particle hardening related material property, k the coarsening constant and r_0 the initial secondary carbide precipitates mean radius. H_i and B_H are material properties related to the hardness of the annealed state of the material and the initial hardness of the material, respectively. The coarsening constant k is defined in Eq. (2), where kI represents the temperature dependent material property, *Q* the activation energy of the tempering transformation and *R* the perfect gas constant (8.13143 J mol^{-1} K^{-1}).

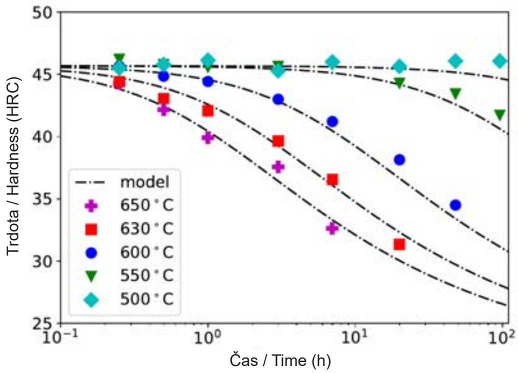
$$\boldsymbol{H = H_i + \frac{B_H}{\sqrt[3]{3kt + r_0^3}}} \tag{1}$$

$$\boldsymbol{k = k_I \frac{\exp\left(-\frac{Q}{RT}\right)}{T}} \tag{2}$$

In Figure 1, hardness measurement results during thermal softening resistance tests of the hot work tool steel Böhler W400 VMR (AISI H11) are shown with differently shaped dots. During thermal softening resistance tests, samples of the analysed material were held at a constant temperature for different times and hardness change in time was investigated. Tests at different constant temperatures were carried out.

Na Slika 1 so s točkami predstavljeni rezultati meritev trdot med testi toplotnega popuščanja orodnega jekla za delo v vročem stanju Böhler W400 VMR (AISI H11). Vzorci analiziranega materiala so bili med testi toplotnega popuščanja izpostavljeni konstantni povišani temperaturi za različno dolge čase testiranja. Testi so se izvajali pri različnih konstantnih temperaturah, spremljal pa se je razvoj oz. spreminjanje trdote materiala v odvisnosti od časa testiranja pri določeni konstantni temperaturi. Pred začetkom testiranja so bili vsi vzorci toplotno obdelani na enako začetno stanje. Iz rezultatov meritev trdot so bile določene vrednosti aktivacijske energije *Q* in temperaturno odvisne materialne lastnosti k_l. Črtkane krivulje na Sliki 1 predstavljajo rezultate napovedi spreminjanja trdote, izračunane z uporabo predstavljenega zakona popuščanja. Na Sliki 2 je prikazana temperaturna odvisnost konstante rasti izločkov *k*.

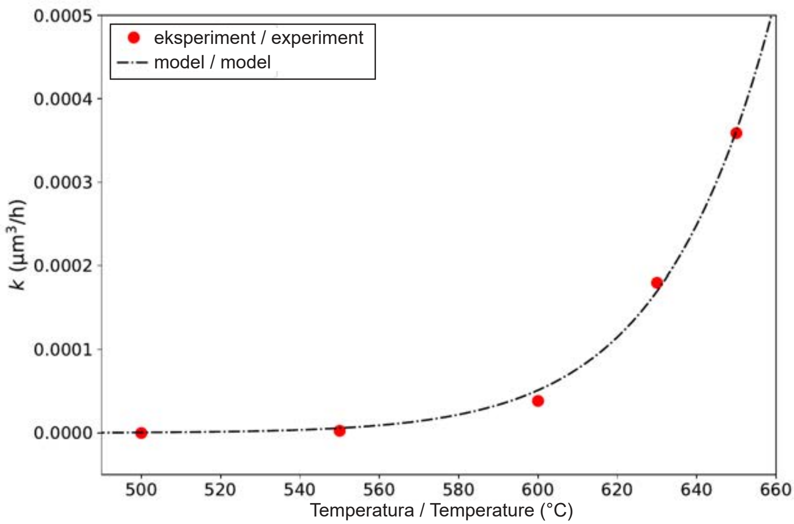
Z uporabo predstavljenega zakona popuščanja in ob poznanih temperaturnih



Slika 1. Rezultati meritev trdote na vzorcih med testi toplotnega mehčanja in rezultati izračuna spreminjanja trdote

Figure 1. Hardness measurement results on samples during thermal softening resistance tests and calculated hardness change prediction results

Prior to testing, all samples were heat treated to the same initial condition. From hardness measurement results, values of activation energy Q and temperature dependent



Slika 2. Temperaturna odvisnost konstante rasti izločkov *k*

Figure 2. Temperature dependence of the coarsening constant *k*

poljih na orodju je možen izračun spremembe trdote orodja med procesom tlačnega litja.

2.2 Izračun temperaturnih polj na orodju

Za izračun temperaturnih polj na orodju med procesom tlačnega litja, ki so zahtevana za napovedovanje spreminjanja trdote, je bil uporabljen komercialni programski paket Magmasoft, različica 5.3, z modulom MAGMAhpdc. Izračunani so bili temperaturni profili na površini orodja med tipičnim procesom tlačnega litja, opisanim s strani Markežiča in sodelavcev [17], kjer je bilo orodje uporabljeno za litje aluminijeve zlitine AlSi9Cu3Fe. Izračunan časovno-temperaturni potek na določenem mestu orodja med celotnim ciklom tlačnega litja je prikazan na Sliki 3.

3 Rezultati in diskusija

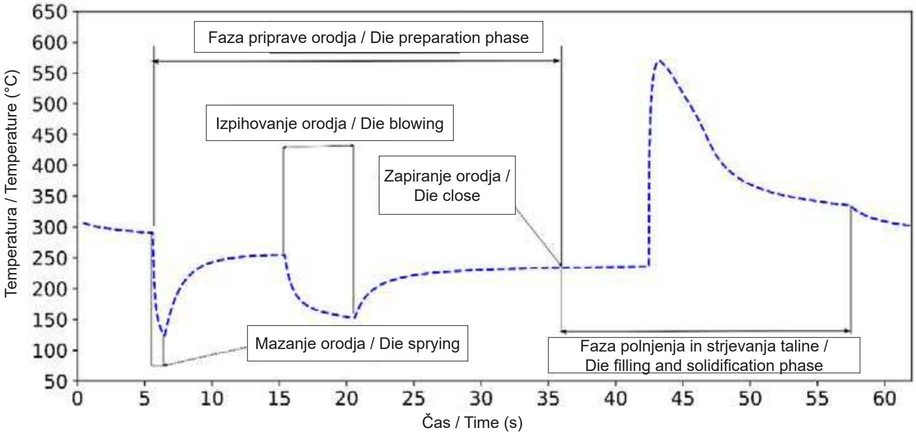
Na podlagi predhodno izračunanega temperaturnega profila na površini

material property kI were obtained. Dashed lines in Figure 1 represent the hardness change prediction results, calculated with the use of the tempering kinetic law. In Figure 2, the temperature dependence of the coarsening constant *k* is shown.

With the use of the presented tempering kinetic law and known temperature fields on die, die hardness change predictions during casting process can be calculated.

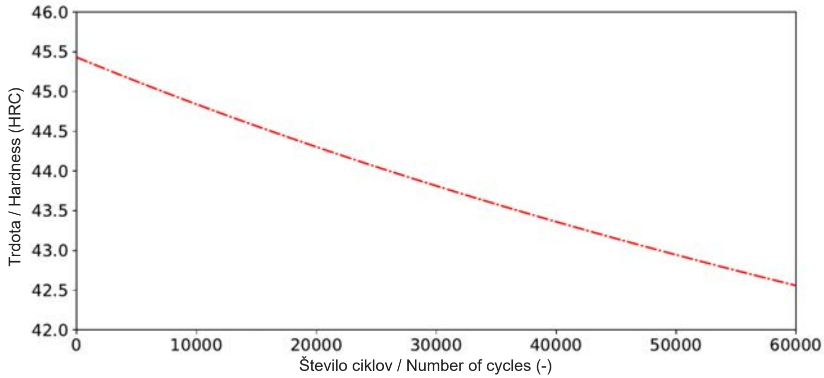
2.2 Die Temperature Calculations

For the calculation of die temperature fields during a high pressure die casting process, needed for hardness change predictions, commercial software Magmasoft version 5.3 with module MAGMAhpdc was used. Die surface temperature profiles during a typical high pressure die casting process were calculated, described by Markežič et al. [17], where the die was used for casting of aluminium alloy AlSi9Cu3Fe. The calculated die surface temperature profile on a specific region of the die surface is presented in Figure 3.



Slika 3. Temperaturni profil na površini orodja med procesom tlačnega litja

Figure 3. Die surface temperature profile during a high pressure die casting cycle



Slika 4. Rezultati napovedi spreminjanja trdote med procesom tlačnega litja

Figure 4. The predicted die hardness change during a high pressure die casting process

orodja med procesom tlačnega litja, predstavljenega na Sliki 3, in z uporabo zakona popuščanja, opisanega v poglavju 2.1, je bilo izračunano spreminjanje trdote orodja v odvisnosti od števila ciklov tlačnega litja. Rezultati napovedi spreminjanja trdote med procesom tlačnega litja so prikazani na Sliki 4.

Iz analize krivulje na Sliki 4 lahko ugotovimo, da trdota orodja pada z večanjem števila ciklov tlačnega litja. Iz oblike krivulje lahko dodatno zaključimo, da je najintenzivnejši padec trdote v začetnih ciklih procesa tlačnega litja, nato pa se hitrost padanja trdote postopoma znižuje z večanjem števila ciklov.

Predstavljena metoda za napovedovanje spreminjanja trdote materiala med procesom tlačnega litja je uporabna za napoved spreminjanja trdote celotnega orodja. Tako lahko v kombinaciji z vplivi ostalih obrabnih in poškodbenih mehanizmov lokaliziramo kritična mesta na orodju že v fazi razvoja le-tega.

3 Results and Discussion

Based on the previously calculated die surface temperature profile during a high pressure die casting cycle, presented in Figure 3, and with use of the tempering kinetic law, described in Section 2.1, the die hardness change with increasing number of casting cycles was calculated. The predicted hardness change profile is shown in Figure 4.

As predicted by the developed method, die hardness decreases with increasing number of casting cycles. From the shape of the curve in Figure 4 it can be concluded that the time-hardness drop rate has the highest value at the beginning of the casting process and it gradually decreases with increasing number of casting cycles.

The presented method for hardness change prediction during high pressure die casting process is applicable to the hardness change calculation of the entire die. In this way, in conjunction with other wear and damage mechanisms, the localization of critical die areas is possible already in the die design phase.

4 Zaključki

V članku je bila predstavljena metoda za napovedovanje spreminjanja trdote orodij med procesom tlačnega litja. Uporaba metode je bila prikazana na primeru procesa tlačnega litja aluminijeve zlitine AlSi9Cu3Fe in orodja, izdelanega iz orodnega jekla za delo v vročem stanju Böhler W400 VMR (AISI H11). Izračun temperaturnih polj na orodju med procesom tlačnega litja je bil izveden z uporabo komercialnega programskega paketa Magmasoft, različica 5.3. Predstavljena metoda omogoča lokalizacijo kritičnih mest na orodjih že v fazi razvoja ter omogoča izboljšano napoved in nadziranje obratovalne dobe orodij za tlačno litje.

4 Conclusions

The application of a method for die hardness change prediction during die casting process is presented in this paper. The use of the method is explained on a case of high pressure die casting of aluminium alloy AlSi9Cu3Fe with a die manufactured from hot-work tool steel Böhler W400 VMR (AISI H11). The calculation of die surface temperature fields, needed for hardness change predictions, was conducted with use of the commercial software Magmasoft version 5.3. The presented method could be used for localization of critical die areas in the die design phase and for improved prediction and control of die lifetime.

Viri in literatura / References

[1] S. Gopal, A. Lakare, and R. Shivpuri, “Evaluation of thin film coatings for erosive–corrosive wear prevention in die casting dies,” Surf. Eng., vol. 15, no. 4, pp. 297–300, 1999.

[2] K. Domkin, J. H. Hattel, and J. Thorborg, “Modeling of high temperature- and diffusion-controlled die soldering in aluminum high pressure die casting,” J. Mater. Process. Technol., vol. 209, no. 8, pp. 4051–4061, 2009.

[3] S. Gulizia, M. Z. Jahedi, and E. D. Doyle, “Performance evaluation of PVD coatings for high pressure die casting,” Surf. Coatings Technol., vol. 140, no. 3, pp. 200–205, 2001.

[4] P. A. Hogan, “Die Solder Prediction and Reduction,” Worcester Polytechnic Institute, 2008.

[5] M. Yu, R. Shivpuri, and R. A. Rapp, “Effects of molten aluminum on H13 dies and coatings,” J. Mater. Eng. Perform., vol. 4, no. 2, pp. 175–181, 1995.

[6] Z. W. Chen and M. Z. Jahedi, “Die erosion and its effect on soldering formation in high pressure die casting of aluminium alloys,” Mater. Des., vol. 20, no. 6, pp. 303–309, 1999.

[7] V. Joshi, A. Srivastava, and R. Shivpuri, “Intermetallic formation and its relation to interface mass loss and tribology in die casting dies,” Wear, vol. 256, no. 11–12, pp. 1232–1235, 2004.

[8] K. Venkatesan and R. Shivpuri, “Experimental and numerical investigation of the effect of process parameters on the erosive wear of die casting dies,” J. Mater. Eng. Perform., vol. 4, no. 2, pp. 166–174, 1995.

[9] F. Medjedoub et al., “Experimental conditions and environment effects on thermal fatigue damage accumulation and life of die-casting steel X38CrMoV5 (AISI H11),” Int. J. Microstruct. Mater. Prop., vol. 3, no. 2–3, 2008.

[10] D. Klobčar, J. Tušek, and B. Taljat, “Thermal fatigue of materials for die-casting tooling,” Mater. Sci. Eng. A, vol. 472, no. 1, pp. 198–207, 2008.
[11] J. Sjöström and J. Bergström, “Thermal fatigue testing of chromium martensitic hot-work tool steel after different austenitizing treatments,” J. Mater. Process. Technol., vol. 153, pp. 1089–1096, 2004.
[12] V. Leskovšek, B. Šuštaršič, and G. Jutriša, “The influence of austenitizing and tempering temperature on the hardness and fracture toughness of hot-worked H11 tool steel,” J. Mater. Process. Technol., vol. 178, no. 1, pp. 328–334, 2006.
[13] G. Roberts, G. Krauss, and R. Kennedy, Tool steels, 5th ed. Metals Park: ASM, 1998, 1998.
[14] X. Hu, L. Li, X. Wu, and M. Zhang, “Coarsening behavior of M23C6 carbides after ageing or thermal fatigue in AISI H13 steel with niobium,” Int. J. Fatigue, vol. 28, no. 3, pp. 175–182, Mar. 2006.
[15] D. Caliskanoglu, I. Siller, R. Ebner, H. Leitner, F. Jeglitsch, and W. Waldhauser, “Thermal Fatigue and Softening Behavior of Hot Work Tool Steels,” Proc. 6th Int. Tool. Conf., pp. 707–719, 2002.
[16] A. Jilg and T. Seifert, “Temperature dependent cyclic mechanical properties of a hot work steel after time and temperature dependent softening,” Mater. Sci. Eng. A, vol. 721, pp. 96–102, Apr. 2018.
[17] R. Markežič, I. Naglič, N. Mole, and R. Šturm, “Experimental and numerical analysis of failures on a die insert for high pressure die casting,” Eng. Fail. Anal., vol. 95, pp. 171–180, Jan. 2019.

AKTUALNO / CURRENT

Pregled livarskih prireditev v letu 2022 / 2023

Datum dogodka	Ime dogodka	Mesto in država
14. - 16. 09. 2022	62. IFC Portorož 2022	Portorož, Slovenija
05. - 07. 10. 2022	Evropska konferenca tlačnega litja cinka	Koblenz, Nemčija
16. - 20. 10. 2022	74. svetovni livarski kongres in generalna skupščina WFO	Busan, J. Korea
06. - 07. 10. 2022	Randhofenski dan lahkih kovin	Salzburg, Avstrija
27. - 28. 10. 2022	Ledebur-Kolokvium	Freiberg, Nemčija
12. - 16. 06. 2023	Mednarodni sejem metalurgije in livarstva (GIFA)	Duesseldorf, Nemčija