

Nov pristop k virtualnemu preizkušanju razkalupljanja ulitkov iz kokil

Novel Modelling Approach to Virtually Test the Part Ejection in Die Castings

1 Uvod

Pomemben korak v visokotlačnem litju (HPDC - High Pressure Die Casting) magnezija je izmet ulitka. Zaradi strjevanja in ohlajanja se ulitek nakrči na orodje. Za uspešno spopadanje s takšnimi močnimi silami in ločevanje dela ulitka od kokile se uporabljajo izmetači, s katerimi ulitek potisnemo iz kokile. Običajno je število izmetačev preveliko. To je posledica dejstva, da je brez preizkusa trenutno težko oceniti, ali je mogoče nek del razkalupiti tudi z zmanjšanim številom izmetačev. Zmanjšanje števila izmetačev bi znižalo proizvodne stroške ter proizvajalcem orodij omogočilo več svobode pri izdelavi hladilnih kanalov, saj ti zasedajo isti prostor kot izmetači.

V tem članku je predstavljen nov pristop modeliranja razkalupljanja delov izmeta ulitkov v virtualnem okolju. Ta pristop predstavlja simulacijska veriga, sestavljena iz dveh korakov. Prvi korak je izvedba večfizikalnega modela procesa litja, ki upošteva vidike pretoka ter termičnih in mehanskih lastnosti. Namen takšne simulacije je napovedati obremenitve v tistih delih ulitka, s katerimi je pritrjen na kokilo. Takšna porazdelitev obremenitve je začetno stanje drugega koraka, ki predstavlja modeliranje procesa razkalupljanja in upošteva vse učinke trenja. Rezultati modeliranja zagotavljajo informacije o tem,

1 Introduction

One important process step in Magnesium HPDC (High Pressure Die Casting) is the ejection of part from the mould. Due to solidification and cooling down the part shrinks onto the mould. To over-come the strong forces that hold the part on the mould, ejection pins are used that push the part out-side. Often the number of ejection pins is exaggerated since it is currently difficult to estimate if a reduced number could already be sufficient to eject the part without actually trying it. Reducing the number of ejection pins would decrease production costs and also give more flexibility to the mould maker to set cooling channels since these are occupying the same design space as the ejection pins.

This article presents a novel modelling approach to virtually test the part ejection. The approach is a simulation chain built of two steps. In the first step a multi-physic modelling of the casting process, taking into account flow, thermal and mechanical aspects, is performed. Target of this simulation is to predict the stresses in the part that fix the part to the mould. This stress distribution is used as the initial state for the second part which represents the modelling of the ejection process taking into account all friction effects. Outcome of the modelling provides information if the stresses in the part during ejection will remain in the elastic

ali obremenitve v ulitku med razkalupljanjem še vedno delujejo v elastičnem razponu oziroma ali obstajajo področja, kjer prihaja do plastične deformacije, kar bi pomenilo, da postopkovni parametri niso ustrezno nastavljeni. Uporaba takšnih metod omogoča virtualno preizkušanje različnih porazdelitev in nastavitvev izmetačev.

Ta članek je sestavljen, kot sledi: prvi del opisuje pristop k rešitvi vprašanja skozi modeliranje. Med drugim opisuje lastnosti materiala, robne pogoje in druge informacije, nujne za modeliranje. Ta okvir bo nato prenesen na konceptualni primer, na podlagi katerega nameravamo prikazati dosledno vedenje modela. Pridobljene rezultate bomo podrobno obrazložili. V zadnjem delu bo model uporabljen na dejanskem industrijskem primeru.

2 Opis glavnega pristopa k modeliranju

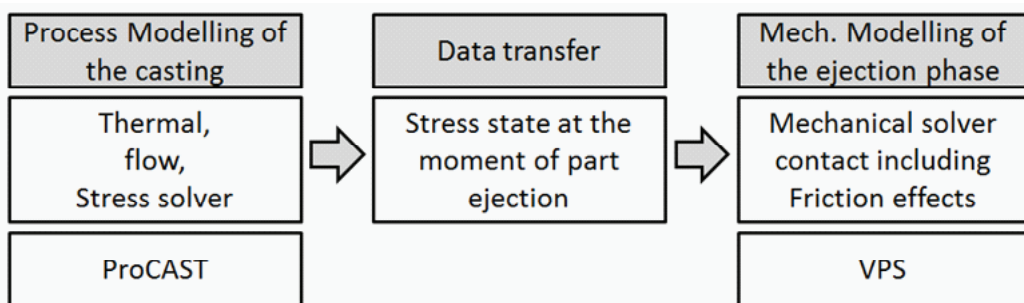
Modeliranje je razdeljeno na dva dela. Prvi del je simulacija procesa visokotlačnega litja (HPDC – High Pressure Die Casting). Modeliranje je sestavljeno iz polnjenja kokile s tekočim magnezijem, strjevanja, ohlajanja ter krčenja ulitka v kokili. Z vidika reševalnika to ustreza hkratnemu izračunu temperatur, pretoka in napetosti. Modeliranje je bilo izvedeno s svežnjem programske opreme za simuliranje industrijskega ulivanja ProCAST [1]. Simulacija poteka do trenutka razkalupljanja ulitka. Stanje obremenitve v tem trenutku se izvozi (Slika 1) ter uporabi za mehansko modeliranje faze razkalupljanja. Namen tega modeliranja je raziskati, kakšne obremenitve nastajajo (ob upoštevanju učinkov trenja), ko izmetači ulitek potiskajo iz kokile. Ta del modeliranja smo opravili z mehanskim reševalnikom programske opreme za modeliranje VPS [2].

range or if there are regions where plastic deformation occurs, which would indicate that the process parameters are not set well. Using this methodology will enable the virtual testing of different distribution and settings of ejections pins.

The article is structured in the following way. First the principle approach to solve the problem by modelling will be described. The details include material properties, boundary conditions and other information that are used by the modelling. This framework will then be applied on a conceptual case to show that the model is behaving in a consistent way. The obtained results of this case will be explained in detail. In the last section, the modelling will be applied on an industrial case.

2 Description of the Principle Modelling Approach

The modelling is divided in two parts. The first part is a process simulation of the HPDC (High-Pressure-Die-Casting) process. Content of the modelling is the filling of the liquid Magnesium in the metallic die, the solidification, cooling down and how the part is thereby shrinking onto the die. From the point of view of the solver this is corresponding to a coupled thermal, flow and stress calculation. The modelling is performed with the industrial casting simulation software package Pro-CAST [1]. The modelling is performed until the moment of part ejection. The stress state in this situation is exported (Figure 1) in order to initialize a mechanical modelling of the ejection phase. Content of this modelling is to investigate what kind of stresses will occur when the ejection pins are moving the part outside the die taking into account friction effects. This part of the modelling is performed with the mechanical solver from VPS [2].



Slika 1: Diagram modeliranja

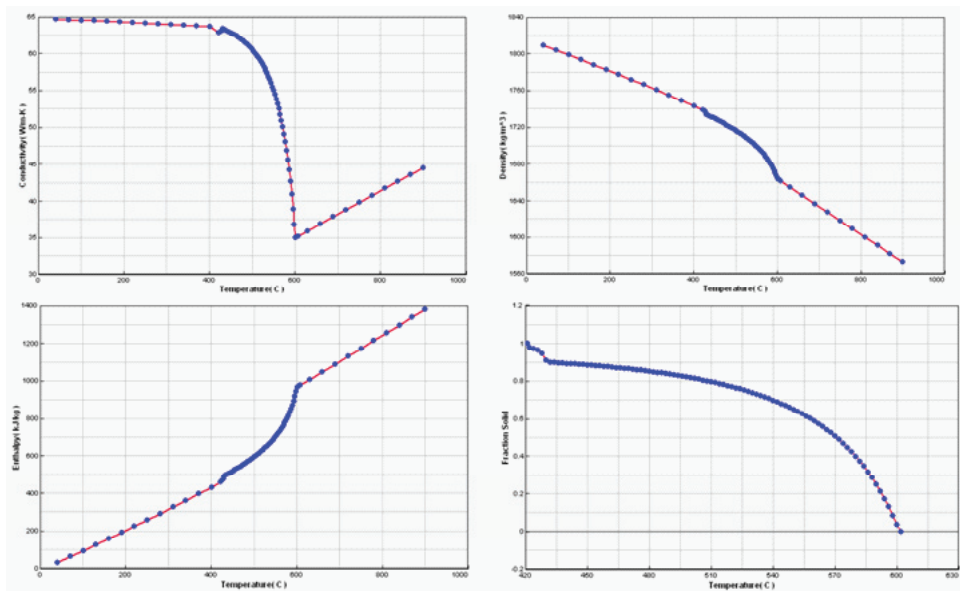
Figure 1: Modelling schema

3 Nastavitve modeliranja

Modeliranje je zajemalo določanje mehanskih lastnosti ter robnih in začetnih pogojev. Lastnosti materiala zajemajo toplotne in mehanske vidike. Na Sliki 2 so prikazane glavne toplotne lastnosti,

3 Modelling Setup

The modelling setup is consisting of setting the material properties, boundary conditions and initial conditions. The material properties are consisting of thermal and mechanical aspects. Figure 2 shows the main thermal



Slika 2: Toplotne lastnosti zlitine AZ91, zgoraj levo toplotna prevodnost, zgoraj desno gostota, spodaj levo entalpija, spodaj desno delež trdne faze

Figure 2: Thermal properties of AZ91, top left conductivity, top right density, bottom left enthalpy, bottom right fraction solid

na Sliki 3 pa glavne mehanske lastnosti, uporabljene za nastavitve modeliranja. Podatke smo pridobili iz podatkovne zbirke o materialih programa ProCAST [1]. Za opisovanje mehanskega vedenja smo uporabili model elasto-plastičnega materiala z linearnim strjevanjem [3]. Za kokilo smo uporabili termične lastnosti jekla H13, za namene modela obremenitve pa smo kokilo označili za togo. Koeficient temperaturne prevodnosti med zlitino in kokilo je bil nastavljen na vrednost 3000 W/(m² K). Za zlitine smo uporabili začetno temperaturo 625 °C, za material kokil pa 225 °C (industrijski primer) oz. 180 °C (študija primera).

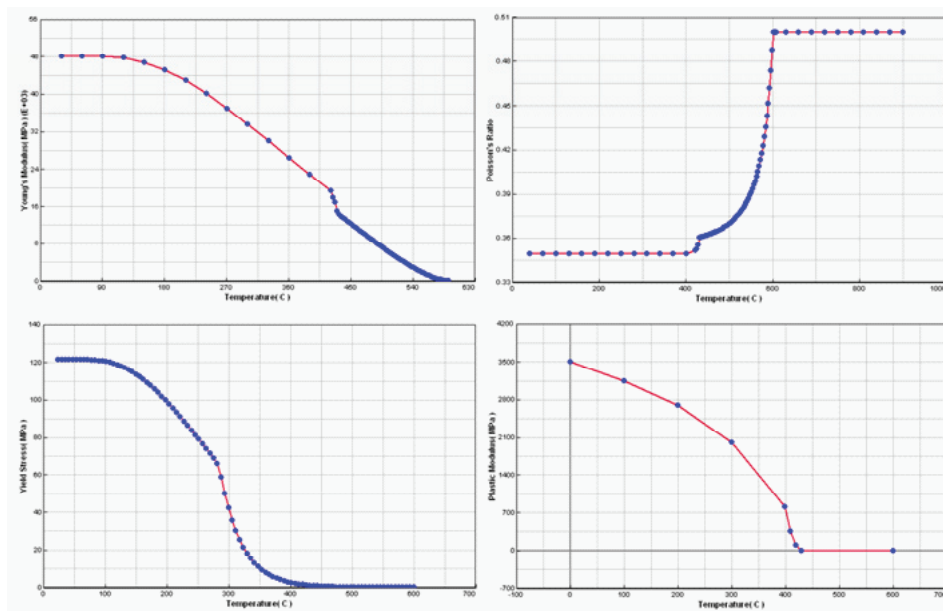
4 Študija primera

Na Sliki 4 je prikazana oblika dela ulitka v tej študiji primera. Gre za votel valj na osnovni

properties while Figure 3 shows the mechanical properties that were used for the modelling setup. The data is taken from the ProCAST material database [1]. As a description for the mechanical behaviour an elasto-plastic material model with linear hardening was used [3]. For the die, the thermal properties of H13 were used and considered as rigid for the stress model. The interface heat coefficient between alloy and die was set to 3000 W/(m² K). An initial temperature of 625 °C was used for the alloys and 225 °C (industrial case) respectively 180 °C (conceptual case study) for the die material.

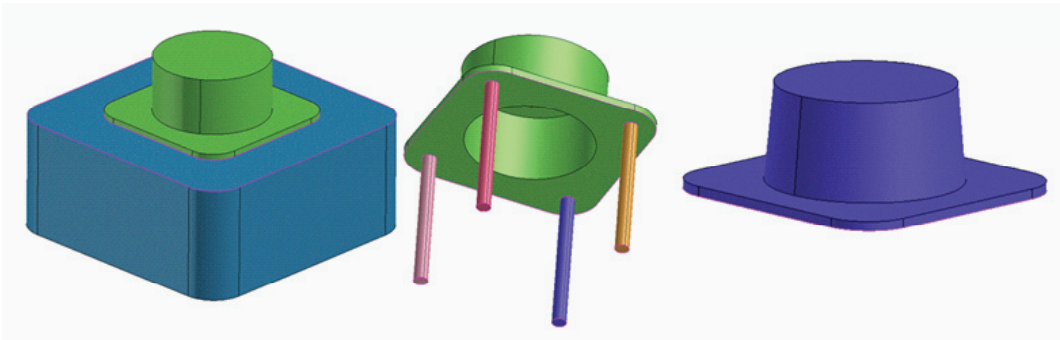
4 Conceptual Case Study

Figure 4 shows the geometry that was used for the conceptual case study. The



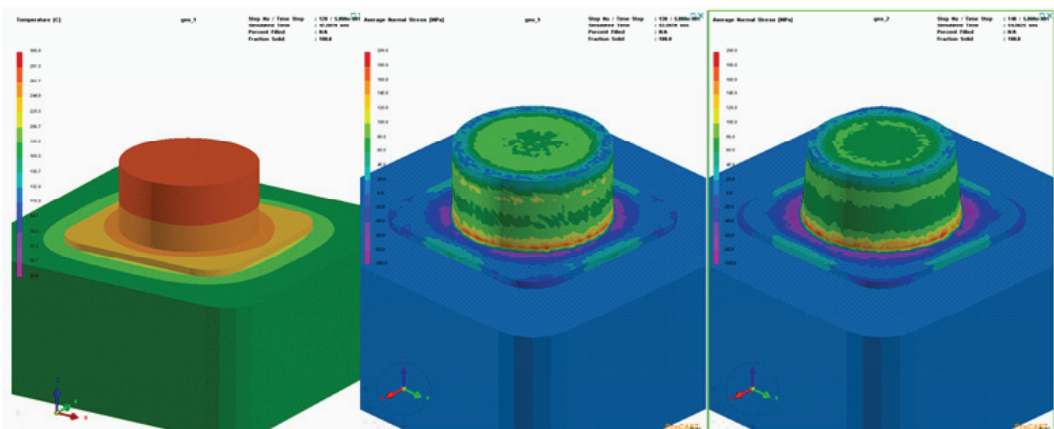
Slika 3: Mehanske lastnosti zlitine AZ91, zgoraj levo Youngov modul, zgoraj desno Poissonovo razmerje, spodaj levo napetost tečenja, spodaj desno modul plastičnosti

Figure 3: Mechanical properties of AZ91, top left Youngs Modulus, top right Poisson ratio, bottom left Yield stress, bottom right Plastic Modulus



Slika 4: Oblika ulitka v študiji primera

Figure 4: Geometry used for the conceptual case study



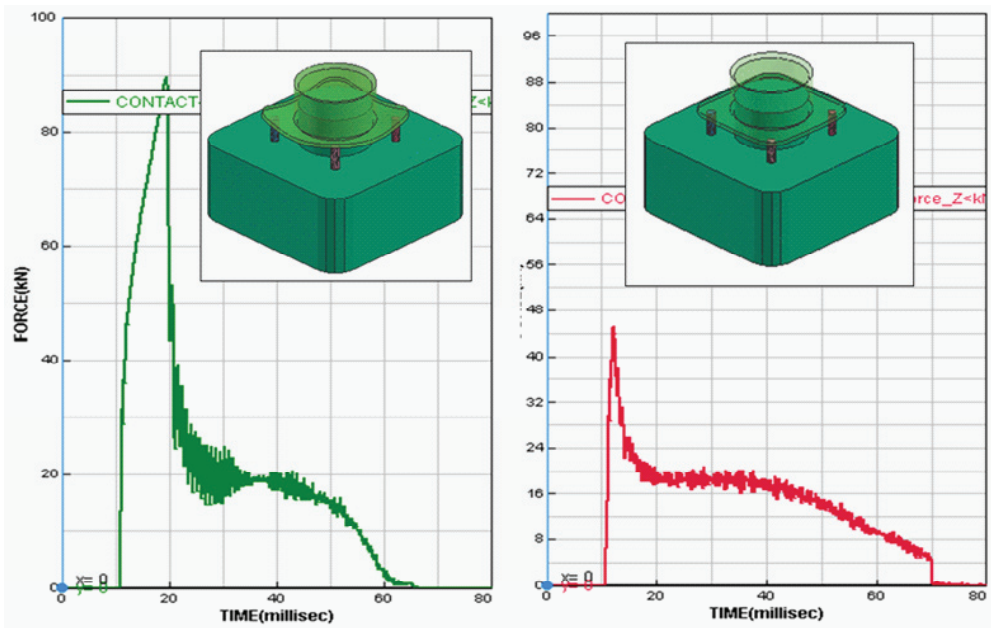
Slika 5: Rezultati termičnega in napetostnega preizkusa v študiji primera

Figure 5: Thermal and stress results conceptual case study

plošči. Izdelali smo ga z dvodelno kokilo (zgornji del ni prikazan), kot je običajno za visokotlačno litje. Osnovne mere dela so: debelina sten 6 mm, zunanji premer valja 120 mm in višina 66 mm (skupaj z osnovno ploščo). V prvem primeru smo zasnovali pokončni krožni valj (Slika 4 na sredini), v drugem pa prisekan stožec s stranicami pod 5-stopinjskim naklonom (Slika 4 na desni). Spodnji del kokile vsebuje štiri valje, ki delujejo kot izmetači.

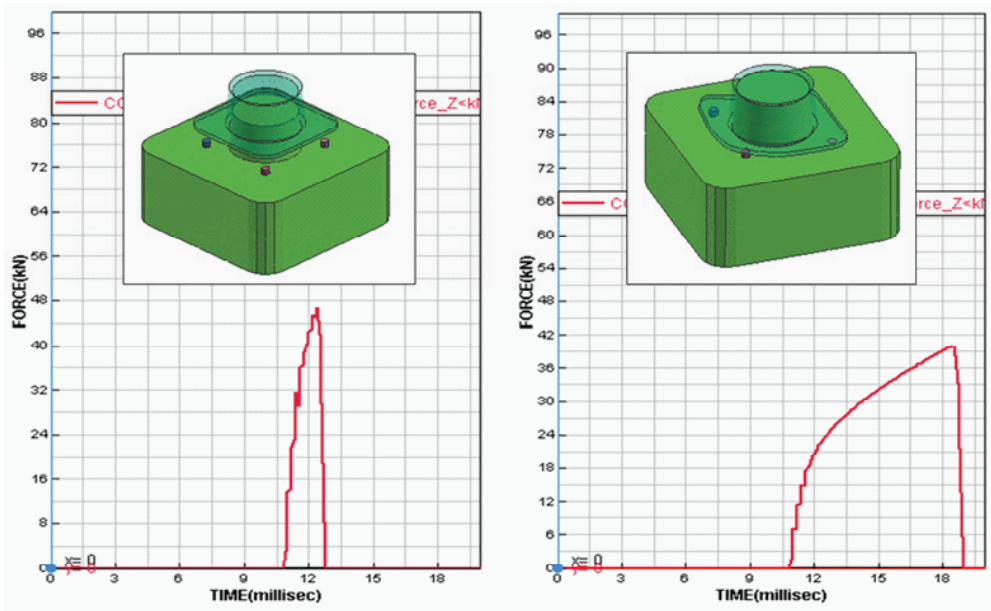
Na levi strani Slike 5 so prikazani temperaurni rezultati ob trenutku razkalupljanja. Ulitek se ohladi do

part is consisting of a hollow cylindrical set on a base plate. It is formed by two parts of a die (upper part of the die not shown) to represent a typical HPDC setup. Basic geometrical features of the part are a wall thick-ness of 6 mm, outer diameter of the cylinder 120 mm and a height of 66 mm (including the bottom plate). In one case the cylinder was straight (Figure 4 middle), in a second case the cylinder wall was inclined by 5 degrees (Figure 4 right side). The bottom die contains four cylinders that are rep-resenting the ejection pins.



Slika 6: Sile v fazi razkalupljanja za pokončni krožni valj (levo $fc\ 0,2$, desno $fc\ 0,1$)

Figure 6: Forces during ejection phase straight cylinder (left side $fc\ 0.2$, right side $fc\ 0.1$)



Slika 7: Sile v fazi razkalupljanja za prisekan stožec (levo 4 vodila, desno 2 vodili)

Figure 7: Forces during ejection phase inclined cylinder (left side 4 pins, right side 2 pins)

temperature približno 260 oC. Zaradi vedno večje gostote v trdnem stanju (Slika 2 zgoraj desno) se ulitek krči na kokili, zaradi česar nastajajo notranje napetosti (Slika 5 na sredini in na desni strani). Na takšnem stanju obremenitve je bila nato izvedena mehanska analiza in raziskana faza razkalupljanja.

Na Sliki 6 in Sliki 7 so prikazani rezultati simulacije faze razkalupljanja. Vodoravna os prikazuje čas, navpična pa pridržalno silo. Vrednost 0 s predstavlja trenutek, ko se izmetači začnejo premikati s konstantno hitrostjo. Na Sliki 6 je prikazan primer pokončnega krožnega valja. V primeru s Slike 7 je bil koeficient trenja f_c spremenjen (leva stran 0,2, desna stran 0,1). Ko se izmetači začnejo premikati, morajo najprej premagati statično trenje, ki ga v grafih prikazuje prvi vrh. Ko je dosežena ta vrednost, se začnejo valji premikati, nanje pa deluje dinamično trenje. Linearno zmanjšanje pridržalne sile po doseženem vrhu lahko razumemo, če upoštevamo, da se stična površina (valja) zmanjšuje linearno s hitrostjo izmetavčev. Vrh je skladno s pričakovanji enak koeficientu trenja f_c . Z znižanjem koeficienta trenja f_c z 0,2 na 0,1 se tudi pridržalna sila s 95 kN zmanjša na 47 kN.

Na Sliki 7 je prikazan primer presekanega stožca. Koeficient trenja f_c je bil v tem primeru nastavljen na vrednost 0,1. Vedenje z leve strani Slike 7 je na začetku v večji meri enako tistemu s Slike 6 na desni, saj je stanje v povezavi s statičnim trenjem precej podobno. V obeh primerih se začne valj premikati, ko je dosežena pridržalna sila 47 kN. Nato začne presekani del izgubljati stik in sile padejo na vrednost 0, medtem ko stožčasti del s Slike 6 vzdržuje silo do zaključenega razkalupljanja. Na Sliki 7 na desni je prikazan primer aktivacije dveh vodil. Zaradi nesimetričnih sil pride do momenta, zaradi katerega se ulitek med

Figure 5 left side shows the thermal results at the moment of ejection. The part is cooled down to a temperature of around 260 oC. Due to the increasing density in the solid state (Figure 2 top right) the part is shrinking onto the die and develops internal stresses (Figure 5 middle and right side). This stress state was then transferred to the mechanical analysis and the ejection phase was investi-gated.

Figure 6 and Figure 7 show the results on ejection phase modelling. The horizontal axis is showing the time and the vertical axis the total holding force. The value of 0 s is the moment when the ejection pins begin to move with constant velocity. Figure 6 is referring to the case of straight cylinder. In the cases corresponding Figure 7 the f_c (friction coefficient) was changed (left side 0.2, right side 0.1). When the pins start to move they first have to overcome the static friction which is corresponding to the first peak of the graphs. Once this value is reached the cylinder starts to move in a dynamic friction mode. The linear decrease of the holding force after the peak can be understood by taking into account that the contact surface (of cylindrical shape) is decreased linearly with the velocity of the ejection pins. The peak value is proportional to the f_c as expected. By lowering the f_c value from 0.2 to 0.1 the holding force is reduced from 95 kN to 47 kN.

Figure 7 is corresponding to the inclined cylinder geometry (truncated cone). The f_c value was set to 0.1 in this case. The behaviour observed in Figure 7 left side corresponds in the beginning very much to the one in Figure 6 right side since the situation of the static friction is quite similar. In both cases the cylinder is starting to move once a holding force of 47 kN is reached. But then the inclined part is losing contact and the forces go to a 0 value while the cylindrical part in Figure 6 is still hold

razkalupljanjem nagne. V takšnem primeru se morajo vodila pred popolnim izmetom premakniti globlje, zaradi česar je pridržalna sila enaka nič.

5 Aplikacija na industrijskem primeru

V nadaljevanju so prikazani rezultati običajnega visokotlačnega litja magnezija na industrijskem primeru. Slika 8 prikazuje temperaturno polje pred izmetom, Slika 9 pa prikazuje ujemajočo porazdelitev obremenitve pred izmetom.

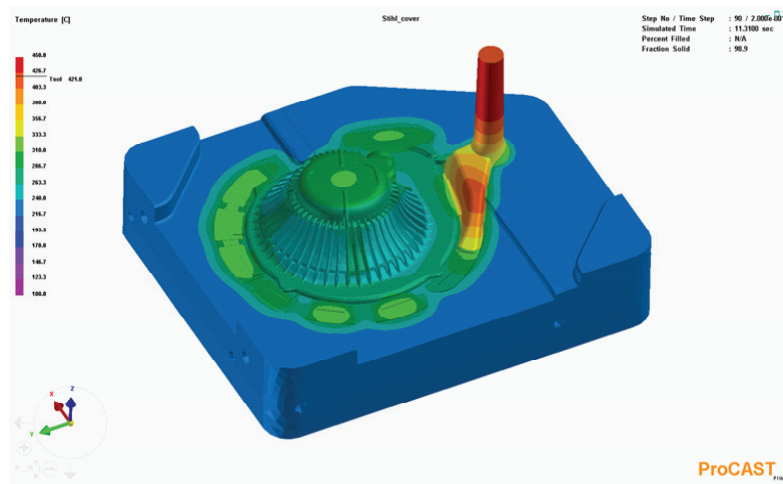
Mrežo ulitka, kokila (premični del) ter izmetače skupaj uvozimo v mehanski reševalnik VPS (Virtual Performance Solution) proizvajalca ESI. Na podlagi porazdelitve obremenitve v delu (Slika 9) se inicializira kontaktni algoritem, ki upošteva sile trenja, ki del zadržujejo v kokilu. Kokila je vedno zasnovana z naklonom; v nasprotnem primeru bi ulitek iz nje zdrsnil brez trenja. V prikazanih rezultatih modeliranja je bil določen koeficient trenja 0,2. Slika 10 prikazuje porazdelitev obremenitve, kot je bila uvožena v reševalnik VPS (enako kot na Sliki 9)

until complete ejection. Figure 7 right side shows the case where only two pins were acti-vated. Because of the non-symmetric forces a momentum is created which cants the part during ejection. In this case the pins need to move further before the part is completely ejected and thus the holding force shows a zero value.

5 Application on an Industrial Case

In the following the results of a typical Mg HPDC industrial case is shown. Figure 8 shows the temperature distribution before ejection. Figure 9 shows the corresponding stress distribution before ejection.

The mesh of the casting part, the die (moving part) and the ejection pins together are imported in the mechanical VPS (Virtual Performance Solution) solver from ESI. Based on the stress distribution in the part (Figure 9), the contact algorithm is initialized, which is taking account the friction forces that hold the part inside the die. Since the die is always designed with a taper the part would otherwise slide out of the die without friction. In the displayed



Slika 8: Termična porazdelitev v trenutku pred razkalupljanjem

Figure 8: Temperature distribution at the moment before ejection

Po izmetu se obremenitev razporedi znova. Na podlagi primerjave Slike 10 in Slike 11 postane jasno, da so se obremenitve po razkalupljanju na splošno zmanjšale.

Proces razkalupljanja bi lahko alternativno proučili tudi tako, da bi analizirali stične sile med razkalupljanjem. Na Sliki 12 so prikazane sile ob trenju 0,2 in 0,5.

V primeru koeficienta trenja f_c 0,5 meri maksimalna skupna sila pribl. 160 kN, v primeru koeficienta trenja $f_c = 0,2$ pa smo zabeležili sile pribl. 50 kN. V sklopu modeliranja je očitno, da vedenje skupne sile ni popolnoma linearno. Sila v primeru

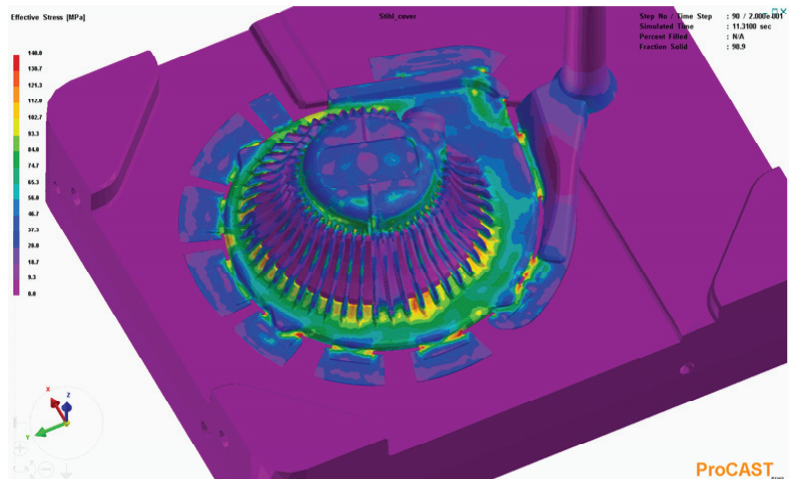
modelling result, a friction coefficient of 0.2 was assumed. Figure 10 shows the stress distribution as imported by the VPS solver (same as Figure 9)

Once the part is ejected the stress field takes a new equilibrium. Comparing Figure 10 and Figure 11 one can observe a general reduction of the stress values after ejection.

Another possibility to analyze the ejection process is to have a look at the contact force during ejection. Figure 12 shows this force for friction values of 0.2 and of 0.5.

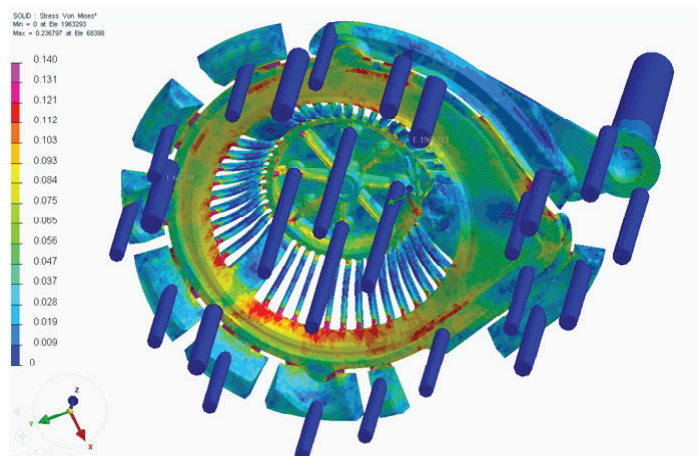
Slika 9: Porazdelitev obremenitve (v Mpa) v trenutku pred razkalupljanjem

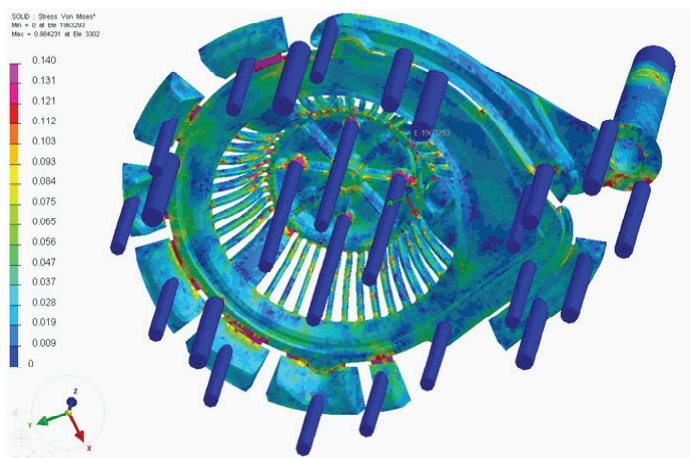
Figure 9: Stress (in MPa) distribution at the moment before ejection



Slika 10: Porazdelitev obremenitve (v GPa), uvožena v reševalnik VPS

Figure 10: Stress (in GPa) distribution as imported in the VPS solver



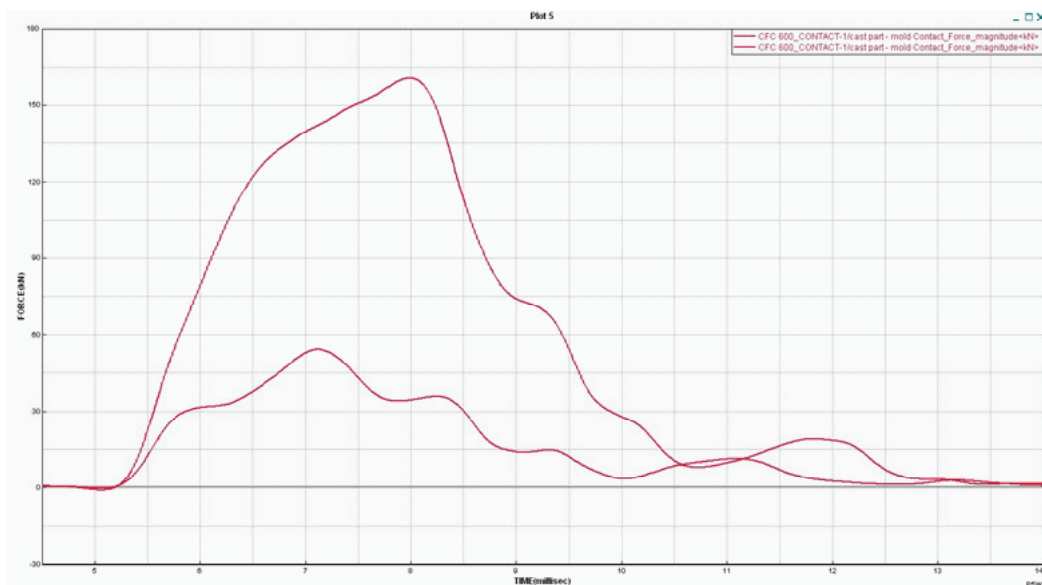


Slika 11: Porazdelitev obremenitve (v GPa) po razkalupljanju

Figure 11: Stress (in GPa) distribution after ejection

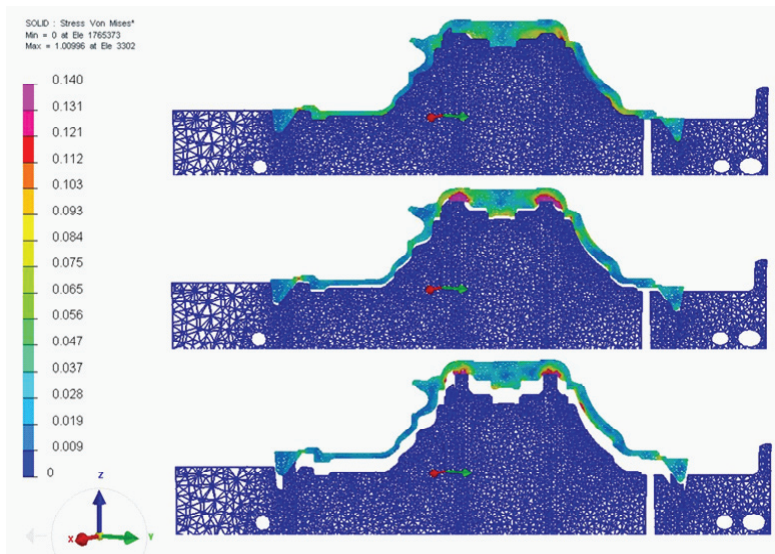
Slika 12: Skupna sila med razkalupljanjem; zgornja krivulja koeficient trenja f_c 0,5, spodnja krivulja 0,2

Figure 12: Total force during ejection, upper curve f_c of 0.5, lower curve f_c of 0.2



trenja 0,5 je rahlo večja od pričakovanj v primerjavi s trenjem 0,2 (če bi pričakovali, da drži načelo sorazmernosti). Razlikuje se tudi oblika krivulj. Videti je, da se pri nižjem trenju razkalupljanje zgodi v dveh korakih (ulitek verjetno najprej izgubi stik z enim mestom in nato še z drugim), v drugem primeru pa izmetavanje sestavlja zgolj en korak.

In the case of a f_c (friction coefficient) of 0.5 the maximum total force is around 160 kN, while in the case of a $f_c = 0.2$ an ejection force of around 50 kN can be observed. From the modelling, it appears that the total force shows not a complete linear behavior. The force in the case of 0.5 friction coefficient is slightly higher than expected comparing to the case of a friction coefficient of 0.2 (if one would expect a proportional law). Also, the



Slika 13: Obremenitev presečne ravnine med razkalupljanjem

Figure 13: Stress in a cutting plane during ejection

Naš pristop omogoča podrobno proučitev faze razkalupljanja. Slika 13 prikazuje obremenitve presečne ravnine med razkalupljanjem. Slika zgoraj prikazuje obremenitve pred razkalupljanjem. Pomniti je treba, da je kokila v trenutnem modelu toga, zato je vrednost obremenitev enaka nič. Ko izmetači izmečejo ulitek, pride na mestu stika do velikih obremenitev. Obremenitve so višje, kadar so mesta stika velika (srednji del Slike 13), oz. se zmanjšujejo z razkalupljanjem ulitka iz kokile (Slika 13 spodaj).

Čeprav so rezultati v industrijskih primerih dosledni s spremembami parametrov modela, jih je mogoče nadalje potrditi zgolj skozi primerjavo z rezultati drugih poskusov. S tem vprašanjem se nameravamo spopadati v prihodnosti.

6 Sklepi in nadaljnji koraki

V tem prispevku je predstavljen nov pristop k modeliranju faze razkalupljanja pri tlačnem litju. Na podlagi simulacije procesa

shape of the curves is different. It seems that in the case of lower friction the ejection is done in two steps (the part is probably losing contact first in one area and then in another) while in the second case the ejection is done at once.

The approach is enabling to look at the ejection phase in all details. Figure 13 shows in this context the stresses in a cutting plane during ejection. The top slide shows the stresses before ejection. To be noted that in the current modelling the die is regarded as rigid and therefore the stresses are zero. When the part is ejected by the pins high stresses can be observed in the contact area. The stresses are higher when the contact areas are still large (Figure 13 middle part) and decrease further when the part is more and more moved out (Figure 13 bottom).

While the results of the industrial case are consistent to parameter changes of the model, a further validation can only be achieved by a comparison to experimental results. This will be addressed in the future.

litja, vključno z vidiki termike, pretoka in obremenitev, je osnovan model obremenitve v trenutku razkalupljanja. Takšen model je nato obdelan v mehanski analizi, v sklopu katere napovemo mehanske sile v fazi razkalupljanja. Raziskave študije primera so pokazale, da so izsledki glede vpliva oblike, trenja in nastavitev izmetačev dosledni. Aplikacija na industrijskem primeru dokazuje, da je mogoče z vidika kompleksnosti oblike takšen pristop uporabiti tudi v dejanskih industrijskih procesih.

Naslednji korak raziskav bo potrditev rezultatov poskusa z namenom umeritve koeficientov trenja, ki bi lahko ustrezali dejanskemu industrijskemu okolju. Po pridobitvi rezultatov se bo pristop uporabil za optimizacijo samega procesa, npr. skozi zmanjšanje števila izmetačev.

6 Conclusions and Next Steps

The article shows a new approach to model the ejection phase in HPDC. Based on process simulation of the casting process including thermal, flow and stress aspects the stress state at the moment of ejection is modelled. This state is further processed with a mechanical analysis in order to predict the mechanical forces during the ejection phase. Investigations of a conceptual case show that the results behave in a consistent manner concerning the influence of casting geometry, friction and ejection pin settings. The application on an industrial example shows that this approach can also be applied on a real industrial process in term of complexity of the geometry.

Next step of the investigations will be the validation by experimental results in order to further calibrate the friction coefficients valid in a real industrial environment. Once such results are available the approach will be used to optimize the process itself for example by reducing the number of ejection pins.

Viri / References

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