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Simple Viscosity Criterion for Injection Moulding Thermoplastics

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Summary

Thermoplastics are available in abundance with immense properties variations, but only few are processed by injection moulding. So this manuscript deals with this issue by proposing a design criteria contingent to a particular combination of material properties, machine specifications and moulding features. Pertinently embracing their behavioural relationships a unique analytical design criterion was deduced directly from first principles. Comprehending injection conduit to an analogous capillary tube; as well as cognising generalized Newtonian concept for thermoplastic melts with power-law description of in-situ rheological behaviour. The proposed criterion being simple and generic easily adapts in early mould design itself and comprehends entire range of thermoplastic in-situates. Hereafter any thermoplastics could be injection moulded by contingently designing an exclusive mould feed system for it. This percipience was elucidated by continuously sensitising a hypothetical intervene across all thermoplastics while explicitly appraising, why melt kinesis lacunae can never be fully rectified, despite manipulating process parameters many times? Finally, the manuscript extends hereto-believed linear relationship between runner-conduit size and in-situ melt state to direct exponential proportionality with discrete slope and altitude for each thermoplastic behaviour. .

KEYWORDS:
Injection moulding
Melt viscosity
Runner conduit
Thermoplastics

KLJUČNE RIJEČI:
cijevni vod uljevnog kanala
injekcijsko prešanje
plastomeri
viskoznost taljevine

Viskoznost – jednostavni kriterij pri konstruiranju kalupa za injekcijsko prešanje plastomera

Sažetak

Plastomeri se odlikuju ogromnim brojem varijacija različitih svojstava. Relativno se mali broj tih materijala injekcijski prešaa. Rad se bavi problemom predlaganja kriterija konstruiranja kalupa koji su neizvjesni za određenu kombinaciju svojstava materijala, specifikaciju stroja i karakteristike kalupljenja. Imperativno obuhvaćajući njihove odnose ponašanja izveden je jedinstveni analitički konstrukcijski kriterij izravno iz prvih načela; shvaćajući uljevni sustav (e. *injection conduit*) prema kapilarnoj cijevi; kao i poznavajući generaliziran Newtonov koncept za plastomerne taljevine opisan reološkim zakonom potencija.. Budući da je jednostavan, predloženi kriterij se lako prihvaća u samoj ranoj fazi konstrukcije kalupa i obuhvaća puni raspon plastomernih *in-situ* stanja. Stoga se svaki plastomer može injekcijski prešati samo ako su odgovarajući dobavni sustav zavisno konstruiran. Kako bi se razjasnila ta činjenica primijenila se hipotetička intervencija kako bi se stalno senzibilizirali svi plastomeri. Pri tome jasno objašnjavajući zašto odgovor kalupne šupljine na tečenje taljevine nikada ne može biti ispravljen, čak i nakon velikog broja promjene parametara procesa. Na kraju, rad se proširuje na ono što se prije smatralo linearnim odnosom veličine dobavnog voda uljevnog kanala prema *in-situ* stanju taljevine uspoređujući izravnu eksponencijalnu proporcionalnost s diskretnim nagibom i visinom za svako ponašanje plastomera.

Introduction

Several injection moulding defects and awkward distortions occur abruptly without any attributed root cause.[1] Even if contentions are established, it would be challenging or impossible to eliminate them[2] because most do not have easy fixes[3] or do not have proven remedies and discrepantly prevail.[4] For injection moulding a plastic, mould design is a decisive activity with direct repercussions to yield quality, productivity and thereby frugality as it involves various crucial decisions; especially designing feed system. Fundamentally, mobility defects like jetting, silver streaks, shrinks, warps, short shot and flash are feed system design error consequences. Mainly because melt kinesis design lacunae significantly vacillates melt injection; like in illustrative figure 1[5] *in-situ* injectant state dissonance with runner conduit[*] design glares as defects.

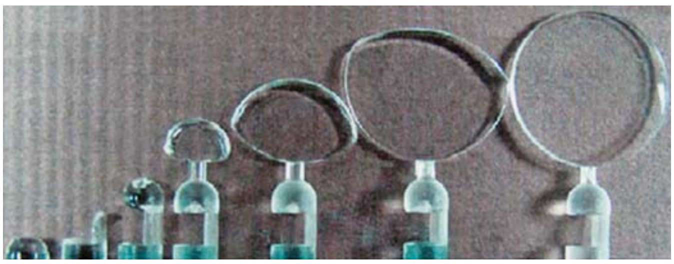

FIGURE 1 – Effect of runner size dissonance with in-situ injectant state[5]

Dissonant runner conduit design unusually resists injection, consumes energy excessively and eventually deprives the ability of holding in-mould pressure.[6] Nevertheless in-depth comprehension accounting gross defect incidence physics to their phenomenal interaction with conduit geometry, injectant conveyance,[3] pressure recovery and injectant phase transformation[7] are still fictional. Obviously even shrewd optimiser can never afford to negotiate beyond some convincing compromise,[8] reasoning the situation would be akin to a seesaw with the maximum for APL (*Acceptable performance level*)[9] and minimum for AQL (*Acceptable*

[*] Here for brevity we attribute conduit to the hallow runner passage or tunnel through which injectant could be injected

quality level)[10] on either side over a design fulcrum. So tottering between sluggish productivity and quality compromise is inevitable.[11]

Functionally runner conduits distribute melt from sprue well to gates over the parting surface[12] with minimal mechanical and thermal energy outlay.[13] So its shape and size significantly influence impression contrivability[14] and its design perfectness is crucial to inject, distribute melt and eject moulded part later.[15] Succinctly injectant conveyance and phase transformation conciliate toward an exclusive conduit geometry design that can essentially leverage highest injectable shear rate (*at operating pressure and temperature*), which actually being reciprocal of minimum fill time.[16] Traditional wisdom driven manipulations rely on adjusting in-situ melt state at a putative fill time;[17,18] like for filling/occupying thin moulding impression gaps just before melt solidifies, rapid injection rates are often used. Instead, the essential basis should have been of ensuring volumetric contiguity, balancing injection effort to occupy impression swiftly and equilibrating fast heat transfer to solidify for quick ejection[19] Accordingly for ideal contrivance and even melt state sustenance runner design should be comprehensively deduced from pressure gradience, shearability and melt-wall interface temperature gradience.[20] Which then endures rapid entrée into the impression by availing rated injection capacity of available machine, swiftest shearable extent of injectant and with almost uniform transit state. Similarly despite discretely fragmented stage vacillations, conduit topology design should convene with corresponding injectant rheology[21] to moderate intra-conduit shear heating[22] and its in-situ behavioural characteristics to avoid differential shrinkage and accomplish homogeneity.[23] Such contentions were unfortunately never pursued likewise first principles deduced design criterion is still unforeseen.[24] Intuitively mould designers habitually specify it with wisdom, then exasperate to optimise or manipulate process control parameters presuming them to be independent.[11] Having that as focal theme, the manuscript aims to deduce an analytical design criterion directly from first principles by imperatively embracing ubiquitous empirical relationships. Then leverage computational intelligence advantage by recognising fallout phenomenal models as conditions to constrain it and obtain a robust criterion.

In pursuit, the inexpensive preventive criterion enables injection moulding any thermoplastic resin at its best characteristics, without impairing either moulding quality or machine's productivity.[25] From afore extensive literature survey, current manuscript systematically deems to assort in-situ spatiotemporal injectant state perplexity of almost all thermoplastics across apparent viscosity's behavioural de-facto range,[26] while anchoring machine and moulding *i.e., without manipulating operating* conditions.[27]

Runner Design Criteria

Idiosyncratic non-Newtonian injectant state exponential functions and injectant's constitutive equation intricacy inherently complicate conserving differential processing functions[28] and its evolutionary character as multiple constraints.[29] With nonlinear complexity among multiple variables,[30] concocting an analytical solution to injection-mould design problem is simply inimitable,[31] in fact, even slight progress is also a great accomplishment. Likewise for solving runner conduit design problem, thermoplastic melt injection was appreciated analogous to a generic capillary tube and its volumetric injection rate was hypothesised from power law equivalent of the celebrated Hagen-Poiseuille equation as,[32]

$$Q[t] = -\frac{n\pi R^3}{(1+3n)} \sqrt[n]{\frac{R}{2\mu}\left(\frac{\nabla P}{L_r}\right)} \tag{1}$$

Substituting corresponding power law index n=1 value corroborates to Newtonianess. While pressure gradience (∇P) between sprue well exit or runner conduit entrance orifice and runner conduit exit orifice could be expressed as a relative quotient of rated injection pressure P_{max} available in the machine as $\nabla P = C_P P_{max}$. Here C_P is characteristic coefficient representing in-mould pressure extent required to perfectly contrive (*which depends on velocity of sound through injectant and obtained as* $C_P = \frac{(P_{max} - P_{in-mould})}{P_{max}}$). Now substituting pressure gradience in terms of available machine's instantaneous volumetric injection rate Q[t] would be,

$$Q[t] = \frac{n\pi R^3}{(1+3n)} \sqrt[n]{\frac{R\, C_P\, P_{Max}}{2\mu\, L_r}} \tag{2}$$

From machine capacity perspective

$$\text{Fill Time} = \frac{\text{Shot Volume}}{\text{Volumetric Injection Rate}} \Rightarrow t_{fill\ time} = \frac{V_{Shot}}{Q[t]}, \tag{3}$$

Similarly from mould design perspective,

$$t_{fill\ time} = \frac{\text{Stroke Volume of M/c}}{\text{Injection rate}} = \frac{V_{Stroke}}{Q_{injection}} \tag{4}$$

Constraining maximum volumetric rate to available rated capacity, Q[t] ≤ $Q_{injection}$ full capacity could be exploited we equate Eqn (3) and Eqn (4) to get,

$$Q[t] = \left(\frac{V_{Shot}}{V_{Stroke}}\right) Q_{injection} \tag{5}$$

Comparing Equation (5) and Equation (2) we get,

$$\left(\frac{V_{Shot}}{V_{Stroke}}\right) Q_{injection} = \frac{n\pi R^3}{(1+3n)} \sqrt[n]{\frac{R\, C_P\, P_{Max}}{2\mu\, L_r}} \tag{6}$$

Now resolving the radius, we get,

$$R = \left(\frac{(3n+1)\, Q_{injection}}{\pi\, n}\left(\frac{V_{Shot}}{V_{Stroke}}\right)\right)^{\frac{n}{3n+1}} \left(\sqrt[3n+1]{\frac{2\mu L_r}{C_P P_{max}}}\right) \tag{7}$$

$$R = \underbrace{\left(\left(\frac{Q_{injection}}{V_{Stroke}}\right)^n \sqrt[3n+1]{\frac{Q_{injection}}{C_P\ P_{max} V_{Stroke}}}\right)}_{\text{Injector}} \underbrace{\left(\left(\frac{(3n+1)}{\pi\, n}\right)^n \sqrt[3n+1]{\frac{2\mu(3n+1)}{\pi\, n}}\right)}_{\text{Injectant}}$$

$$\underbrace{\left((V_{Shot})^n \sqrt[3n+1]{L_r\ V_{Shot}}\right)}_{\text{Impression}} \tag{8}$$

From Eqn. (8) runner conduit size is specific to a particular set of impression, injector and injectant functional combination and its active dependence characterise yield quality and performance. As well appreciating apparent viscosity's significant local bias in the proposed criterion is worth; because as a true fluid property it describes en route spatiotemporal melt state's resistance of diffusing through designed conduit. More specifically, it accounts melt strain rate response for an applied (*stimulation*) shear (*injection*) stress[33] and quantitatively discriminates injectant's character. Since Eqn (8) categorically quantifies material, machine and moulding influences, their sensitivities would be independent. Distinctly perturbing thermoplastic material characters or specific in-situ behaviours infers broad apparent viscosity sensitivity intellect, which would be highly valuable to enable prudence in specifying conduit design.[34] The combinational set of shear rate (*injection effort capacity of machine*), temperature and pressure (*thermoplastic melt state characteristics*),[35] and fill time (*component volume*)[18] intrinsically govern in-situ thermoplastic steady-state apparent viscosity and that prolifically manifests its importance to attribute the onset of several concerns.[36] Hence from rheological perspective apparent viscosity change has deterministic influence on shear injection rate depth[37] (*which otherwise is conduit size*). So sensitising runner conduit size over rational range endures physical relevance to decisiveness with uncertainty. Correspondingly ghettoising Eqn (8) quantitatively as an explicit function of available machine specifications; desired moulding component features; apportioning from gross defect initiation and shear rate limit incorporates comprehensiveness in designing apt runner-conduit size. Particularly balancing shear to elongation deformation quotient significantly abridges transit variability severeness.** Therefore, Eqn (8) ascribes an appropriate size that can possibly stabilise streamlines and reduce the amplitude of defects.

Several other paradigms of viscosity influence on conduit size were in literature with varying complexity and form. Like, most were upfront empirical attempts by relating shear stress to shear rate,[8] while few others embraced statistical mechanics theory[36] by applying kinetic theory or theory of rate to aqueous injectant state mobility.[38] Nevertheless despite these the credibility of educing a robust criterion to entwine conduit size with phenomenal mechanisms persists with many unlinked themes.[39]

Illustration

Precautious appreciation of injectant's behavioural character while designing runner conduit size would tremendously benefit, rather than remedying consequent defects after occurrence[6] and eventually improve overall mould design perfection. Above literature review and apparent viscosity perturbation ascended two enthrals for designing best runner conduit,

a) inoculation of in-situ phenomenal defect initiation;
b) repressing injection effort that stimulates indiscriminate mobility of injectant, such as detaching or dragging away[40]

Conventional design analogy involves casual mathematical substitution just enough to specify some discrete or finite runner size value presuming it to be an independent parameter. In contrast, Continuous Sensitivity Method (CSM) endures its relative complexity over an infinite dimensional range. CSM adopts illustrative intervention of Eqn (8) to holistically deliberate conduit design sensitivity across in-situ injectant state at a wisdom level much beyond pragmatic experimentation or classical philosophy can achieve. Though full analytical inference is still atypical, CSM intervention compliments a unique perspective over rife myths. Further to perspire comprehensiveness, power law parameters (*apparent viscosity and shear thinning index*) are independently perturbed to cognise their exclusive bias.[41] In pursuit of this discernment following hypothetical case is adopted,

a. Representatively Windsor sprint series horizontal injection moulding machine has been adopted,

TABLE 1 – Sprint 650T Machine Specifications[45]

Injection Pressure	P_{Max}	147 to 211.5 MPa
Based on BSR	C_P	75%
Barrel Stroke Volume	V_{Stroke}	3,770 to 5,430 cm^3
Injection Rate	$Q_{injection}$	483 to 720 cc/sec
Nozzle orifice	D_n	2.5 mm

Now, considering the machine term of Equation (8) and substituting Table 1 ranges, we get

$$Ms = \left(\frac{Q_{injection}}{V_{Stroke}}\right)^n \sqrt[3n+1]{\frac{Q_{injection}}{C_P\ P_{max} V_{Stroke}}} = \left(\frac{\{483,\ 720\}\times 10^6}{\{3770, 5430\}\times 10^6}\right)^n$$
$$\sqrt[3n+1]{\frac{\{483,\ 720\}\times 10^6}{0.75\times\{147, 211.5\}\times 10^6\times\{3770, 5430\}\times 10^6}}$$

Simplifying, we get,

$$Ms == \{0.12811671, 0.132596685\}^{\frac{n}{3n+1}}$$
$$\sqrt[3n+1]{\{9.07029478458, 6.304176517\}\times 10^{-9}} \left(\frac{1}{sec^n}\sqrt[3n+1]{\frac{m^2}{N\ sec}}\right) \tag{9}$$

For mathematical simplification, we opt for Equation (9) range at corresponding nominal values to get,

$$Ms = (0.130357)^{\frac{n}{3n+1}} \quad \sqrt[3n+1]{7.68723565079\times 10^{-9}} \tag{10}$$

b. A typical injection moulded part has been representatively adopted with the following hypothetical features from Table 2

TABLE 2 – Characteristic properties of ABS[46]

Shot volume of injection moulding component	V_{Shot}	2,500 cc
Runner insert length	L_r	80 mm

Now, considering the component term of Equation (8) and substituting Table 2 values, we get

$$Comp = (V_{Shot})^n \sqrt[3n+1]{L_r\ V_{Shot}} = \left(2500\times 10^{-6}\right)^n$$
$$\sqrt[3n+1]{80\times 10^{-3}\times\ 2500\times 10^{-6}} = \frac{1}{2^{\left(4n+\frac{3}{1+3n}\right)} 25^{\left(n+\frac{2}{1+3n}\right)}} \tag{11}$$

Now, substituting Equation 10 and Equation 11 in Equation 8 we get,

$$R = (0.130357)^{\frac{n}{3n+1}} \sqrt[3n+1]{7.68723565079\times 10^{-9}}$$
$$\underbrace{\left(\left(\frac{(3n+1)}{\pi\ n}\right)^n \sqrt[3n+1]{\frac{2\mu(3n+1)}{\pi\ n}}\right)}_{\text{Polymer}} \frac{1}{2^{\left(4n+\frac{3}{1+3n}\right)} 25^{\left(n+\frac{2}{1+3n}\right)}} \tag{12}$$

If in case (n) is representatively anchored at 0.33 (ABS), then $R = 0.23681665 \times 10^{-3}\ \mu^{0.497636228}$ m

In-situ influx injectant viscosity and shear thinning index dominance on runner design criterion is evident in Eqn (12), so divergence and uncertainty in corresponding behaviour would obviously also affect efflux state and phase transformation variance. Therefore, to determine an ideal runner size Eqn (8) analytical model is proposed.

Discussion

In relevance to our goal of being generic to all existing thermoplastics, figure 2 sensitises ideal runner size across de-facto influx apparent viscosity range with a corresponding array of shear thinning index curves. Most erstwhile researchers[18] have presumed the relationship between runner conduit size and viscosity to be almost linear,[44] perhaps owing the literal appearance in terse range. Surely, with recognised non-Newtonian viscoelastic shear thinning behaviour in thermoplastics[16] mere linearity is just an illusion; rather the relation would be exponentially sensitive in nature.[45] With apparent viscosity being base, it's coefficient and exponent functions would be shear thinning index factorials. Within de-facto range of both these factorials, the coefficient factor describes survival or existential nature and exponent factor describing scaling nature. Also first-order interactive sensitivity of shear thinning index and apparent viscosity pair toward ideal runner size being cognitively negligible, so differing curve slopes intersect at some large viscosity value, beyond which their slopes proliferate. Figure 2 plot imply that ideal runner size persists for all real-world thermoplastic melts offering apparent viscosity range from 10^2 to 10^5 Pa*sec,[46] with direct exponential proportionality of runner size to viscosity representing in-situ injectant state. So manipulating in-situ melt state has imperious influence on overall runner conduit size design incongruity,[18] implying even a large in-situ viscosity tweak could

** Like molten PC having high viscosity requires bigger conduit size than PA that has comparatively low viscosity. Because PC's rigid repeating units, heavy molecular weight, fibrous structure and so forth would increase apparent viscosity and constrain mobility between certain limits. Minimum for shear strain and maximum beyond which defects like degradation, microstructure heterogeneity, anisotropy, yield surface quality and so forth would be probable.[49]

only rectify very nominal perfection and eventual injection moulding consistency. Hence mere in-situ manipulation is inadequate to generalise feed system design even for thermoplastics having same or nearly equal viscosity.[26] As an inference from Figure 2, we illustrate curve trend with a tractile injectant behaviour of n = 0.7, at lowest in-situ viscosity state of 10^2 Pa*sec approximately 1,183mm of runner conduit size would be needed, in contrast an obdurate highly viscous state 10^6 Pa*sec would need 23mm. Accordingly we surmise that a'priori runner conduit size design contingent to injectant's rheological properties only accomplish ideal performance.

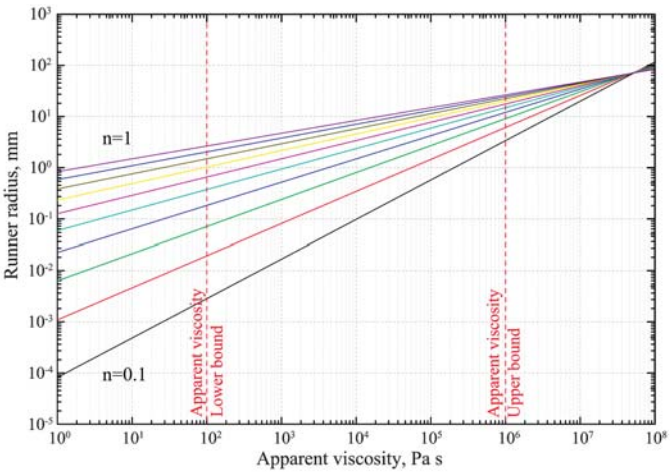

FIGURE 2 – Apparent viscosity influence on runner radius

Conclusion

Confined to empirical relations injecting non-Newtonian melt appears simple and manageable amazingly the spatiotemporal dependence involves intense computation. Besides the challenge aggravates even more, when mould design has to manage corporeal complexity. To accomplish best performance and superior quality with a particular set of injectant's behavioural characteristics, runner system has to be designed specifically attributing afore deliberated contentions. O'er modelled runner conduit size designing criterion coerces injecting all thermoplastic melts in correspondence to their respective in-situ rheological parameters easily obtainable from exclusive rheological studies[47,48] and also convenes to wide-ranging circumstances arising in actual injection moulding. This proposed exclusive criterion manifests parametric fine-tuning of exemplary performance because Eqn. (8) clearly discriminates machine, material and moulding influences. Hence it would be logical to conclude that all thermoplastics are injection mouldable subject to appropriate feed system designs. Nevertheless synchronising material properties and mould design revive best advantage and compliment several other gainable benefits through stretched competence; affective and cognitive in-situates like injection fill time, injection ramping speed for packing, operating temperatures, compatibility and so on. Further as an elite implication, the deliberations articulate an argument to incorporate computational intelligence in design criterion itself by constraining it through defect phenomenal incidence models.

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iCAT 2014 – *5th International Conference on Additive Technologies*

Every two year in October most famous conference about additive manufacturing is held in organisation of network rapiman.net. This year conference was held in Vienna from 14 till 16 October 2014. The conference attend 78 participant and 45 papers was presented. Conference was divided in 6 sections about materials, processing, design and medicine.

Svake dvije godine održava se konferencija o aditivnim postupcima (AM). Konferencija *iCAT 2014* održana je u Beču od 14. do 16. listopada u suorganizaciji *rapiman.net* (e. *RApid Prototyping and Innovative MAnufacturing Network*) i udruženja *F-AR*. Konferencija je bila podijeljena u šest sekcija: *AM i inovacije, Dizajn i AM postupci, Polimeri u AM, Lasersko srašćivanje i taljenje polimera, Metali u AM – lasersko taljenje i taljenje s pomoću snopa elektrona* i *AM u medicini*. Prvi put u sklopu konferencije organizirane su paralelne sekcije. Na skupu je sudjelovalo 78 predstavnika iz dvadesetak zemalja iz Europe, Amerike, Afrike, a najviše iz Njemačke. Iz Hrvatske je sudjelovalo dvoje predstavnika. Konferenciju je otvorio glavni organizator prof. dr. sc. Igor Drstvenšek, koji je govorio općenito o dosadašnjim konferencijama održanima u Celju, Ptuju, Novoj Gorici i Mariboru, ali i o organizaciji ovogodišnjeg skupa koji se s prostora Slovenije, gdje je pokrenuta inicijativa za organiziranje konferencije posvećene samo aditivnim postupcima, preselio u Beč. Prof. Drstvenšek i ove godine okupio je izvrsnu ekipu pozvanih predavača iz područja strojarstva i medicine iz cijeloga svijeta, a dodatno je na konferenciji svoje radove predstavilo 45 autora.

U sklopu konferencije organizirana je i veoma uspješna jednodnevna radionica o primjeni AM u medicini. Tijekom radionice sudionici su mogli raditi na stvarnim medicinskim problemima primjenjujući specijalne računalne programe za planiranje operacija i modeliranje implantata i instrumenata. Radionica je zamišljena tako da spoji liječnike medicine i inženjere u namjeri stvaranja interdisciplinarnog inkubatora novih ideja jer se sve inovacije temelje na znanju i na tome kako povezati različita područja te iskoristiti njihov sinergijski učinak. Cilj radionice bio je omogućiti uvid u to kako računalni programi mogu pomoći u konstrukciji, dizajnu i proizvodnji specijalnih implantata za potrebe maksilofacijalne kirurgije, neurokirurgije i ortopedije.

Sudionici konferencije o aditivnim postupcima *iCAT 2014.*

U stankama konferencije sudionici su mogli pogledati izložene tvorevine načinjene postupcima 3D tiskanja pijeska tvrtke *Voxeljet*, selektivnoga laserskog srašćivanja tvrtke *EOS* i stereolitografije na temelju računalnih modela tvrtke *Materials*.

Osnovna ideja konferencije je povezati akademske (znanstvene) zajednice i industriju. I svatko tko želi biti ukorak s novostima na području AM ili se upoznati sa svim vidovima AM, od konstrukcije i dizajna do upotrijebljenih materijala, postupaka, softvera, ekonomskih aspekata, medicine, inženjerstva..., svakako treba sudjelovati.