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Comparison of cooling simulations of injection moulding tools created with cutting machining and additive manufacturing

József Bálint Renkó^{a,*}, Dávid Miklós Kemény^a, Dr. József Nyirő^b, Dorina Kovács^a

^aBudapest University of Technology and Economics, Faculty of Mechanical Engineering, Department of Materials Science and Engineering, Bertalan Lajos street 7, Budapest 1111, Hungary

^bBudapest University of Technology and Economics, Faculty of Mechanical Engineering, Department of Manufacturing Science and Engineering, Műegyetem rkp. 3., Budapest 1111, Hungary

Abstract

Nowadays injection moulded products are gaining ground worldwide. The production time of the technology is relatively short, and it can produce thousands of products. The manufacturing speed depends on the injection moulding cycle, which is one of the most time-consuming parts of the cooling time [1]. As a consequence, the primary aim of the manufacturers is to minimize the cooling time within the injection moulding cycle. The aim of the research is to investigate whether the cycle time of an injection moulding can be reduced by using an additive manufacturing instead of traditional machining. MoldEx 3D program was used for the simulation. According to the simulation results, the cooling time has decreased more than 9% for a simple geometry product. The cycle time of complex structures can be decreased significantly with using more efficient cooling system. The dimensional accuracy also improved due to the decrease in warp.

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1. Introduction

Injection moulding is one of the most versatile and the most dynamically developing cyclic process to produce polymer products [1]. The reason is, the production time of the technology is relatively short and hundreds of thousands of products can be produced over a life cycle of a tool [2]. During the process, a thermoplastic polymer

* Corresponding author. Tel.: +36-30-842-2131

E-mail address: renko.jozsef@edu.bme.hu

was being warmed up to temperature of viscous liquid. The viscous flowing plastic material was injected with high speed and pressure through a narrow inlet opening into the tempered moulding tools [3]. The polymer took up their arbitrarily complicated shapes. Due to the cooling system of the injection moulding tools, the polymer was congealed, thus it created a point-sized workpiece [3, 4]. The manufacturing speed depends on a large extent on the injection moulding cycle, which is one of the most time-consuming part is cooling time [3, 5, 6]. Consequently, the primary aim of the manufacturers is to minimize the cooling time within the injection moulding cycle. If the cooling time can be reduced in some way, the manufacturing time of the product can be minimized. Typically, if different manufacturing parameters are changed, it can reduce the cooling time [2, 7]. However, that is not the only way to reduce the cycle time. The tool construction can also be transformed a more complex form-fitting cooling system [8]. Transforming the cooling system additive manufacturing offers an easy solution [9, 10–12].

Complex products can be produced with great accuracy within a relatively short period of time with additive manufacturing technology [13]. The advantage of the technology is the geometry, which is almost freely selectable and its design is confined only by the designer's imagination [14, 15]. Therefore, it is possible to create 3D bodies, that are not, or to produce with conventional cutting machining is difficult [9, 16, 17]. Initially, the technology was used as a rapid prototyping process of polymers, but nowadays almost all materials can be manufactured with the technology, which can be the different combination of metal, plastic, ceramics and paper [10, 18–23].

The aim of the research is to investigate the decreasing of the cooling time of an injection moulding which tool was made by additive manufacturing. The injection moulding tools of a product selected from real manufacturing was converted so that they can be produced only by Direct Metal Laser Sintering [18] or Selective Laser Sintering [11]. The form-fitting cooling system and the original were compared after the simulations of the manufacturing processes.

2. Materials and Methods

2.1. Materials

During the product selection, some important aspects had to be set up. Since it is not our intention to completely replace injection moulding tools created with conventional technologies, it is not worth choosing a very simple product. Simultaneously, however, the running time of the simulations may be increased by a large, extremely complex product geometry [24, 25]. After careful consideration we have chosen the product shown in Fig. 1. The chosen product's geometry is not very complex, but it has a sufficient depth to make use of a deep tool insert. The design of the cooling system inside the tool is further complicated by the fact that there is little room for the cooling circuit to reach internal components of the product.

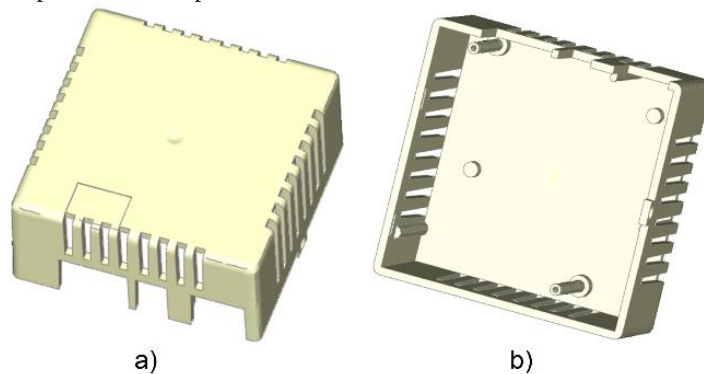


Fig. 1. The chosen product's geometry from two different direction. a) shows the outer, b) shows the inner geometry of the product

The material of the product is BayBlend FR3000, which is a V-0 flame-resistant PC / ABS mixture. The production serial is 500.000 pieces in a year. This number is enormous, so a few seconds of improvement in the

cycle time will significantly reduce the production time [26, 27]. If it can be decreased, the injection moulding machines can be released to give an opportunity for manufacturing other products.

The used tool to the manufacture is seen in Fig. 2. It is a single-cavity tool. One product can be produced per sequence. Although the large number of pieces of production could justify the multi-cavity design, it's cost would have been greatly increased due to the heated distribution channel connected to the cavity [7, 8]. As the aim of the research is not to optimize the number of products per cycle. We used the original design with the given technological parameters.

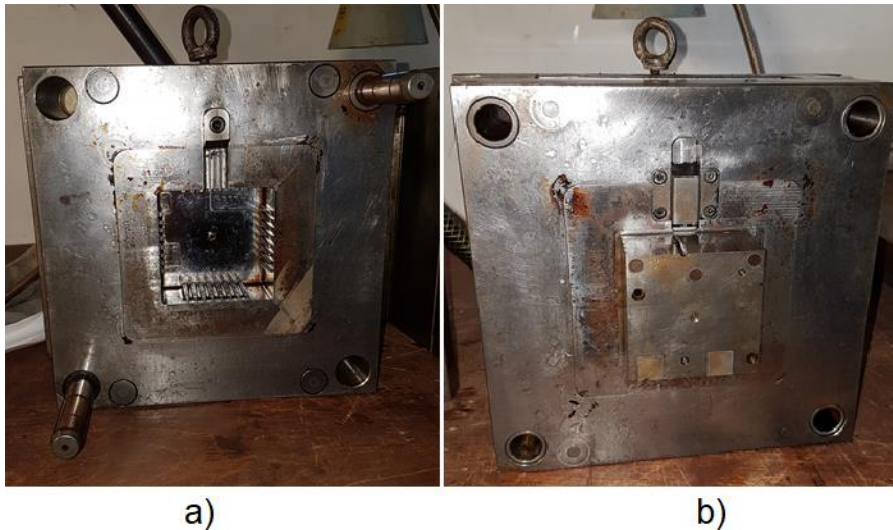


Fig. 2. The stationary (a) and the moving (b) tools used in real industrial production

The cooling system passes through two tool elements. These inserts have the direct connection with the injected plastic. The cooling circuits in these tool inserts are shown in Fig. 3. It can be seen the cooling circuit of the stationary tool perfectly surrounds the workpiece, while the circle of the moving side tries to manage the cooling inside of the product with two so called „cooling fingers” [7].

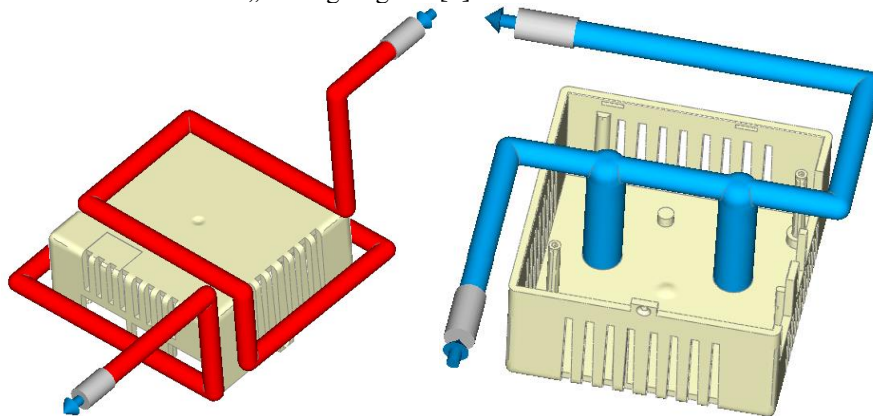


Fig. 3. The position of the cooling circuit around the product at the original tool. The red cooling circuit running through the stationary, while blue is running through the moving tool.

The cooling circle of the stationary side fits properly to the workpiece's outer surface, so changes are not required here. However, the cooling circuit inside the product cannot provides adequate cooling efficiency, so it must be changed. One of the most important aspects of converting the tool inserts was to modify only the cooling circuit,

without changing the ejection system. Although, the technology provides an opportunity to redesign these parts too, we have not touched them [15, 23]. Thus, only the effects of the cooling circuit changes can be investigated.

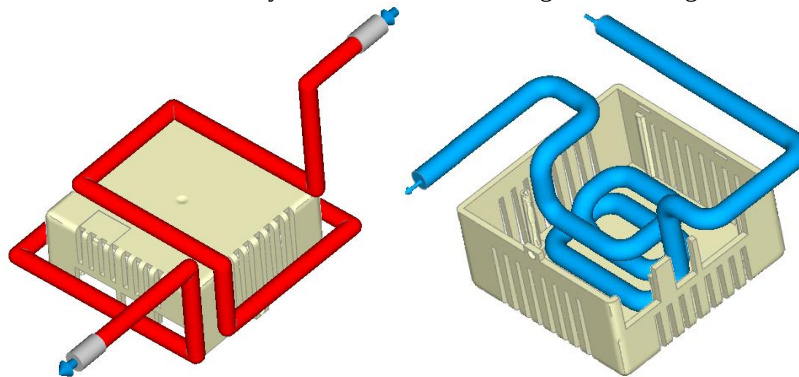


Fig. 4. The position of the cooling circuits around the product inside the modified, form-fitting tool. The red cooling circuit running through the stationary, while blue is running through the moving tool

Fig. 4 shows that rectangular pipe joints resulting from conventional cutting machining have disappeared. Due to the additive machining, the redesigned geometry of the cooling circle does not contain excess holes. This design can never be economically processed by traditional methods. Another advantage of the sintered cooling circuit is the number, the position and the diameter of the cooling circuits can be easily controlled. The modified cooling circuit inside the moving tool has the same diameter throughout its full length. Thus, the efficiency of the cooling circuit will be influenced only by the location and length of the cooling system.

2.2. Simulations

Simulation was performed using Moldex3D R.15.0 Software Family. Product and tool geometry as well as the technological parameters used in real industrial conditions were provided by the manufacturer. The tool was made by DIN 1.4404 corrosion-resistant steel. The quality of the material is also available for additive manufacturing, so the tool material at the simulations was not be changed and the results was not be affected by the material [28, 29, 30, 31, 32]. The size of the tool inserts was 246 mm x 246 mm x 283 mm. The tool movements, pressures and different temperatures during the injection moulding were used according to the product's manufacturing sheet to ensure that the results are as close to reality as possible. The model was meshed using Boundary Layer Mesh (BLM) method. The body near the surfaces densely, while the inside was loosely meshed.

During the injection, the polymer melt went through the hot-running system into the mould cavity. After the process the polymer melt was cooled from two sides, 50 °C water circulated inside the tools. The cooling time on the technology sheet is 25 seconds, which limits the cooling process. The "original" (created by cutting machining) and the "form-fitting" (created by additive manufacturing) cooling systems were simulated in transient mode. This way the temperature of the tools could be measured. After the comparison of the simulations' results, the form-fitting cooling circle was further developed in several steps.

3. Results and discussion

The conventional simulations results and form-fitting cooling circuits have been compared in different aspects. Firstly, the optimum for ejection were investigated. Secondly, the temperature distribution was examined both in the product and in the injection moulding tool. Finally, the temperature difference between two sides of the product and their effects were investigated.

3.1. Determination of cooling time

25 seconds of cooling time was provided on the manufacturing sheet of the product, this cooling time was used during the simulations. However, the real time requirement is lower, as this for safety reason involves some extra time. If the body was taken out before it solidified in the full volume, the product can be damaged. At least 95% of the tested elements must reach the ejection temperature, thus the product can be safely removed. Depends on the cooling time, the individual elements can be used to determine the ejection temperature.

Cooling time of measured elements using different cooling circles

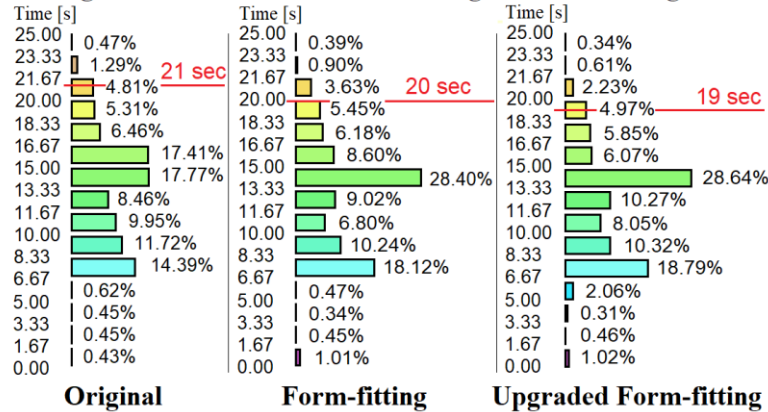


Fig. 5. Time the elements needed to reach ejection temperature

It can be observed on Fig. 5 where the line of the 95% limit is drawn, the cooling time for the conventional cooling circuit is 21 sec. However, if we use the tools created by additive manufacturing, the cooling time is been decreased by 1 sec, which is 4.8% improvement.

3.2. Ejection Temperature of the product

Based on the values on the manufacturing sheet, the product can be ejected at the end of the injection moulding, if it has cooled below 80 °C. Fig. 6 shows the temperature of the external elements of the product. This interval is very expressive because it shows while using the original cooling circuit, the temperature of the product's surface elements at corners are far higher than the ejection temperature. It can be observed the size of areas with insufficient temperature is negligible at the same locations of the form-fitted cooling circuits. It is also noticed, the temperature inside the product is much lower.

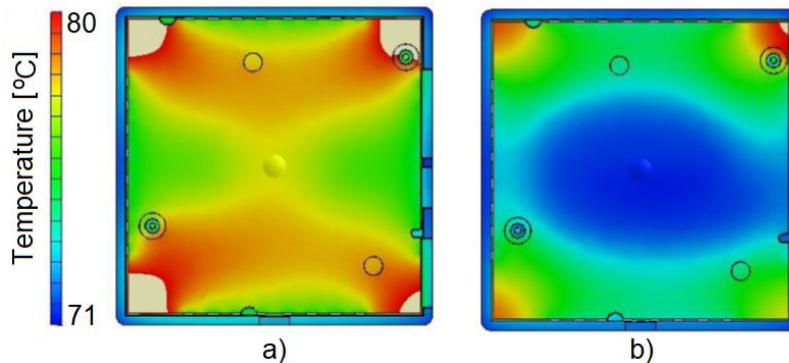


Fig. 6. Temperature of the surface elements at the moment of ejection. a) shows the results of the original cooling system, b) shows the results of the form-fitting cooling system after 21 sec cooling

3.3. Ejection Temperature of the tools

The temperature measured in the tool shows the extent of the thermal load is applied to the tools during each injection moulding cycle. Fig. 7. shows the temperature distribution of the tool. Various sections were made of the tool at the moment of ejection.

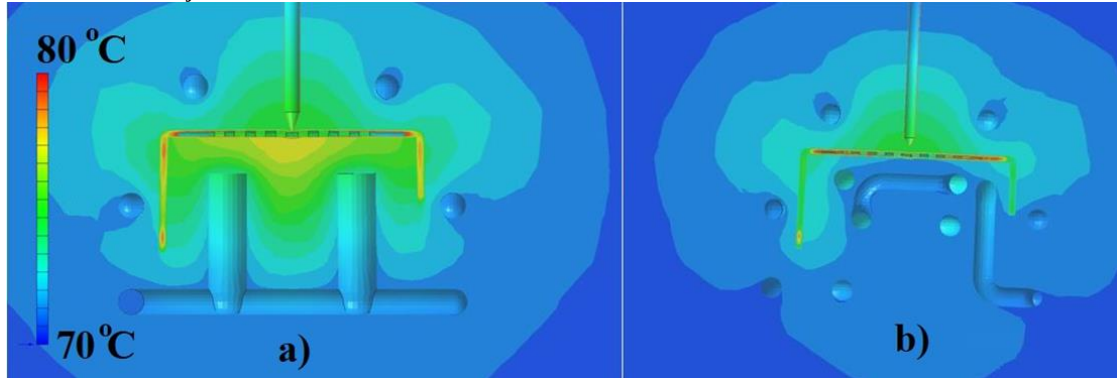


Fig. 7. Temperature of the cross-section elements of the tools at the moment of ejection. a) shows the results of the original cooling system b) shows the results of the form-fitting cooling system after 21 sec cooling

At the moment of ejection, the coolant fingers of the conventional cooling circuit could not lead all the heat. The temperature of the tool cannot be restored to the pre-injection level. However, at the form-fitting cooling circuit the tool inserts temperature was more even and it could almost completely cool down the tool. Due to the tool's thermal load is reduced and the thermal fatigue occurred much later.

3.4. Temperature Difference between two sides of the product

When the product is ejected, one of the greatest hazards is when the product is not cooled evenly. The heat extracted by the cooling circuits of the moving and stationary tools are not nearly the same. If the temperature difference is too large when the ejection is released, the product can be warped.

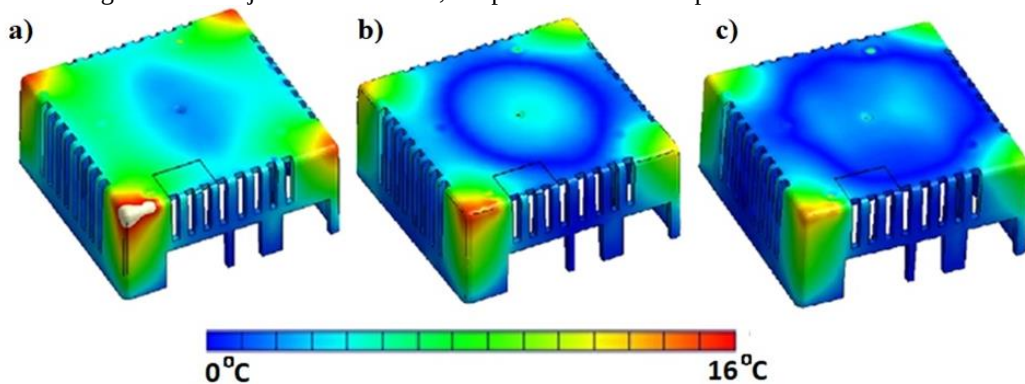


Fig. 8. Temperature difference between the opposite sides of the product at the moment of ejection. a) shows the results of the original, b) shows the results of the form-fitting, c) one shows the results of the upgraded form-fitting cooling system

Fig. 8 shows a form-fitting cooling system, when critical areas with a difference of more than 16 °C (white corners) have completely disappeared and the temperature difference between the two sides of the product has dropped significantly. The temperature difference is closely related to warpage and although the maximum value of warpage only slightly decreased according to the simulation results. The number of heavily warped elements fell significantly.

3.5. Upgraded form-fitting cooling circuit

Since additive machining provides almost unlimited freedom in tool geometry design, the form-fitting cooling system can be optimized until it has reached the "ideal" tool that needs a minimal cooling time. In the first version of form-fitting cooling circuit, primary consideration was the comparison to the original cooling circuit. Thus, the cooling circuit had the same internal diameter as the original cooling circuit. As a result, critical areas such as corners or protrusions could not be cooled properly fast enough. To solve that problems, the cooling system was optimized in multiple steps so that the tool insert can still be incorporated into the previously manufactured tool and it can withstand mechanical stress.

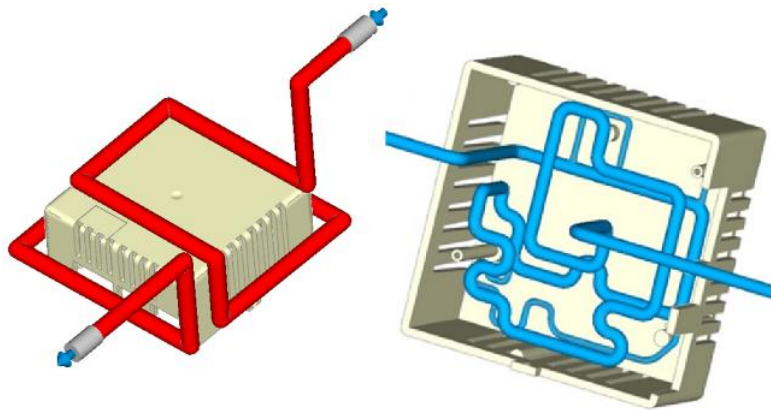


Fig. 9. In multiple steps redesigned and upgraded form-fitting cooling system. The red cooling circuit running through the stationary, while blue is running through the moving tool

With this cooling system simulation, the cooling time was only 19 seconds. The cycle time decreased by another 1 second. Compared to the original one, it is more than 9% of improvement in cooling time (Fig. 5). The cooling is more even with further development, so at the moment of ejection, the temperature difference between the product's outer and inner surfaces is extremely dropped (Fig. 8).

4. Conclusions

If the tool inserts required for the production of the product are manufactured by additive machining, it is possible to produce more economically and more accurately in the case of large-scale production despite possible additional costs. More than 9% savings during this cooling time can be achieved even with such a low complexity. It is also important to mention the improvement in dimensional accuracy due to the decrease in warp. However, the additive manufacturing will never completely replace traditional cutting tools, as the advantages of technology cannot be exploited in simple geometries. Technology can be used in industry, but its use is justified only if the proper construction of a conventional cooling system is not possible due to the complexity of the product. Any geometry can be created with this technology. The tool's cooling circuit can be developed again and again, with only human imagination imposing boundaries.

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References

- [1] Young Il Kwona, Eunju Limb, Young Seok Songa, J. Curr. Appl. Phys. 18 (2018), 1451-1457
- [2] Dunai A., Macskási L.: Műanyagok fröccsöntése, Lexica Kft., Budapest, 2003
- [3] T. Czvikovszky, P. Nagy, J. Gaál: A polimertechnika alapjai, Műegyetemi Kiadó, Budapest (2007)
- [4] Gurjeet Singh, M. K. Pradhan, Ajay Verma, Mater. Today-Proc. 5 (2018) 8398-8405
- [5] C. A. Griffiths, S. S. Dimov, E. B. Brousseau, R. T. Hoyle, J. Adv. Mater. Res-Switz. 189 (2007) 418-427
- [6] W. D Brouwer, E. C. F. C van Herpt, M. Labordus, Adv. Mater. Res-Switz. 34 (2003) 551-558
- [7] B. Sha, S. Dimov, C. Griffiths, M. S. Packianather, J. Adv. Mater. Res-Switz. 183(2-3) (2007) 284-296
- [8] D. E. Dimla, M. Camilotto, F. Miani, J. Adv. Mater. Res-Switz. 164-165 (2005) 1294-1300
- [9] Dirk Herzog, Vanessa Seyda, Eric Wycisk, Claus Emmelmann, Acta Mater. 117 (2016) 371-392
- [10] S. Matthes, S. Szemkus, S. Jahn, Jena, YPUC 2017 – 3rd Young Welding (2017)
- [11] A. Simchi, F. Petzoldt, H. Pohl, Mater. Proc. Technol. 141 (2003) 319-328.
- [12] Levy GN, Schindel R, Kruth JP, CIRP Ann-Manuf Techn 52 (2003) 589–609
- [13] A. Gebhardt: Understanding Additive Manufacturing, Carl Hanser Verlag, München (2011).
- [14] Gurjeet Singh, Ajay Verma, Mater. Today-Proc. 4(2) (2017) 1423-33
- [15] Frazier, W.E. J. of Mater. Eng. Perform. (2014) 23: 1917
- [16] R.Hölker-Jäger A.E.Tekkaya, Electronic and Optical Materials (2017) 439-464
- [17] Bernhard Mueller, J. Assembly Automat 32 (2012) 2
- [18] RaviPrakash Magisetty, Naga Srilatha Cheekuramelli, J. Appl. Mater. Today 14 (2019) 35-50. Professionals International Conference, August 16-18. 2017, Germany
- [19] Dr. -Ing. Simon Jahn., MSc. Stefan Szemkus, MSc. Sebastian Matthes, 27. Schweissteschnische Fachtagung, 2017. November 08.
- [20] J.S. Zuback, T.A. Palmer, T. DebRoy, J. Alloys Compd. 770 (2019) 995-1003
- [21] Donghong Ding, Zengxi Pan, Dominic Cuiuri, Huijun Li, J. Robot. Cim-int. Manuf. 31 (2015) 101-110
- [22] Ferry P.W.Melchels, et al., J. Prog. Polym. Sci. 37 (2012) 1079-1104
- [23] J.-P. Kruth, M. C. Leu T. Nakagawa, CIRP Annals 47 (1998) 525-540
- [24] Z. Keresztes, et al., Biomechanica Hungarica X:(2) (2017)
- [25] Ville Matilainen, Heidi Piili, Antti Salminen, Tatu Syvänen, Olli Nyrhilä, J. Physics Proc. 56 (2014) 317-326
- [26] T. Barrière, J. C. Gelin, B. Liu, J. Adv. Mater. Res-Switz. 125-126 (2002) 518-524
- [27] W. Li, S. Kara, F. Qureshi, International Journal of Sustainable Engineering 8(1) (2015) 55-65
- [28] J. Von Oh, Seung Kyu Ryu, Won Sik Lee, Seong Jin Park, J. Powder Technol. 322 (2017) 1-8
- [29] J. Dobránszky, et al, 15th IMEKO TC10 Workshop on Technical Diagnostics in Cyber-Physical Era. 206 (2017)
- [30] Todd M. Mower, Michael J. Long, J. Mater. Sci. Eng. (2016) 198-213.
- [31] Xiaohui Chen, Jia Li, Xu Cheng, Bei He, Huaming Wang, Zheng Huang, Mater. Sci. Eng. 703 (2017) 567-577
- [32] Xiaohui Chen, Jia Li, Xu Cheng, Huaming Wang, Zheng Huang, Mater. Sci. Eng. 715 (2018) 307-314