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Plug production for thermoforming using fused deposition modelling

Eriyik yığıma modelleme kullanarak ısıl şekillendirme için erkek kalıp üretimi

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Plug Production for Thermoforming using Fused Deposition Modelling

Highlights

- ❖ Plug, a type of male mould in thermoforming was produced using Fused Deposition Modelling
- ❖ Plugs were produced using Polylactic Acid (PLA) and Aluminium (Al) particle reinforced PLA filaments by a 3d printer.
- ❖ Thermal effects such as temperature distribution on the region where the plug touches the heated plastic sheet, were investigated using a thermal imaging camera.

Graphical Abstract

In this study, plugs which have hemispherical shape were produced using Fused Deposition Modelling. PLA and Aluminium particle reinforced PLA filaments were used in 3d printing operations.



Figure. Plug assembly which was produced in experimental study.

Aim

The goal was to assess the efficacy of additive manufacturing in production of plugs in thermoforming.

Design & Methodology

In this study, plug production was made by Fused Deposition Modelling which is a kind of Additive Manufacturing. Plug design was determined according to a female mould used in thermoforming operations. After plugs were printed, without allowing the plugs to cool, a M10 hexagon nut was inserted to the plug's cavity. Then a fully threaded stud bolt which has a 100 mm length, was assembled with the M10 nut and plug assembly.

Originality

A large and growing body of literature has investigated manufacturing of thermoforming moulds. But there is a relatively small body of literature that is concerned with thermoforming mould production with FDM. Also, this study provides new insights into thermoforming plug production.

Findings

This paper argued that surface roughness and plug material was important in determining thermoforming temperature and final thermoformed product's thickness distribution. Less energy was required to heat the PVC sheet when plastic plugs were used. Also, using metal plug increased the forming temperature of PVC. Moreover, it was observed that the Al particles in the PLA filament had no significant effect on the surface quality of the plug.

Conclusion

It has been found that FDM can be a significant alternative for male mould production in thermoforming. Additionally, PLA filaments have great potential for tool production in thermoforming.

Declaration of Ethical Standards

The author of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Plug Production for Thermoforming using Fused Deposition Modelling

Araştırma Makalesi / Research Article

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ABSTRACT

Plug, a type of male mould in thermoforming, is mostly produced by conventional processes such as machining. However, in this study, plugs that are used in thermoforming were produced using Fused Deposition Modelling (FDM). Plugs were produced using Polylactic Acid (PLA) and Aluminium (Al) particle reinforced PLA filaments by a 3d printer. Plugs that are produced by FDM, were polished using 800, 1000, 1200, 1600 and 2000 grit sandpapers to reduce friction. Also, thermal effects such as temperature distribution on the region where the plug touches the plastic sheet, were investigated. It has been found that FDM can be a significant alternative for male mould production in thermoforming. Additionally, PLA filaments have great potential for tool production in thermoforming.

Keywords: Fused deposition modelling, thermoforming, plug, PLA.

Eriyik Yığıma Modelleme kullanarak Isıl Şekillendirme için Erkek Kalıp Üretimi

ÖZ

Isıl şekillendirme yönteminde erkek kalıp çoğunlukla talaşlı şekil verme gibi geleneksel yöntemlerle üretilir. Ancak, bu çalışmada, ısıl şekillendirmede kullanılan kalıplar Eriyik Yığıma Modelleme (EYM) ile üretildi. Erkek kalıplar, Polilaktik Asit (PLA) ve Alüminyum parçacık takviyeli Polilaktik Asit filament ile 3 boyutlu yazıcı kullanılarak üretildi. EYM ile üretilen kalıplar, sürtünmeyi azaltmak için 800, 1000, 1200, 1600 ve 2000 kum zımpara kullanılarak yüzey parlatma işlemi uygulandı. Ayrıca, erkek kalıbın ısıtılmış levhaya temas ettiği bölgelerdeki sıcaklık dağılımı gibi termal etkiler araştırıldı. EYM'nin ısıyla şekillendirmede erkek kalıp üretimi için önemli bir alternatif olabileceği bulunmuştur. Ek olarak, PLA filamentler ısıyla şekillendirmede kalıp üretimi için büyük bir potansiyele sahiptir.

Anahtar Kelimeler: Eriyik yığıma modelleme, ısıl şekillendirme, erkek kalıp, PLA.

1. INTRODUCTION

Fused Deposition Modelling is a type of Additive Manufacturing (AM) that uses some thermoplastics including ABS, PLA and Polycarbonate (PC) to build a new part. FDM process uses thermoplastic filaments with varying diameters (1.75 mm, 3 mm). FDM starts with creation of 3d cad data. This can be done by various Computer Aided Design Software. Then 3d cad data is sliced into layers. The data is then transferred to 3d printer which constructs the part layer by layer. Support material and thermoplastic filaments are used to create each cross section of the part. There is an extrusion nozzle which moves in horizontal xy plane, as the build platform moves down by building the part layer by layer. At the end of the process, finished part is removed from the building platform. Support material is released from the built part. Finished FDM parts have usually rough outer surfaces. Because of this reason, multiple finishing operations such as hand sanding and cosmetic paint, are applied to finished parts for providing smooth surfaces. FDM is utilized in many industries such as automotive, commercial, medical and aerospace [1-6].

The thermoforming is a manufacturing process that uses heat and vacuum to form a flat plastic sheet or film. Thermoforming temperature and amount of vacuum depends on the type of the thermoplastic material. Especially amorphous thermoplastics are used in thermoforming since they have wide forming temperature ranges. This feature makes amorphous thermoplastics easy to thermoform. Also, semi crystalline thermoplastics such as Polypropylene (PP) and Polyethylene (PE) are possible to thermoform. Thermoforming is used in a number of industries such as packaging, automotive and medical. Especially in the packaging industry, thermoforming is one of the most important and widely used processes. One of the advantages of thermoforming compared to other processes is the low cost of mould production. Thermoforming moulds are generally manufactured using machining. Because machining is the easiest, fastest and most efficient way to form plastic, metal and even wood raw materials in mould production. Mostly, metals are used in female and male mould production. In female thermoforming moulds, both heating and cooling can be found together. However, male thermoforming moulds (plugs) have a heating system rather than cooling.

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Since plugs have a simpler design than female moulds and mostly do not contain cooling systems, their production is also easier [7-10].

Patil et al. [7] studied on the ability of providing uniform thickness distribution in thermoformed products which were manufactured by pressure forming. They thermoformed Polymethyl methacrylate (PMMA) sheets using a hemispherical shaped mould. They proposed a numerical approach for pressure thermoforming using a hyperplastic material model. That numerical approach revealed an estimation of thickness distribution for pressure thermoforming of PMMA sheets. Not only shape of the mould but also coefficient of friction (COF) between sheet and plug affects the deformation of plastic sheet that is being thermoformed. Marathe et al. [8] thermoformed High Impact Polystyrene [HIPS] sheets using plug assist. They sought to find the frictional effects between the plug and HIPS sheets. They measured the COF, depending on the plug temperature. They increased the plug temperature from ambient temperature to the 100 °C. They found that, COF between sheet and plug decreased when the plug temperature is less than 100 degrees. Otherwise, COF increased and affected the biaxial deformation of the HIPS sheet and its thickness distribution. Leite et al. [9], developed models for estimation of vacuum forming process parameters using artificial neural networks (ANN). They used polystyrene in thermoforming experiments to produce samples for ANN data input. Also, they carried out with various ANN structures and configurations for validation. After validation tests completed, they revealed that ANN models are accurate to model the vacuum thermoforming using numerous parameters. Additionally, Mieghem et al. [10], studied on an alternative method that is for determining the process parameters that affect the thermoformed part quality significantly. They used Digital Image Correlation (DIC) for controlling thickness distribution of thermoformed part using surface strain measurements. They used wall thickness equations from the previous literature studies. They calculated the wall thickness distribution using DIC. They compared the data obtained from previous literature and calculated by DIC. Comparison showed the accuracy of the DIC based thickness distribution results.

In food packaging; cups, boxes and trays can be manufactured by thermoforming. Especially in mass production lines, plugs play an important role in thermoforming of products. Thickness distribution of a thermoformed part is provided with an appropriate pre-stretching of the plastic sheet or film using plugs. The thickness distribution directly affects the shelf life of the packaged product. So, plug design must be created accurately. In addition, the plug material should be chosen in the most accurate way. Since metals have high thermal conductivity coefficient, plugs made of metals decreases the heated plastic sheet's temperature significantly. Plastic raw material solidifies and becomes hardened where the metal plug touches the flat plastic. To prevent this, materials which have low thermal

conductivity coefficient than those of metals should be chosen for plugs.

A large and growing body of literature has investigated manufacturing of thermoforming moulds. But there is a relatively small body of literature that is concerned with thermoforming mould production with FDM. This study provides new insights into thermoforming plug production. Additionally, the experimental work presented here provides one of the first investigations into how thermoforming plugs are manufactured by FDM using different thermoplastic filaments.

Numerous studies have attempted to explain the effects of parameters related to plug, in Plug Assisted Thermoforming (PAT). These parameters are plug diameter, plug material, plug shape, plug's friction coefficient, plug's temperature etc. Furthermore, several studies have investigated effects of some variations such as plug depth in female mould and plug duration in pre-stretching of flat heated plastic. It has been found from the literature that the change of the plug design significantly affects the thickness distribution of thermoformed part. Especially, thickness distribution on bottom, sidewalls and at the top of the thermoformed product significantly depends on the plug design. In addition to this, some thermoforming parameters such as plug surface roughness, friction conditions, temperature conditions, plug duration during forming, plug depth in female mould, changes thickness distribution of the part remarkably [11-21].

In this study, plugs were designed and manufactured by 3d printing using PLA and Al particle reinforced PLA filaments. Plugs that are produced by FDM, were polished using 800, 1000, 1200, 1600 and 2000 grit sandpapers to reduce friction. Also, thermal effects such as temperature distribution on the region where the plug touches the plastic sheet, were investigated. It has been found that FDM can be a significant alternative for male mould production in thermoforming. Additionally, PLA filaments have great potential for tool production in thermoforming.

2. MATERIAL and METHOD

Initially, a plug design was determined according to a female mould used in thermoforming operations. Figure 1 shows the thermoforming mould that was used in plug design. The mould in Figure 1, has a hemispherical cavity with a diameter of 100 mm. Because of the shape, mould cavity height is 50 mm. That female mould designed according to a special h/d ratio. h/d ratio is a criterion which is used for thermoformability of a part. Considering the dimensions of the mould cavity, h/d ratio was determined as 1/2. If the h/d ratio is bigger than 1/2, mould is called as "deep", otherwise mould is considered as "shallow". Also, 1/2 is a special h/d ratio value between the both cases. So, mould in Figure 1 is neither shallow nor deep. That makes the female mould unique.

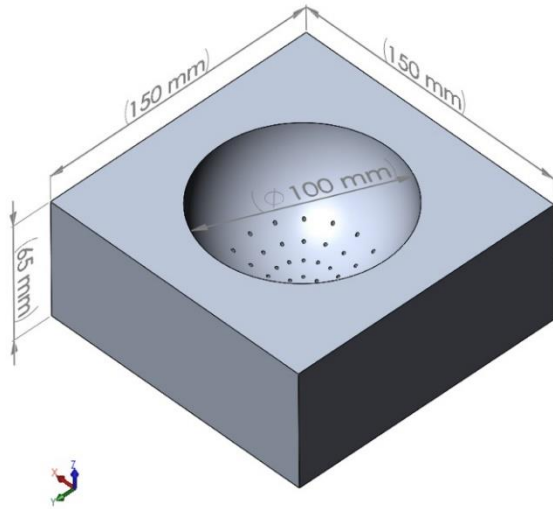


Figure 1. Thermoforming mould which was used in plug design.

Plug shape was selected as hemisphere (Figure 2). Also, plug diameter was selected as 40, 45, 50 mm. Additionally, in the selection of the plug diameter, the depth of the female mould was considered to be 50 mm. All plug diameter values were chosen smaller than the female mould depth.

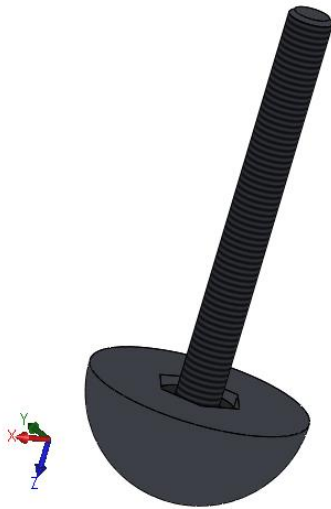


Figure 2. Plug with 50 mm diameter as SolidWorks assembly file.

In this study, plug production was made by Fused Deposition Modelling which is a kind of AM. Plug production could also be made by plastic injection process and machining. This method was used for the faster production of the plug. Also, in this study, the availability of a new method different from conventional manufacturing methods was investigated for plug production. In experimental work, PLA and Al particle reinforced PLA filaments were used in production of plugs by 3d printing. Some properties about these filaments are given in Table 1. The reason for choosing

an Al reinforced PLA filament is also to investigate the effect of Al on the surface quality of the plug to be produced. In particular, it is aimed to investigate the effect of Al particles on the polishing of the surface of the plug.

Plug design was created by SolidWorks software as *.sldprt. To use and transfer the Plug's design data to the 3d printer, sldprt file type converted to stl file type using SolidWorks again. In this study, MY 3D Printer Z23 (Türkiye) was used in production of the plugs. This 3d printer has a maximum printing volume of 20x20x23 cm³. MY 3D printer Z23 uses Simplify3D software to import and process the stl file data in FDM. After plug's design data imported to Simplify3D software, FDM process parameters can be adjusted as desired. Figure 3 shows the plug with 50 mm diameter in Simplify3D software.

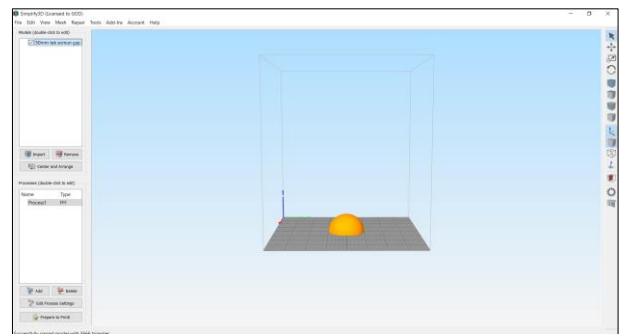


Figure 3. Plug with 50 mm diameter in Simplify3D software before FDM.

Then 3d printing options were selected according to the type of filament and nozzle diameter. Nozzle diameter is 0.4 mm and PLA and Al reinforced PLA were used. Additionally, number of top and bottom layers and thicknesses were determined in this stage (Figure 4). Other critical requirement is related to infill percentage. All plugs which produced in this work, have 100% infill percentage. Also, internal and external infill angle offsets may be adjusted in this stage. Additionally internal and external fill pattern may be selected in this stage. Figure 5 shows infill percentage details about plug production. Heated bed temperature was selected as 70 °C, extruder temperature was selected as 230 °C for both PLA and Al reinforced PLA filaments. Considering 100% infill percentage, to provide better surface quality default printing speed was selected as 35 mm/s for both types of filaments. Slower the printing speed, better surface quality. Other required adjustments may be clearly seen in Figure 6. Before printing starts, Simplify3D software displays some statistics such as build time, filament length, part weight and material cost. After plugs were printed, without allowing the plugs to cool, a M10 hexagon nut was inserted to the plug's cavity. Then a fully threaded stud bolt which has a 100 mm length, was assembled with the M10 nut and plug assembly.

Table 1. Some properties of PLA filaments which was used in 3d printing.

Filament	Frosch PLA Filament	Frosch PLA Metal Filament
Filament diameter (mm)	1.75	1.75
Printing temperature (°C)	180-230	180-230
Additive material	-	Aluminium particles
Percentage of additive material	-	20 wt%
Heated bed temperature (°C)	90-110	90-110
3d printing speed	60-100 mm/s	60-100 mm/s

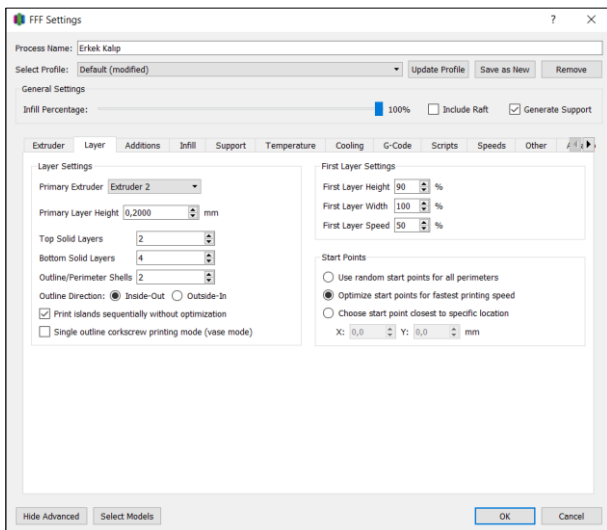


Figure 4. Selected 3d printing options for layers and their thicknesses.

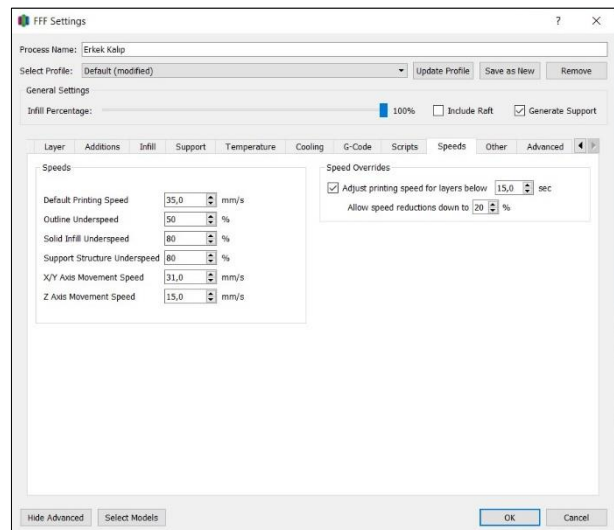


Figure 6. Selected speed values in xy plane.

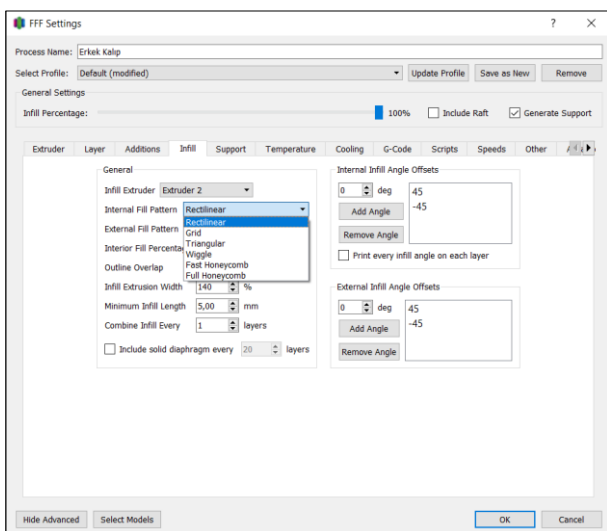


Figure 5. Infill percentage details about plugs.

3. RESULTS AND DISCUSSION

Surface roughness may be considered as one of the main parameters that affect the forming characteristics of plastic sheet in forming temperature. Therefore, friction coefficient between the plug and sheet in high temperature becomes more important. Initially, PLA plugs that are produced by FDM, were polished using 800, 1000, 1200, 1600 and 2000 grit sandpapers to provide a smooth surface (Figure 7). In polishing, Metallographic grinding and polishing machine was employed using sandpapers with different grit numbers. To show variation in plug's outer surface, firstly visual inspection was achieved using a 48-megapixel camera. Images taken from plugs which were produced with Al particle reinforced PLA filament, are shown in the Figure 8 before and after polishing. Additionally, in order to show shape and dimension of the Al particles in the PLA filament, some images were recorded using Scanning Electron Microscope (SEM). These images may be seen in Figure 9. Moreover, in order to determine surface roughness of the plugs precisely, roughness tester was used. Because of the hemispherical shape of the PLA and Al reinforced PLA plug, surface roughness could not be measured.

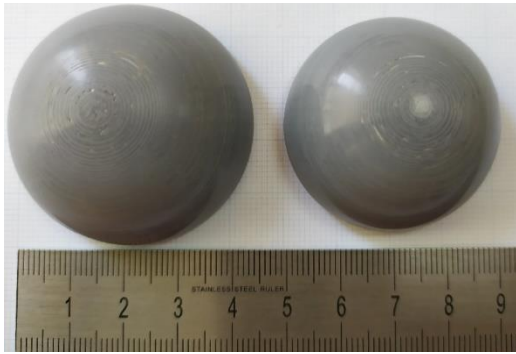


Figure 7. PLA plugs after polishing by sandpapers in different grit numbers.



Figure 8. Captured images from plugs that are produced with Al reinforced PLA filament, before and after polishing.

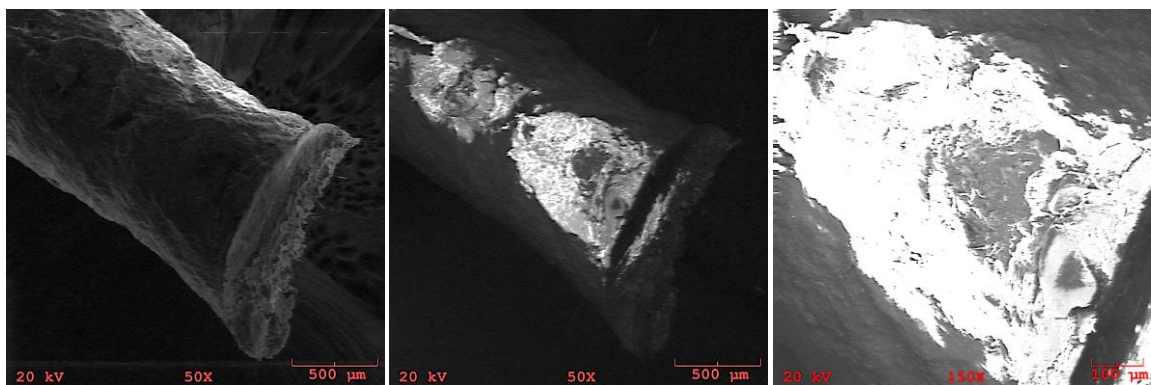


Figure 9. Images from Al particle reinforced PLA filament using SEM.

A plug which is made of Al, was produced by machining to compare with others that were made of PLA. Figure 10 shows, top and bottom views of plugs which were made of Al reinforced PLA, PLA and Al respectively. All plugs have 45 mm diameter. Additionally, M10 hexagon nuts may be seen as assembled to the plugs which were produced by FDM. Finally, the last part of plug assembly, fully threaded stud bolt was mounted.



Figure 10. Plugs made of Al reinforced PLA, PLA and Al respectively.

In order to examine the thermal effects of metal and plastic plugs during thermoforming, a thermal camera (TESTO) was utilized to capture required images from thermoformed samples. Figure 11, 12 and 13 show the thermal images that were captured after and during thermoforming using different plug materials. Additionally, average temperatures were determined in plugs' touching surfaces. These images are given in Figure 14, 15, and 16. In thermoforming, PVC-S (Suspension PVC) Petvinil S 23/59 sheet which has a thickness of 0.25 mm was used. For a successful thermoforming operation, heater temperature was selected as 300 °C for 30 seconds heating time using Al plug. Additionally, 25 seconds was selected as heating time for 250 °C heater temperature using Al reinforced PLA and PLA plugs.

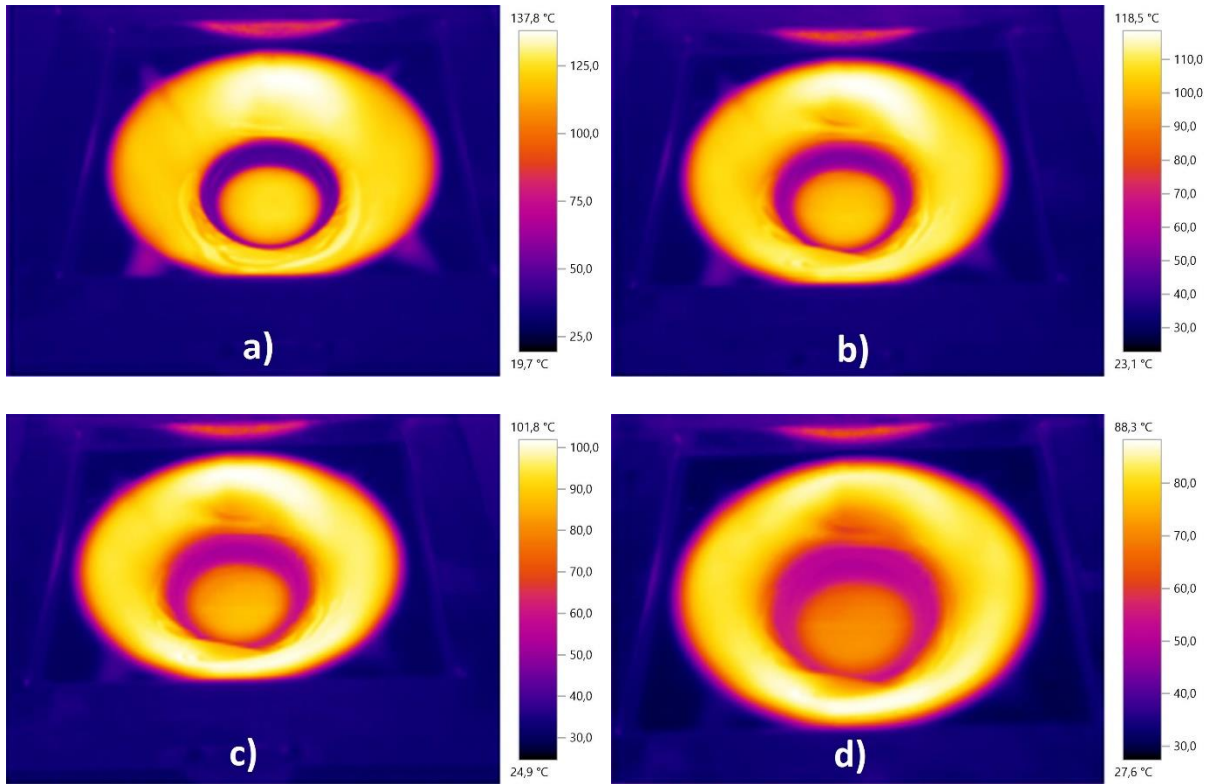


Figure 11. Thermal images captured a) 1, b) 3, c) 5 and d) 10 s after Al plug touches the heated sheet.

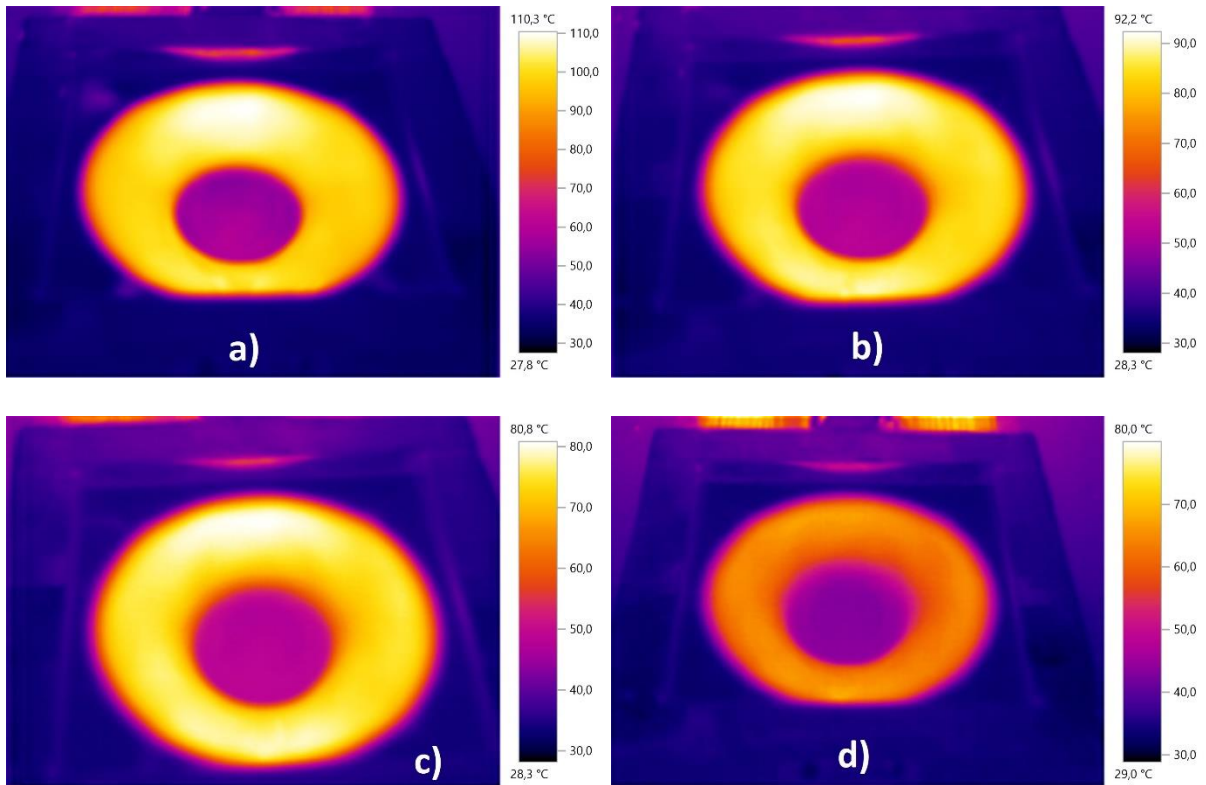


Figure 12. Thermal images captured a) 1, b) 3, c) 5 and d) 10 s after Al reinforced PLA plug touches the heated sheet.

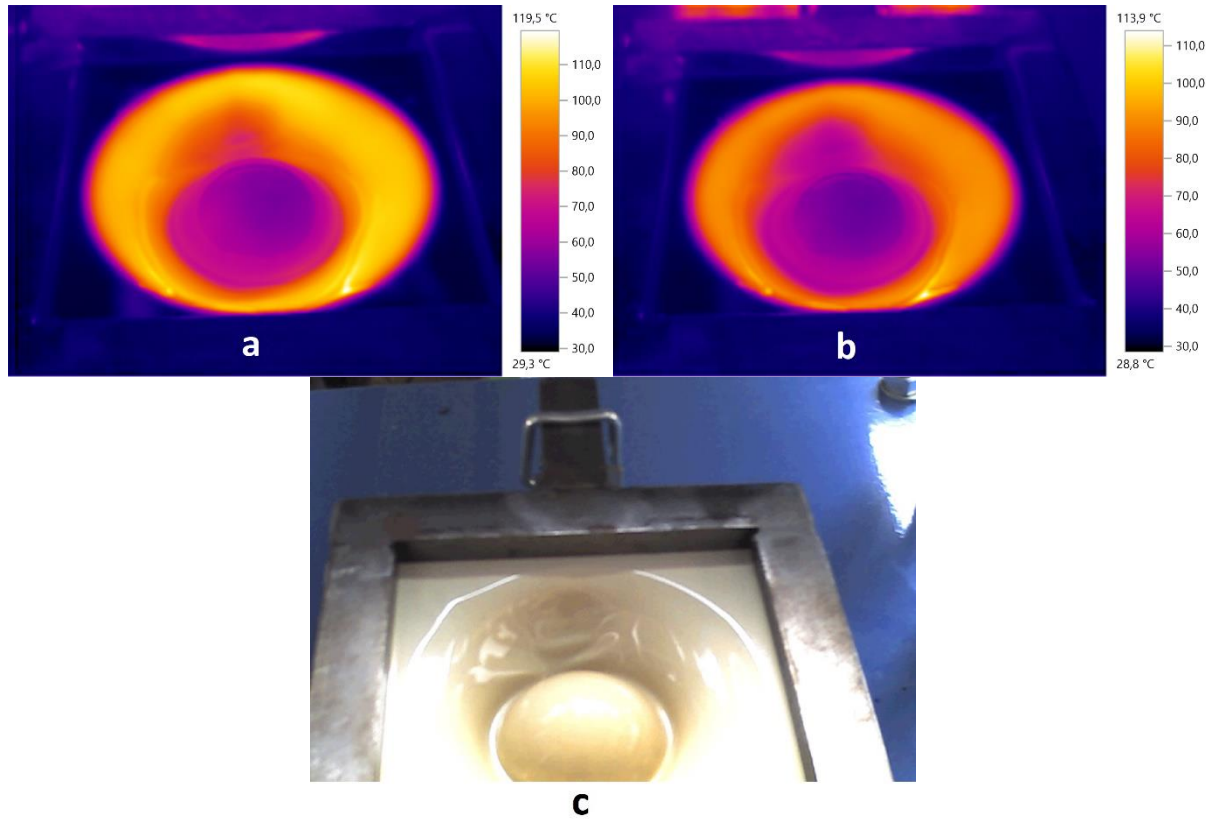


Figure 13. Thermal images captured a) 1, b) 3 s after PLA plug touches the heated sheet, c) Actual image of sticking area.

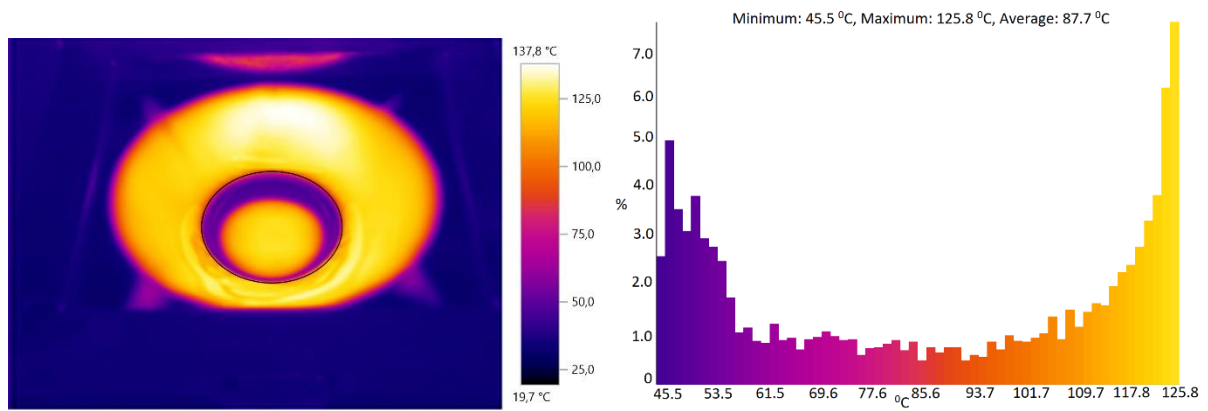


Figure 14. Histogram of plug's touching surface (selected ellipse) for Al plug case.

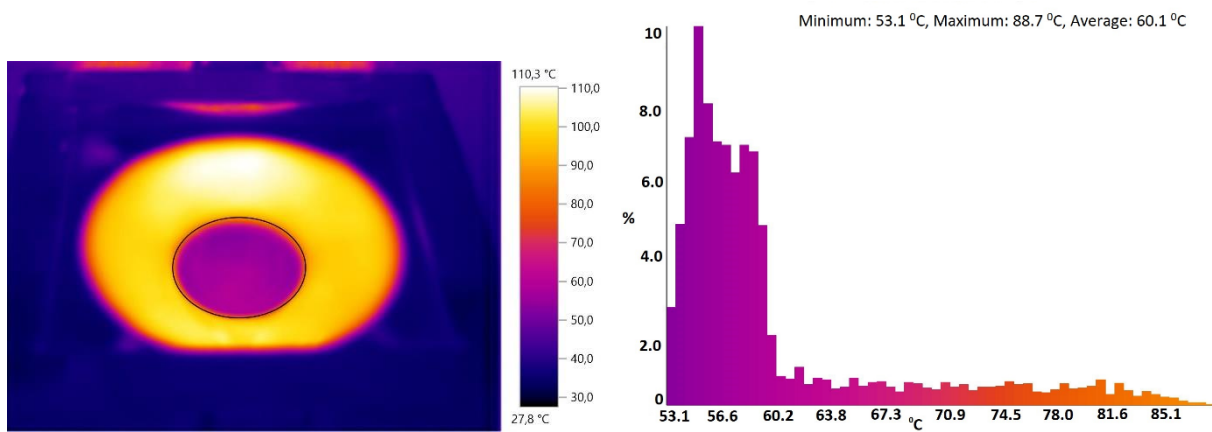


Figure 15. Histogram of plug's touching surface (selected ellipse) for Al reinforced PLA plug case.

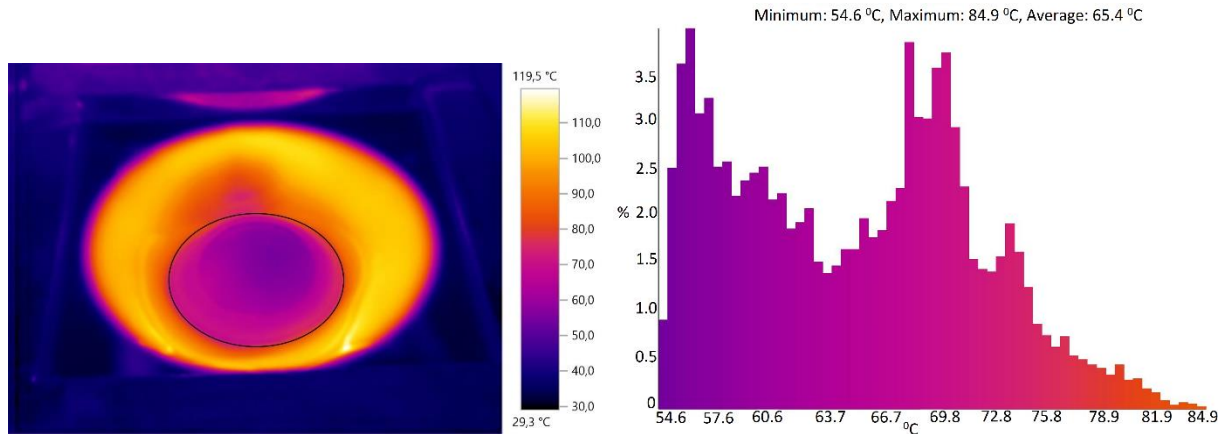


Figure 16. Histogram of plug's touching surface (selected ellipse) for PLA plug case.

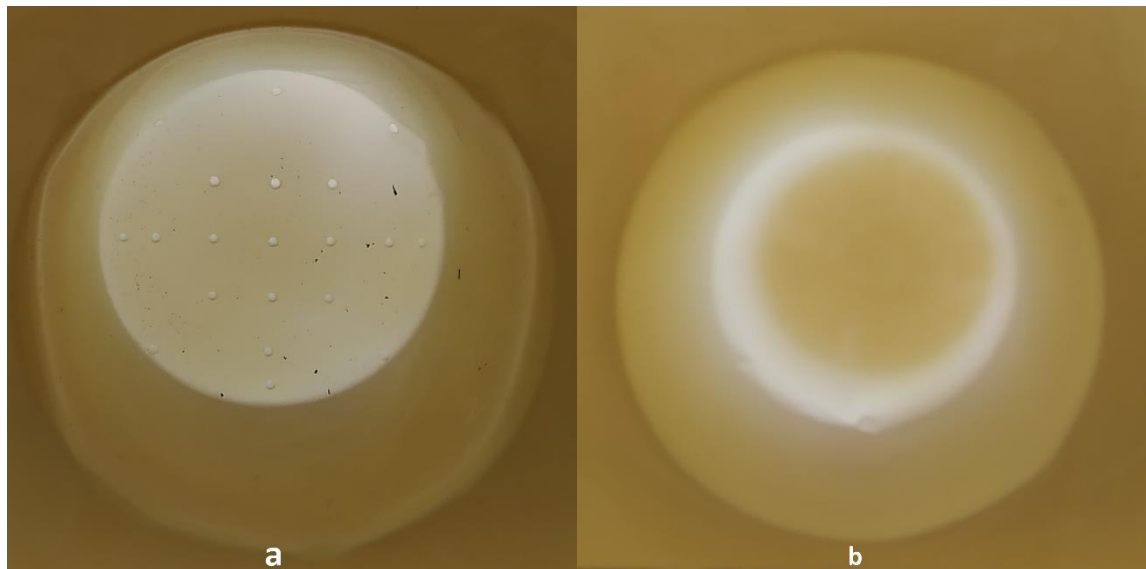


Figure 17. Images which show thickness distribution of thermoformed samples in front of the light source. a) Sample which was thermoformed without plug assist, b) Sample which was thermoformed by Al reinforced plug assist.

Figure 11 shows the heated sheet, 1, 3, 5 and 10 seconds after plug touches the heated sheet. Cooling in heated PVC sheet after plug assist, may be seen gradually. Cooling of PVC sheet after Al reinforced PLA and PLA plugs applied, is given in Figure 12 and 13. Maximum and minimum forming temperature was obtained as 137 °C and 88 °C in Figure 11 respectively. In Figures 12 and 13, max. and min. forming temperatures were measured as 110 °C and 80 °C, 119 °C and 113 °C respectively. From Figures 11, 12 and 13, temperature is lower in some regions of the sheet where the plugs touched. Surface temperature in that semi-cylindrical portion of the sheet was measured around 50 °C in Figure 11. This temperature was measured above 55 °C in Al reinforced PLA and PLA plugs' touching surface which has a hemispherical shape in Figure 12 and 13. Due to its higher thermal conductivity coefficient Al plug caused more heat loss than Al reinforced PLA and PLA. However, sticking was observed between PLA plug and heated sheet. Although the PLA plug touched the heated sheet in a short time like 1 second, the temperature of the plug increased and it caused an undesired sticking. When

plug moved back its initial position, it brought the stucked sheet with itself for a while. It was expected that the area where PLA plug contacts the sheet would form a hemispherical cavity. Instead of forming a hemispherical cavity, the heated sheet formed a dome (Figure 13.c). It can be considered as a manufacturing defect that is caused by PLA plug's smooth surface and temperature difference compared to heated sheet. But this phenomenon was not observed in Al reinforced PLA plug case.

In Figure 14, average temperature in plug's touching surface was measured as 87.7 °C. In Figure 15 and 16 average temperatures were obtained as 60.1 °C and 65.4 °C respectively. Following Figure 14, Al plug's touching surface temperature is higher than that of Al reinforced PLA and PLA plugs. This is because, PVC sheet was heated to a proper temperature for a successful thermoforming operation by trial and error method. Because of the selected heating time and heater temperature for Al plug case, were higher than Al reinforced PLA and PLA case. As Figure 15 and 16 show, there is a clear trend of decreasing in plug's

touching surface temperature compared to Figure 14. The type of material from which the plug is made, can be given as the reason for this. The results, as shown in Figure 17, indicate that there is a significant variation in thickness distribution in both images (a and b). Especially, thickness in the base of the thermoformed product changed following the type and shape of plug. Also, the use of plug played an important role in thickness distribution of thermoformed sample.

4. CONCLUSION

In this investigation, the goal was to assess the efficacy of additive manufacturing in production of plugs in thermoforming. Additionally, this paper argued that surface roughness and plug material was important in determining thermoforming temperature and final thermoformed product's thickness distribution. Less energy was required to heat the PVC sheet when plastic plugs were used. Also, using metal plug increased the forming temperature of PVC. Moreover, it was observed that the Al particles in the PLA filament had no significant effect on the surface quality of the plug. It has been found that FDM can be a significant alternative for male mould production in thermoforming. Additionally, PLA filaments have great potential for tool production in thermoforming. Further study with more focus on composites should be done to investigate the efficacy of FDM in composite materials production.

DECLARATION OF ETHICAL STANDARDS

The author of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

AUTHORS' CONTRIBUTIONS

Olca EKŞİ: Performed the experiments and analyse the results. Wrote the manuscript.

CONFLICT OF INTEREST

There is no conflict of interest in this study.

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