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Original Article

The Impact of Thermal Conductivity Mold Material in the Injection Molding Process

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Abstract - *Removing heat from an injection mold, part solidification, and factors that control and eliminate shrinkage and warpage are important in the injection molding process. As the injection molding process progresses, the time taken to remove the heat energy is equivalent to the amount of heat removed from the polymer melt by cooling. This study investigates the strategies employing Beryllium copper material application in thermal conductivity to resolve the issues on mold cooling and give a better effect of change in temperature and change in thermal conductivity since the mold material is a major factor in temperature control. Beryllium copper has two times the thermal conductivity value compared to steel and about four times the stainless-steel material. Minimizing cooling time plays a crucial role in reducing the cycle time during the injection molding process. Based on the material change for the core pin and the subsequent trial taken, the observations are a reduction of filling and 100% balancing of the fill pattern without any short filling. Uniform filling and packing occurred with a maximum injection pressure of 65.61 MPa, reduced from 80 MPa to fill the part. Factors such as melt viscosity, melt temperature, mold temperature, and packing parameters significantly influence the final pressure needs. The author finds that Beryllium copper reduces molding cycle time from 32 seconds to 28 seconds by cooling time reduction, provides uniform cooling to produce defect-free components, and increases productivity by 12.50% in real-time production. Hence, Beryllium copper plays a prominent role in injection molding cooling time determination in the area of cycle time reduction to improve productivity in mass-production industries.*

Keywords - *Beryllium copper**,** Cooling time, Core pin, Ejection temperature, Productivity.*

1. Introduction

The injection molding process is used for manufacturing plastic products by controlling various factors during its process, such as melting temperature, injection pressure, hold-on pressure, cooling time, mold opening time, ejection time, etc, depending upon its part thickness. The material used for the core and cavity plays a major contribution in controlling the cooling time by transferring the heat from the injection molded part and mold to solidify the part as quickly as possible to reduce cycle time, specifically on cooling time.

In this study, two mold materials, AISI 420 and Ampcoloy 83, were taken for experimentation and examined concerning thermal conductivity and its effects on cooling time using calculated and measured results. The main objective of this work is to identify the reduction of cooling time during injection molding operation and eliminate quality issues such as shrinkage, warpage, etc., by using Beryllium copper material to Core pin. The proposed approach effectively integrates quantitative and qualitative parameters. In this work, the experiment is carried out for both Steel and Beryllium copper (BeCu) with Moldex3D software for filling, packing, and cooling analysis, and its thermal conductivity calculation is then carried out. ANSYS Workbench is used to model the part, and mold elements are analyzed systematically for optimized process parameters and increased productivity. The specific mold modifications are done to improve the effectiveness of the part. This paper focuses on presenting a methodology for the cooling time evaluation of plastic mold, aiming to reduce cooling time during injection molding. This type of analysis is the motivation behind this work being used for determining the production of quality components, making decisions to arrive at capacity planning for the marketing requirement, and considering improving plant capacity by using machine spare capacity. This study finds that the proposed system of in-house manufacturing is able to map the quality and the molded part surface with respect to the core. Existing research findings compared simulations using various materials for mold inserts. There was not a single study on Beryllium copper and particular tool steel comparison. Earlier research did not show that strategically maintaining the heat dissipation of polymer material through Beryllium copper optimization can shorten cooling times.

The motive behind this research work is to improve productivity by reducing the cycle time with the help of high thermal conductivity materials used as mould elements materials to reduce cooling time since cooling time is the most consuming time in injection molding cycle with the help of innovation and contribution to be made with the possibilities in the area of material science by using Beryllium copper material with a thermal conductivity of

106 – 130 W/m·°K, which is 3–5 times higher than tool steel and due to its electronic conduction by the linear variation of conductivity with temperature. The authors reduce the time spent in this phase and then improve productivity without affecting quality.

2. Literature Review

When it comes to injection molding applications involving beryllium copper, Moldex3D can be used efficiently, especially for cooling system optimization and mold temperature distribution prediction. This is important for materials like beryllium copper, which needs exact temperature control. The Moldex3D software assists in forecasting the temperature and flow field of cooling systems, verifying forecasts through investigating substitute materials, such as beryllium copper, to attain comparable results, potentially lowering expenses and environmental impact. The high thermal conductivity of beryllium copper molds necessitates the careful design of cooling systems to guarantee consistent cooling and avoid warping or deformation of the molded part. By using Moldex3D's "Cool" module, users can forecast mold temperature distribution, simulate and optimize cooling channels, and spot possible problems like hot spots or uneven cooling. Using beryllium copper to simulate the injection molding process, Moldex3D can assist in figuring out the ideal injection parameters, mold temperature, and gate thickness to reduce molding issues. The filling process can be simulated with Moldex3D, weld line locations can be predicted, and gate sizes and locations can be optimized to reduce defects. It is especially crucial to precisely control the flow and temperature distribution in complex parts or molds made of beryllium copper. Based on the thermal conductivity of beryllium copper, it can cool four times faster than stainless steel molds. Injection molding research has attracted many researchers for studies and investigations with reference to cooling systems. Wang et al. [1] created a system that uses water cooling and electrical heating to quickly heat and cool molds.

In comparison to other traditional rapid mold heating and cooling systems, it is beneficial to remove weld lines, improve the glossiness of the part's outer surface, and use less energy. Prasetiyo and Fauzun [2] compared the straight and conformed cooling channels using ANSYS Fluent software to analyse the temperature distribution within the mold and the cooling performance of the component inside the mold with its effects on temperature, cooling, and efficiency. Yadegari et al. [3] examined the influence of cooling systems as the most crucial element in plastic injection molding optimization, which is crucial for manufacturing quality, efficiency, and cost-effectiveness. Patel et al. [4] reviewed the system design for improving cooling performance in injection molding by various cooling channel models with reference to quality defects of the product during its molding process. Sanchez. R. et al. [5] examined the impact of cooling conditions on warpage and investigated the influence of temperature on the shape of components. Migule R. Clemente and Migule R. Oliveira Danco [6] created an innovative cooling channel arrangement for a mold insert, featuring a streamlined design for both the inlet and outlet flow to enhance the cooling system's efficiency. Kessler and Pitz [7] revealed that the advantage of cooling time gained from pulsed cooling is less than 3%, and it has to be optimized by correcting mold surface temperature. Ferreira and Mateus [8] presented an approach to integrate advanced processing technology, such as rapid prototyping and rapid tooling with composite materials chilled by conformal cooling channels to manufacture plastic injection molds. By incorporating a sub-groove into the cooling channel itself, Kamarudin et al. [9] provided a passive enhancement technique for a square cooling channel to increase its cooling efficiency. This greatly accelerated the heat transfer and cooling velocity rate between two surfaces, such as molten plastics and a cooling fluid.

Wahab et al. [10] discussed the selection of the best cooling channels in terms of temperature performance with the shortest cooling time, which contributes to the improvement of quality and productivity during the process of injection molding operation. Marques et al. [11] evaluated the simulation model for the cooling circuits and showed that conformal cooling was not delivering reasonable results if not properly designed, and it is costly to manufacture such cooling channels. Patel and Sudheendra [12] studied the layout of the cooling channel and the effects on cooling time for conformal cooling channels in plastic injection molding. Abelardo Torres-Alba et al. [13] presented a hybrid cooling model with a fast cool material insert designed based on the conformal cooling channel method. Shaochun Feng et al. [14] conducted a review and comparison of the design methods, layouts, and fabrication processes for conformal cooling channels in molds. In the paper, Ognen Tuteski and Atanaskocov [15] presented the technology for the production of the conformal cooling channel used in injection molding processes and the technique for the manufacturing of the channel.

María Virginia Candal and Rosa Amalia Morales [16] described that geometric factors determining the process conditions, cavity pressure during filling stages, the cooling, and the dimensional stability of the part were used. Saifullah and Masood [17] analysed the virtual models created to predict cycle time minimization with part quality improvement and conformal cooling through ANSYS thermal analysis software. Gangber et al. [18] studied four different types of micro-cooling channel layouts for cooling a plastic molded part and concluded that the cooling channel of the mold has to be as close as possible to the component surface to ascertain expeditious and homogeneous cooling. Fischer et al. [19] investigated the impact of various cooling behavior during the semi-crystalline thermoplastics injection molding process using a mold temperature concept of segmented heating ceramics, which was created to create parts with its characteristics to enable new application areas. Engelmann and Dawkins [20] studied the application of material for mold elements with respect to high thermal conductivity / high strength copper alloys for the temperature and thermal conductivity change. Bociaga et al. [21] investigated the stresses caused by unequal mold temperature towards injection molded parts based on polymer flow, wall thickness, part shape, ejection force, etc. Shih-Chih Nian et al. [22] designed to prevent component warping and use mould temperature settings in cooling systems; the temperature distribution of molds is analyzed in cooling systems. Kowelska [23] expressed that the specific volume's derivatives according to the temperature and pressure, it is important to use the first derivative to determine the coefficient of volume expansion and the coefficient of compressibility in the conception of injection molding dimensions.

Zhang [24] analysed the injection molding process by using Finite Element software, with the model having a gating system, cooling system layout, flow process analysis, and warpage analysis to optimize the process settings with its results. Tang et al. [25] presented the development and design of a mold that can be used in injection mold for test specimens with software for design. FEA was used for thermal analysis with reference to uneven cooling in the molding cycle and its effect on the warpage. Naranjo et al. [26] stated that the effects of simulation results in the heat exchange coefficient, boundary conditions, and flow temperature, which are related to the material rheological conditions. Attila Fodor [27] carried out the calculation of the temperature on the boundary layer of the wall and the heat transfer coefficient. Didier et al. [28] proposed a methodology for mold designers using analytical models to provide quick results to attain the ejection temperature according to the temperature and position of cooling channels in the plate and for the determination of solidification time to solidify a semi-crystalline polymeric slab. Fabian Jasser et al. [29] studied the role of heat transfer in injection molding and its influence on assembling temperature and part quality and found that controlling mold temperature is an important factor in mold efficiency.

Suplicz et al. [30] concentrated on the molding stage, which was determined by the thermal properties of filled Polypropylene, resulting in a significant influence on the cooling rate. Bashir M Suleiman [31] studied the polymer's diffusivity and thermal conductivity. Zink and Kovacs [32] compared and analysed the measured values results with the numerical simulations of thermal analysis of prototype molds for the epoxy acrylate-based materials. Gerald R. Berger et al. [33] examined the cooling effect in injection molding among cooling channels, heat conductive mold, and plastic material. Huang et al. [34] designed the material of Mg alloys and their microstructure and designed their microstructure for thermal conductivity and its mechanical properties. By increasing Sb content, Mg-Zn-Sb alloys can have a lower thermal conductivity. Tom Kimerling [35] analysed the standard cooling geometry and microchannel cooling geometry for the determination of robustness. Yanichen et al. [37] revealed that the thermal conductivity of metals contributed to thermal transportation in metals, weakened the distribution of four-phonons, and reduced the thermal conductivity of lattices. Celio Fernandes et al. [38] examined research on the mathematical modeling and optimization of the injection process, including the runner system, cooling channel configurations, process variables, gate positioning, and cavity pressure equilibrium. Khor. C. Y et al. [39] examined polymer rheology in a small-scale injection molding process through three-dimensional simulation and experimental techniques and discovered that the mold flow profiles for different temperatures and time steps align well in addressing injection mold filling issues.

Kelly et al. [40] investigated how the copper alloy mold material performed with reference to the injection molding process cycle time and component quality, and results showed that cooling rates are faster than the Tool steel. Reddy and Panitapu [41] carried out the experimental work through mold flow analysis with simulations for different materials of the core insert having high thermal conductivity to reduce cooling time in the injection mold. Alfredo Gonzaleza and Ernesto Gustavo Maffiaa [42] studied the microstructure of the CuNiSiCr alloy with Beryllium copper alloy based on its hardness and conductivity and observed that it is closer to the Beryllium copper. Zhong et al. [43] compared aluminium alloy with Beryllium copper and 6061-grade aluminium alloy with reference to the insert material of the mold in terms of their hardness, wear rate, and performance during molding and resulted in Beryllium copper has the lowest wear rate. Amit Kumar et al. [44] addressed the injection molding simulation in which the flow rate is constant during the cycle when used with a low-density polyethylene material and solves the governing equations using the finite difference method. Berto et al. [45] summarized that the results from uniaxial tension stress are controlled by 650ºC. Xiaomin Meng et al. [46] investigated the relationship between the microstructure and performance of beryllium copper alloy along with their lifetime.

Jennifer L. Bennett et al. [47] investigated the [1]use of directed energy deposition to layer copper onto steel in order to shorten cycle time and produce multi-material injection molds. but it has not come up to the expected level. Kenneth C. Apacki [48] investigated how copper alloy mold materials influenced the productivity of injection molding. Aliff Abdul Rahman and Aznizam Ahmad [49] investigated the processing parameters of injection molded components made from the NAK 80 Steel material and Beryllium copper. Thomas Lucyshyn et al. [50] investigated the influencing factors of polymers for the cycle time reduction, which were injection melt, mold, and ejection temperature. Andre F. V. Pedroso et al. [51] examined the production methods and machinability issues regarding the mold materials in addition to failures encountered during their production and use. Ken N. Mwangi et al. [52] assessed the surface quality and productivity in the end-milling of Copper Beryllium by examining how feed rate, minimum quantity lubrication, flow rate, and cutting depth influence surface roughness (Ra) and material removal rate. Marton Huszar et al. [53] examined the experimental and numerical case study related to injection molding and the influences of the mould filling/cooling phases. They discovered that thermal conductivity had a minimal impact on pressure forecasting. In order to eliminate the swirl mark and create superior surface quality micro-cellular foaming for external products, Yoon et al. [54] suggested surface treatment of the mold. Zhang T et al. [56] examined the tests developed based on the orthogonal experiment method involving different factors at multiple levels conducted on the injection molding machine, and related data were assessed using the range analysis method.

Wen-Chin Chen et al. [60] introduced a novel quality prediction system based on neural networks for a plastic injection molding process, where manufacturing process parameters and product quality were focused on training and evaluating the proposed system. Rahul Bhowmik et al. [61] developed the emergence of experimental synthesis based on the influence of specific heat on polymers. Saeid Saeidi Aminabadi et al. [62] studied through industry 4.0 methods that mold temperature is one of the controlling parameters in the process of injection molding.

In this study, two mold materials such as AISI 420 and Ampcoloy 83 have been taken for experiment and examined with reference to thermal conductivity and its effects on cooling time using calculated and measured results. This work's primary goal is to determine how to shorten the cooling period during injection molding operations and eliminate quality issues such as shrinkage, warpage, etc., using Beryllium Copper material to Core pin. By validating Moldex3D simulations on-site, users can improve their models, design iterations, and ensure that the final mold and process parameters fulfil the necessary performance requirements. Users can greatly cut down on development time, minimize errors, and improve overall efficiency by using Moldex3D for mold development and optimization. This is especially true for complex products with high development costs, such as those that use beryllium copper. The proposed approach effectively integrates quantitative and qualitative parameters. In this work, the experiment is carried out for both Steel and Beryllium Copper (BeCu) with Moldex3D software for filling, packing, and cooling analysis, and its thermal conductivity calculation is then carried out. By simulating and analyzing the thermal behavior of molds, Ansys Workbench is used in injection molding to examine the effects of the mold's thermal conductivity. Transient thermal analysis and injection molding simulation allow engineers to forecast cooling times, spot possible flaws like sink marks, and improve mold designs for quicker cycle times and higher-quality products. Ansys Workbench is used to model the part, simulate thermal behavior, assess the effect of the thermal conductivity of mold material, optimize mold design systematically for optimized process parameters, forecast possible flaws, and increase productivity. The specific mold modifications are done to improve the effectiveness of the part. This paper focuses on presenting a methodology for the cooling time evaluation of plastic mold aiming at reducing cooling time during injection molding. This type of analysis is the motivation behind this work being used for determining the production of quality components, making decisions to arrive at capacity planning for the marketing requirement, and considering improving plant capacity by using machine spare capacity. This study finds that the proposed system of in-house manufacturing can map the quality and the molded part surface with respect to the core.

This study explains the improvement in the productivity of injection molding components based on the BeCu material used for the core pin in the mold can increase the productivity of injection molding components by predicting factors like injection pressure, filling, locking tonnage (clamping pressure), etc. and are prevalent to know the impact of various parameters on quality issues and cycle time.

3. Materials and Methods

Figure 1 is the test piece taken for this research work, and it is produced from polypropylene material used in injection molding operations. The tested material grade is Moplen RP240N from the manufacturer, LyondellBasell. Its melt flow index is 12 g/min, and density is 0.90 g/cm^3. Its processing conditions include melting temperatures ranging from 190°C to 270°C. The mold temperature is 50°C, and the ejection temperature is 100°C. This component is one of the parts of the writing instrument assembly.

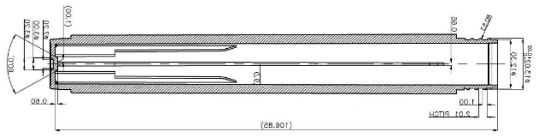

Fig. 1 Test piece

The breakup of the existing cycle time shown in Table 1 is based on stainless steel grade AISI 420 materials used for the core pins. Table 1 shows the details of cycle time break up during the injection molding process, in which mold closing takes 2 seconds followed by unit forward is 2 seconds, continued with injection times takes 7 seconds with holding time of 2 seconds where cooling times take 16 seconds. After that, the mold opening time is 2 seconds, and then ejection takes place for 1 second.

Table 1. Cycle time in seconds using AISI 420 Steel

Mold close	2.00	Unit forward	2.00
Injection	7.00	Hold on	2.00
Cooling	16.00	Mold open	2.00
Ejection	1.00	Total cycle time	32.00

This break-on cycle time shows that 50% of the total cycle time occupies cooling time, and the remaining 50% occupies unit forward, injection, hold on, ejection, mold open, and mold closing time. The unmolding operations are mold close, unit forward, ejection, and mold open. Hence, cooling time is a vital component of the injection molding process.

The production capacity is described in Table 2 based on the existing cycle time of 32 seconds. The production is considering 3 shifts based on 8 hours per shift on 30 days per month, working with the twenty-impression mold with a cycle time of existing 32 seconds. Its total quantity produced calculation is shown in Table 2 with 95% efficiency.

Table 2. Production capacity with the existing cycle time of 32 seconds - 20 impression mold

No. of shots / Hour	112
No. of components produced/ Hour	2,240
No. of components produced/ Shift	17,920
No. of components produced/ Day	53,760
Efficiency @95%	51,072
Total quantity produced/ Month	15,32,160

The plastic part is unmolded too early; it indicates displacement in all axes due to insufficient cooling, as shown in Figure 3. The solidification after un-molding of the plastic part leads to a warpage.

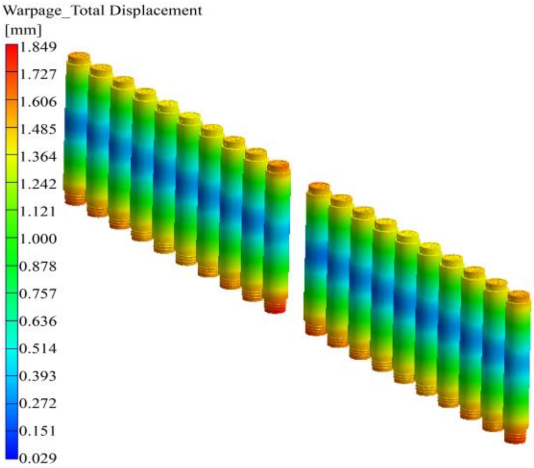

Fig. 3 Total displacement

Also, partial solidification can lead to increased shrinkage. In this case, the plastic part would not be exact to size of actual [5], and it shows the total displacement (PVT and mold cooling effects are considered) in the x/y/z axis after the part is ejected and cooled down to room temperature. The polymer melt temperature distribution is shown in Figure 4. It illustrates the predicted melt front distribution on the cavity surface.

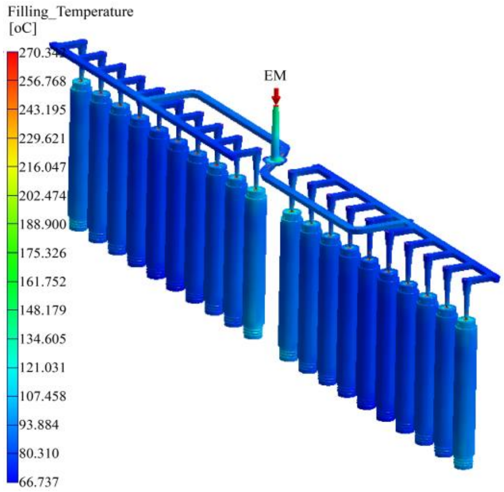

Fig. 4 Plastic melt temperature distribution

The cooling channels alone are insufficient, and thermal conductivity is an important factor as a measure [39] of the performance of a material's ability to transfer heat in the injection molding process. The injection molding process requires that the mold temperature be lower than the polymer melt temperature; otherwise, it leads to tough filling and results in quality issues such as short shots, flow marks, jetting marks, and weld lines. Mold temperature must be monitored during filling because it reduces the cooling time during injection molding when using beryllium copper. Plastic melt temperature distribution at the current instant expresses temperatures in all three dimensional for the whole cavity, and the material freeze temperature is 120°C.

The injection molding process parameters affect the mechanical properties of polypropylene material. Various suitable steel-grade materials are available that meet the requirements for both processing and the intended performance of molded components. The existing core pin material used is AISI 420. The core pin model is shown in Figure 5.

The selection of material for the beryllium copper core pin in place of stainless steel is based on the concept by flow chart as shown in Figure 5, and it is decided to use beryllium Copper to overcome the issue of cooling time, and it helps in reducing cycle time [6] too based on its higher thermal conductivity properties. AISI 420 is well-known as a standard material in the domain of engineering plastics because of its outstanding characteristics and advantageous fluidity throughout the molding procedure. AISI 420 is a high-strength plastic mold steel that has remarkable characteristics, such as outstanding mirror finish, impressive electrical discharge machining properties, and greater hardness, among others. Beryllium copper molds are used in plastic injection molding due to their outstanding thermal properties, which allow for rapid heat dissipation from the plastic parts during the injection molding process. Mindivan. H [55] investigated the WC/C coating applied to beryllium copper molds through physical vapour deposition and showed that it improved wear resistance without reducing corrosion behavior. The injection moulding process is made up of several process parameters that can influence the product cycle time, shrinkage, and part weight. This study concentrates on two process parameters: melting temperature and injection pressure. Melting temperature plays a crucial role in plastic flow. In the absence of a defined melting point, it relies on the melt flow temperature.

Temperature impacts molecular rigidity in varying ways and must be taken into account for polymer materials. Injection pressure impacts material density, reduces voids, and influences packing and holding phases in the moulding process. Mohan Manoraj et al. [57] investigated how process variables affected the warpage, shrinkage, and strength of injection molded plastic components and stated that the injection molding process leads to discrepancies between the intended shape and actual components, all of which are linked to shrinkage and warpage effects. Roman Cermak et al. [58] studied the effects of mold temperature and hold-on pressure in injection molding, which influenced the crystallinity of the part during polypropylene material generated at an elevated melting temperature, which can improve the filling process and the quality of the molded component. Feng-Yang Wu et al. [59] examined the relationship between the injection molding material structure, properties, and process used by machine learning, and it is useful for reducing the development cycle to minimize the trial-and-error method. The subsequent stage included the impact of the injection moulding process parameter through the experiment on the injection of the test part with both core pins. Upon the conclusion of [1]the injection molding process, the cooling period was recorded. Several iterations are done. This is done to achieve a more precise cooling time for this research. The aim is to examine the heat removal factors and parameters at various levels that could influence the cooling time occupied during the process.

The core pin material selection is carried out with reference to the methods mentioned in the flow diagram of the experimental process chart in Figure 5. The length of the core pin and the wall thickness between the cavity surface and core pin diameter have been maintained based on part thickness. Each stage of the manufacturing process of the core pin has been inspected and analysed for its bend level and controlled. Based on the confirmation, the dimension of the core pin in all aspects has been confirmed, and surface treatment has been done without affecting the process.

Machining processes such as turning, cylindrical grinding, and electrical discharge machining for the core pin are performed using conventional and CNC machines. The cooling hole is produced in the EDM drilling machine. Based on the confirmation of the material, the trial is conducted. Subsequently, a pilot lot production is carried out, and finally, mass production is carried out based on the material in the long run.

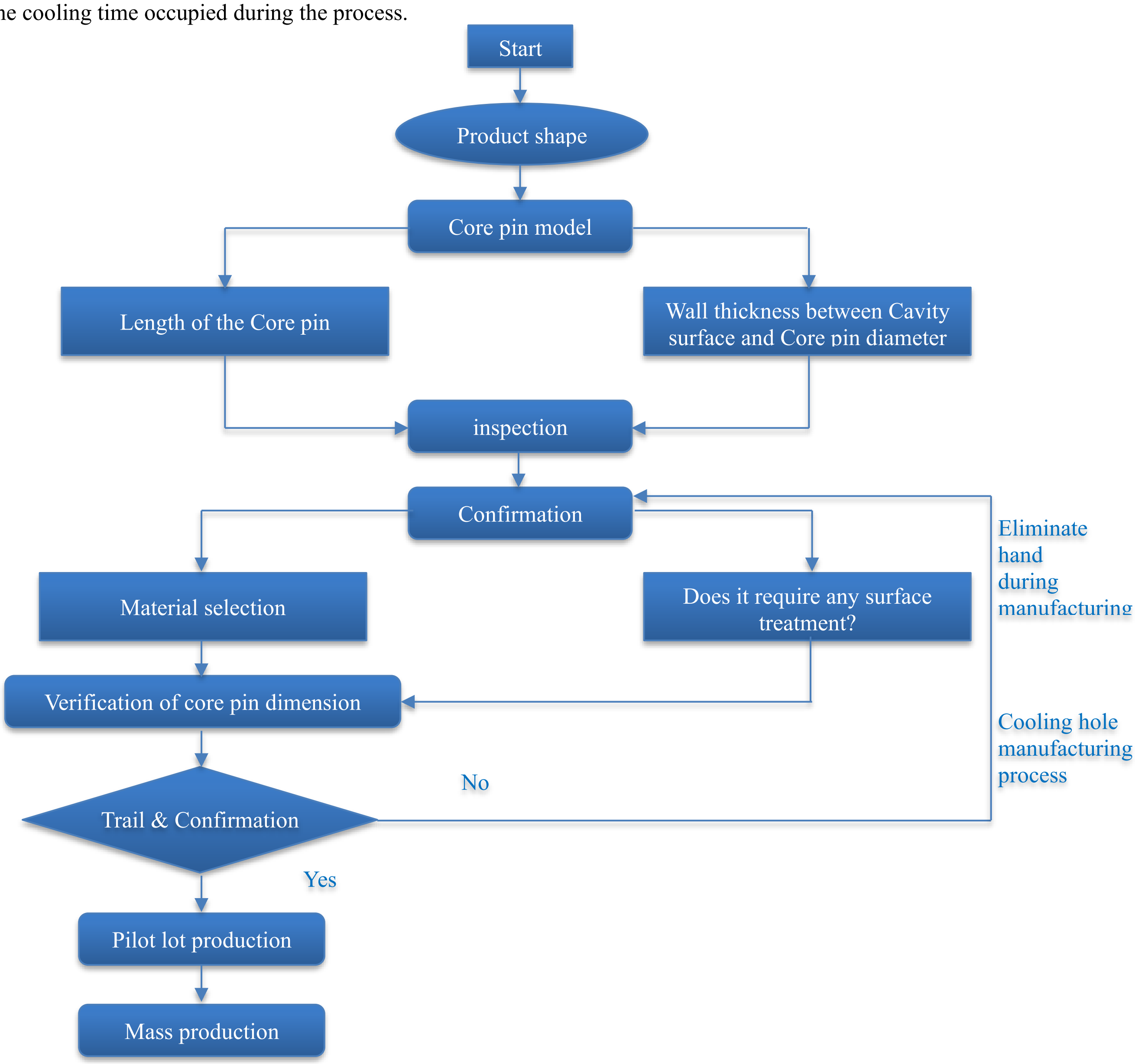

Fig. 5 Core pin material selection and production

Due to their high hardness and resistance to wear, Ampcoloy 83 and AISI 420 stainless steel are both excellent options for applications requiring reproducibility, particularly in tooling and mold making. The high conductivity and strength of Ampcoloy 83 make it the preferred material for chill plates, inserts, and cooling systems in molds, while the high hardness of AISI 420 makes it appropriate for cutting tools and precision instruments. AISI 420 is suitable for reaching a hardness of 50–55 HRC after heat treatment. It can withstand corrosion well in mild conditions, making it appropriate for various uses. Extensively utilized in injection mold cooling systems. Their well-defined properties, including hardness, wear resistance, and corrosion resistance, allow for predictable performance in various applications, leading to reproducible outcomes.

Table. 3 Main Characteristics of Ampcoloy 83

Density "ρ"	8.26 g/cm^3
Tensile strength "R_m"	1250 MPa
Thermal conductivity "λ"	106 W/m·K
Modulus of elasticity "E"	131 GPa
Yield strength Rp 0.5	1000 MPa
Specific heat capacity	380 J·kg^{-1}·K^{-1}

Ampcoloy 83 is appropriate for applications where heat dissipation is essential due to its exceptional electrical and thermal conductivity. Because of its remarkable strength and hardness, it is resilient to wear and long-lasting. Frequently found in cooling pins, inserts, chill plates, and other parts for injection molds. Because of their consistent performance and characteristics, these materials help to ensure reproducible results. Their high hardness levels guarantee consistent durability and wear resistance. Hardness, wear resistance, and corrosion resistance are just a few of their well-defined qualities that enable consistent performance across a range of applications and produce repeatable results. Their capacity to maintain exact dimensions and form while in use facilitates high accuracy and reproducibility in manufacturing processes.

Fig. 6 Core pin

The material for the core pin used in this research work is shown in Figure 6, a high thermal conductivity material, namely Ampcoloy 83 grade Beryllium Copper, and its main characteristics are described in Table 3. Using in-process monitoring, the performance characteristics of beryllium copper in injection are evaluated regarding cooling time, total cycle time, and quality of the part. The mold core pin manufactured from conventional stainless steel is compared with beryllium copper alloy, which has copper content ranging from 90-98%. This study shows that the cooling rate of BeCu (Beryllium Copper) is faster than conventional steel. This difference is attributed to the alloy's thermal conductivity. Lower cycle time achievable with BeCu material is significant in the reduction of cooling time without compromising part quality. The cooling stage [2, 3] has the biggest impact on the final properties of the molded component and takes 50% of the cycle time. The set mold temperature, the mold material's thermal conductivity, and the polymer material's thermal characteristics all affect cooling time. Reducing overall cycle time can increase productivity by increasing throughput. [1]The high thermal conductivity of beryllium copper makes it a popular option for heat removal in plastic injection molds. The influences of mold material during molding temperature play the predominant role, and hence, to increase the amount of heat removed [1] with injection molding, the material BeCu (Ampcoloy 83) is examined with regard to its thermal conductivity related to cooling time. The choices of a BeCu alloy follow on heat conductivity, hardness, very limited heat conductivity properties of tool steel, limits of the design and feasibility, cooling system close to the surface [4], and physical limits.

Thermal conductivity significantly affects injection molding's cooling time and product quality. Faster heat dissipation results from higher thermal conductivity in the plastic material and the mold, which shortens cooling time. On the other hand, longer cooling times due to lower thermal conductivity can result in problems like internal stress, sink marks, and warping, which can lower product quality.

Faster heat transfer from the plastic component to the coolant is made possible by mold materials with high thermal conductivity, which shortens cooling times. The plastic's inherent thermal conductivity affects cooling as well. Some engineering plastics and other materials with a higher thermal conductivity cool more quickly than those with a lower one. Regardless of the mold or material's thermal conductivity, a well-designed cooling system with ideal channel placement and efficient coolant flow is essential for efficient heat removal. Inadequate cooling time may result in the part warping after ejection due to unequal cooling and temperature gradients inside. If the plastic surface cools down too quickly, heat may be trapped inside the core, creating imperfections like sink marks. Overcooling can create internal stresses in the plastic, which, may lead to warping or cracking over time. In addition to minimizing variances in part quality, proper cooling guarantees consistent part dimensions. In conclusion, speedier cooling times and the production of high-quality injection-molded parts depend on optimizing thermal conductivity in the mold and the plastic material.

Because of its high heat conductivity, beryllium copper is a material of choice for injection molds, particularly when combined with simulation programs such as ANSYS Workbench and Moldex3D.

In order to optimize cooling channels, guarantee even temperature distribution, and anticipate possible problems like warping or sink marks, these simulations can simulate heat transfer and stress in the mold. The Mold wall temperature fluctuation is shown in the Figure 7.

According to Figure 7, heat conductivity is reduced when temperature increases. Temperature increases by approximately 12°C after 270 seconds. Both Steel material and BeCu material have been tested for the result findings. The continuous cycle is run during injection molding for the testing to identify wear of the core pin along with the quality performance of the component produced during mold running. The inspection of the wall thickness and rib formation of the part is carried out at an interval of every 2100 shots from the injection point where the gate point entry exists. Wall thickness on the circumferential side is also checked for the deflection of the core pin. The factors that lead to faster cooling, i.e., thermal conductivity, heat capacity, and thermal diffusivity, are given in this section when comparing stainless steel with BeCu.

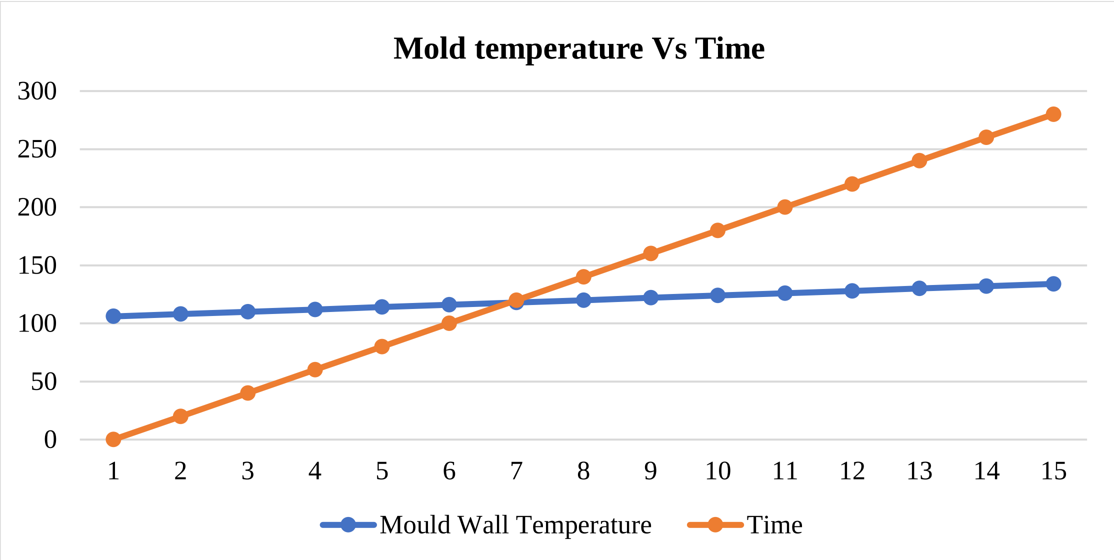

Fig. 7 Mold temperature vs time (Tool steel and AISI 420)

Table 4. Thermal properties of various materials used in this research

Matl.	Thermal conductivity (W/m.K)	Heat capacity (J/K)	Thermal diffusivity m^2/s
BeCu	106	3.43 X 10^6	1.13 X 10^{-4}
AISI 420	14.6	3.59 X 10^6	4.0 X 10^{-6}
PP	0.238	89.5 X 10^6	9.6 X 10^{-8}

The thermal properties of various materials used in this research were tabulated in Table 4. The factors considering the heat transfer during this injection molding process are such that as the melt enters the mold, it convects due to the incoming heat. Then, the conduction out of the melt goes through the mold and to the cooling channels [18]. Shear heating due to the melt deformation because of polymer flow into the cavity.

This paper focuses on the process of using Beryllium copper as the core pin in injection molding. The purpose of the subsequent molding process analysis is to determine the component's quality. Next, the core pin's dimensions are changed to account for the shrinkage effect. The time needed for cooling to achieve the ejection temperature was identified using simulation, which was conducted through Moldex3D injection molding simulation software, and the following equation was used for Equation (1) [36].

$$t_{cooling} = \frac{S^2}{\pi^2 \times \alpha} \ln \left[\frac{8}{\pi^2} \times \frac{T_p - T_m}{T_e - T_m}\right] \quad (1)$$

Where $t_{cooling}$ = Cooling time (sec); S = Wall thickness (mm); α = Heat diffusion rate of the polymer at the cavity surface temperature ; T_p = temperature of the molten plastic in °C ; T_e = temperature of taking out the molten component (at ejection) in °C ; T_m= temperature of taking out the molten component (mold temperature) in °C and the values are S=2.39 mm; $\propto = 0.0664$; $\rho = 0.905$; $\theta_p = 230$°C; $\theta_e = 56$°C and $\theta_m = 30$°C.

The rate of heat transfer is calculated from the Equation (2).

$$\frac{Q}{t} = k\frac{A}{l}\Delta T \quad (2)$$

Where Q/t = The rate of heat transfer, k = Material constant, A = The cross-sectional area, l = The thickness, and ΔT = The temperature difference.

4. Results and Discussion

The outcomes were obtained by conducting experiments with two distinct materials, namely beryllium copper [40] and AISI 420 steel. The polymer material used for this research work is polypropylene material. The cooling time in injection molding is influenced by the processing parameters configured during the process and the parameters chosen for this research work, which are injection pressure and melting temperature towards both materials. According to Wiedemann-Franz's law, materials with good electrical conductivity also exhibit good thermal conductivity. The part's wall thickness, the distance between the cooling hole and the cavity surface, and the temperature differential all affect heat conductivity. The thermal conductivity of Polypropylene [34] is higher in the solid state than in the polymer melt stage when solidification occurs. The BeCu provides high thermal conductivity [41] and wear resistance apart from its hardness and strength. It has a thermal conductivity of 3-4 times more than that of stainless steel. The heat removal rate from a mold depends upon the thermal conductivity of the core, cavity, and related mold plate material, too. BeCu [42] core pins minimise residual stresses in molded components, and due to that, no warpage and distortion take place, including shrinkage after molding.

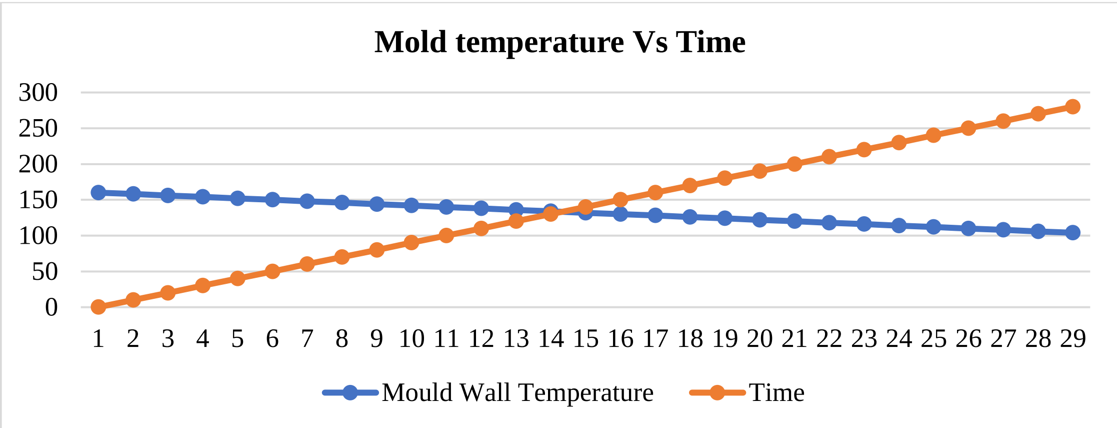

Fig. 8 Mold wall temperature fluctuation in BeCu Core pin

From the collected data, the total number of shots is compared for both steels and BeCu core pins. BeCu obtains a lower temperature as compared to steel with reference to solidifying the polymer melt and cooling the part in a faster manner with reference to mold wall temperature variation with time, which is shown in Figure 8.

The optimized cycle time is 28 seconds, and its break up is as follows when using high conductivity beryllium copper alloys for the purpose of cooling time reduction of 14.28% (from the exiting cooling time of 16 seconds to 12 seconds), which is shown in Table 5, also for the other process timings such as injection, packing (hold on), mold open, ejection, mold closing, unit forward, etc because the specific volume or density of polypropylene material is defined as a function of phase state, temperature, and pressure…etc., the authors commonly derived and quantified it with a state equation (or a PVT equation).

Table 5. Optimized cycle time (in seconds)

Mold close	2.00	Unit forward	2.00
Injection	7.00	Hold on	2.00
Cooling	12.00	Mold open	2.00
Ejection	1.00	Total cycle time	28.00

Once the parameters in the PVT equation were acquired from the experiments, they can be used to calculate the value of the specific volume or density at any given temperature and pressure, according to Figure 10.

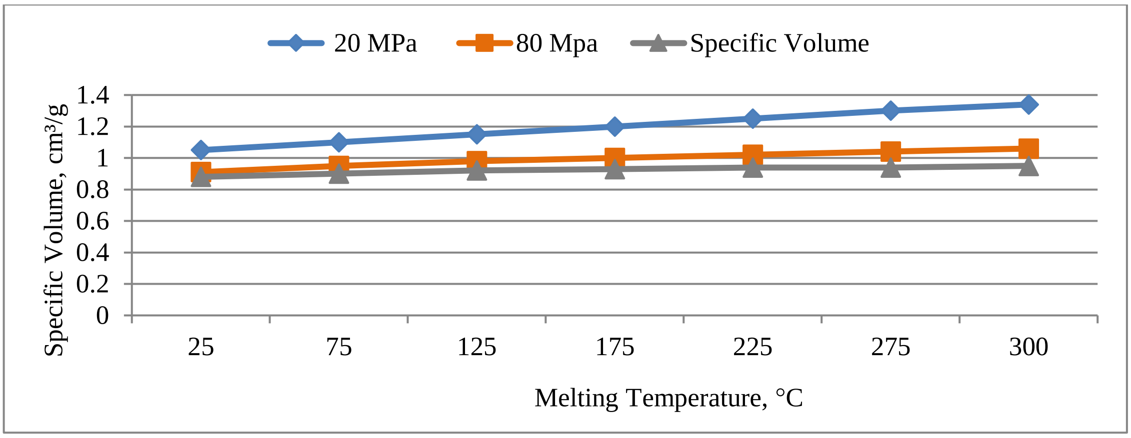

Fig. 10 PVT relationship of polypropylene

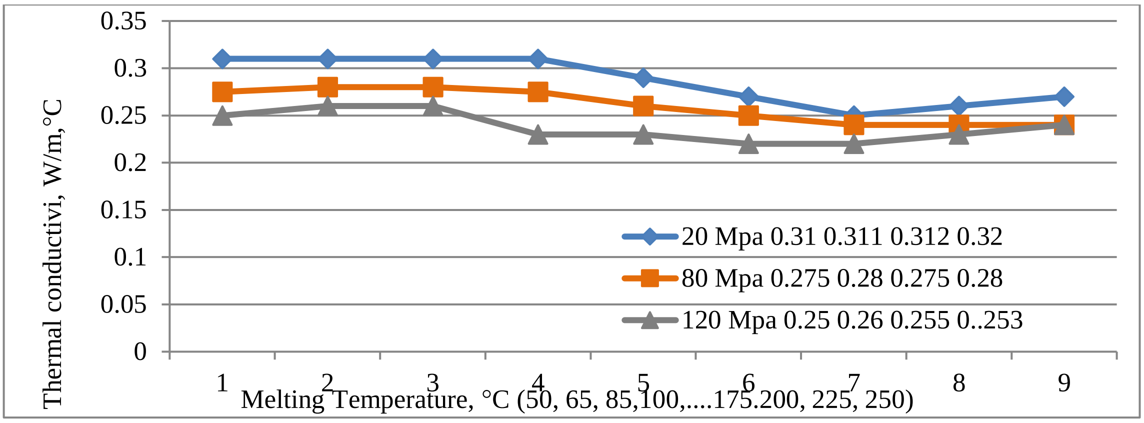

Fig. 11 Thermal conductivity of polypropylene

With reference to Figure 11, as the temperature rises [30], the electrical resistance also rises, thus leading to a decrease in heat conductivity when the electrons absorb heat as kinetic energy.

Heat conductivity through phonons refers to the Figure. 12, the matrix and crystal structures of the material are crucial for thermal conductivity via phonons. Coupled oscillators may influence heat conductivity in various ways, such as combining multiple heat oscillators to enhance the capacity for heat transfer and storage. It represents the heat transfer through a pair of oscillators that are coupled not just to one another but also to a third, 'correlated' or common oscillator, which establishes an effective interaction between the two oscillators, changing the heat transport characteristics.

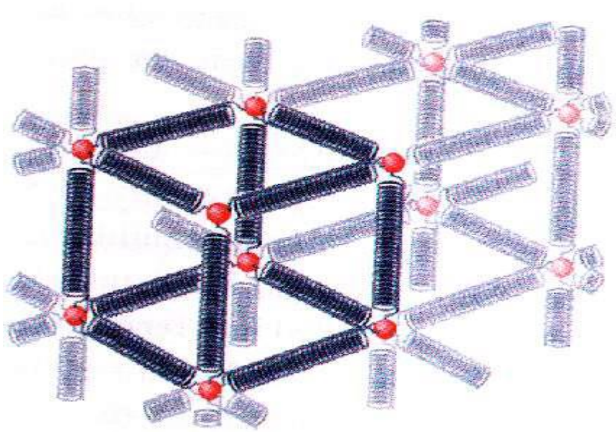

Fig. 12 Heat conductivity through phonons

Phonons represent quantized vibrations of the lattice that facilitate the movement [43, 44] of heat within the material. Volumetric heat capacity is influenced by the frequency of phonons, temperature, and their polarization. The conduction of heat by phonons relies on the volumetric heat capacity associated with phonon modes, which impacts the quantity of heat transmitted by phonons [37]. The group velocity dictates the speed at which phonons move through a given material. The mean-free path refers to the average distance that phonons can travel without encountering scattering. When the thickness of the metal layers reaches a minimum, phonon conduction can improve thermal transport. Phonons transfer heat from areas of higher temperature to those of lower temperature. Heat flow can be determined from the phonon dispersion relation of a crystal by applying the Boltzmann transport equation.

In injection molding, heat moves from the liquid plastic to the mold cavity via conduction and subsequently through convection as a cooling fluid flows through channels within the mold to carry heat away from the molten plastic. Effective cooling is crucial to solidifying the plastic and reducing stresses and imperfections. According to the principle of energy conservation, the heat released from the solidifying plastic in the mold must be removed by the water. The heat extracted from the plastic is equivalent to the heat released as the temperature of the plastic decreases from 250°C to 50°C, in addition to the heat of solidification, which is equal in magnitude to the heat of fusion but has an opposite sign. Heat is released when the plastic solidifies, and the molecules cease their random movement. The typical increase in temperature caused by viscous dissipation can be determined based on the premise that the process is adiabatic. This assumption is indeed quite reasonable for flows through channels and dies. Assuming that the pressure exerted by the molten plastic transforms into heat [20], the author can easily prove that the temperature rise will be

$$\Delta T = \frac{\Delta P}{\rho C_p} \tag{3}$$

Where, ΔT=The difference in temperature, ΔP=Change in pressure, ρ=The density of the material, and Cp= Specific heat capacity.

Table. 6 Production capacity after the BeCu material used for the Core pin with a cycle time of 28 seconds with 20 Cavity

No. of shots / Hour	128
No. of components produced/ Hour	2,560
No. of components produced/ Shift	20,480
No. of components produced/ Day	61,440
Efficiency @95%	58,368
Total quantity produced/ Month	17,51,040
Production increased	12.50 %

Based on the material change for the core pin and the subsequent trial taken, the observations include a reduction of filling and a 100% balancing of the fill pattern without any short filling. Uniform filling and packing occurred with a maximum injection pressure of 65.61 MPa to fill the part. Suitable air vents are facilitated for easy filling and avoid weld lines. In the present condition, the number of days required to produce the existing production capacity of 15,32,160 Nos. is 26.25 days, and hence, the remaining 3.75 days in a month for the particular machine can be used for another part manufacturing, and this is shown in Table 6.

5. Conclusion

BeCu can be used to provide uniform cooling to produce defect-free components and core pin material. Based on improved cooling with the BeCu core pin, a reduction of 12.50% in cooling time is obtained in this research. Hence, BeCu is helpful in minimizing the cooling time in the injection molding cycle, and it can withstand longer cycles in terms of mass production as well as mold life, having the following features. Beryllium copper's elevated thermal conductivity enables it to transfer heat away from the plastic more effectively than other substances. This aids in swiftly cooling the molten plastic, thereby minimizing cycle durations. The thermal characteristics of beryllium copper assist in regulating the temperature throughout plastic processing, thereby aiding in the management of the molding cycle. Beryllium copper helps maintain a consistent mold wall temperature, which enhances product quality. It possesses outstanding thermal conductivity, which facilitates effective cooling of the mold, leading to quicker cycle times and diminished warping of the molded components. As heat conductivity rises, the mechanical properties also improve. The exceptional thermal properties of copper beryllium alloys assist in swiftly dissipating heat from plastic components produced by the molds, possibly shortening cycle times and also preserving good hardness while reducing the necessity for repair and refurbishment of the molds.

Conclusively, Ansys Workbench is an effective instrument for examining the thermal behavior of injection molding molds, enabling engineers to optimize mold design, choose appropriate materials, and enhance the process as a whole. In instances of mold damage during the molding process, there would be no harm to the cavity and other sections of the mold. Excellent corrosion resistance to water, cooling fluids, and the injected polymer exist. There is no rust formation on the mold surface during both processing and storage. No obstruction of cooling channels occurs compared to steel core pins. It requires no maintenance since it prevents heat generation owing to friction during the molding cycle due to its abrasion resistance. The machining time is shorter than that of the steel core pin. Enhanced productivity of up to 12. 50% results from a decrease in cooling durations. Improved product quality is achieved due to minimal or no warping. Extended service life is provided owing to reduced thermal stress and a diminished likelihood of thermal cracking. Thus, beryllium copper material presents substantial potential for cost savings through optimal mold cooling in injection molding processes.

Implications

- One-time investment due to the cost of the material is high compared to steel.
- Material is bonded with the grinding wheel during cylindrical and surface grinding operations and is easy to use in other operations.
- Polishing the Core pin takes more time.

Future Work

Future efforts could try the following work to further shorten the cooling period during the injection molding process.

- Surface treatment can be done in the core and cavity before being put into mold assembly for quick heat transfer during injection molding, which leads to a reduction in cooling time.
- A chiller can be provided in place of the normal cooling line to reduce cooling time further.

Acknowledgments

Author 1 and Author 2 contributed equally to this work.

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