Minimizing wax shrinkage in investment casting: A novel design for paste-form wax injection

A. Palaniappan, S. N. Vithun*, H. N. Praveen, Prakash Vinod

Central Manufacturing Technology Institute, Bengaluru, Karnataka, India

KEYWORDS

Wax Injector,
Investment Casting,
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ABSTRACT

Investment casting refers to an industrial manufacturing process that involves dipping wax patterns into the slurry of refractory material to form a ceramic, plaster, or plastic shell. The wax pattern is further melted, and metal is poured into the shell to create a casting. This process is commonly used to manufacture complexshaped components that require tighter tolerances with a better surface finish. The quality of the final cast component mainly depends on the quality of the wax pattern and ceramic shell. The Quality of wax patterns produced mainly depends on the linear shrinkage, surface roughness, and hardness, so there is a need to remove these defects to improve the quality of the wax patterns and, in turn, the casted product. Among the challenges mentioned above, wax shrinkage plays a crucial role in producing precise components; wax shrinkage can be reduced if injected at a lower temperature or in its paste form, i.e., around 45°- 49°c. To address this shrinkage, a wax injection unit is designed and tested, capable of injecting wax at lower temperatures. The developed subsystem can be integrated with a wax injection moulding machine and can inject wax in its paste form.

1. Introduction

Investment casting, or lost-wax casting, is an industrial manufacturing process that involves dipping wax patterns or structures into the refractory material slurry to form a ceramic, plaster, or plastic shell (Pattnaik et al., 2012). The wax pattern is further melted, and metal is poured into the shell to create a casting. This process is commonly used to manufacture complex-shaped components that require tighter tolerances with a better surface finish. This process minimizes the wastage of energy, material, and subsequent machining and helps create intricate designs with accurate and better surface finish. This process finds extensive applications in various sectors, such as automotive, aerospace, military, medical, oil & gas.

The quality of the final cast component mainly depends on the quality of the wax pattern and ceramic shell. Usually, Wax patterns are fabricated /produced using a Wax injection machine. These machines are the most sophisticated and are important in generating better and more precise casted products. The Quality of wax patterns produced mainly depends on the linear shrinkage, surface roughness, and hardness, so there is a need to remove these defects to improve the quality of the wax patterns and, in turn, the casted product. The quality of the wax pattern produced also depends on the way the wax pattern is handled during the melting and injection stage of pre-pattern production. Hence, a proper handling method can eliminate many wax pattern defects.

The basic principle of a wax injection molding machine is to inject wax in its molten state into a closed die cavity, where it is allowed to solidify to produce a required wax pattern (Zorzi et al., 2003). The major factors affecting injection molded components' quality broadly depend on part design, mold design, machine performance and processing conditions. Among the parameters mentioned above, the part and mold design are assumed as fixed parameters that depend on the initial design.

*Corresponding author E-mail: vithun@cmti.res.in

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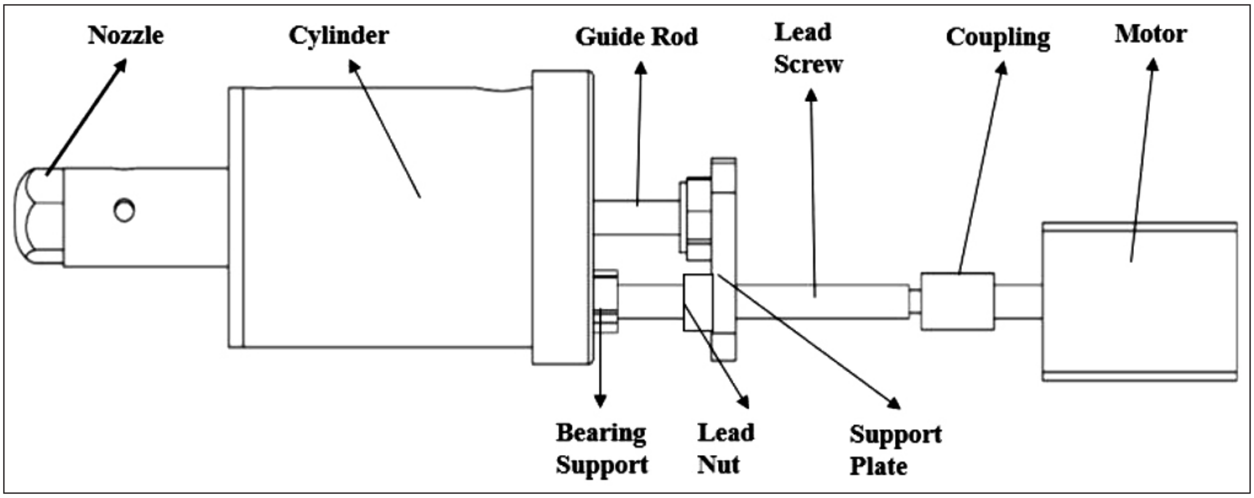

Fig. 1. Line drawing showing the wax injector prototype.

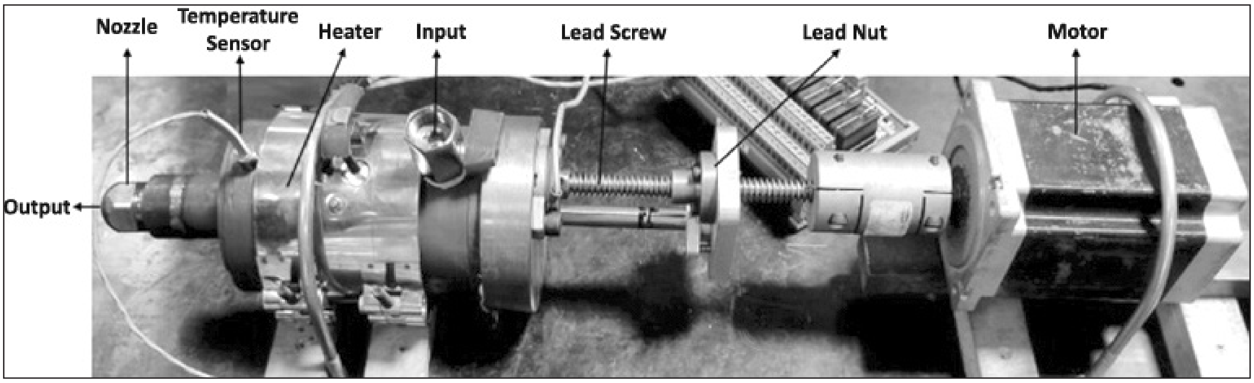

Fig. 2. Pictorial view of wax injector prototype.

The machine's performance depends on parameters like pressure, wax temperature, die temperature, and holding time (Rahmati et al., 2009). Apart from the wax temperature, the types of wax used also play a role in the quality of the wax pattern; the various types of waxes, namely Paraffin wax, Bees wax, Montan wax, Carnabua wax, and China wax, are generally used for the production of wax pattern. Each wax has its own advantages and disadvantages in the production of wax patterns. The increase in injection temperature increases wax shrinkage, whereas an increase in die temperature reduces the wax shrinkage. Slow injection and short holding time reduce dimensional variation in castings. Among the above-mentioned challenges, wax shrinkage plays a crucial role in producing precise components; wax shrinkage can be reduced if the wax was injected in its paste form, i.e., wax at a temperature of 45-49° C.

To address this shrinkage, a wax injection unit was designed and tested and can inject wax at lower temperatures. The developed subsystem can be integrated with a wax injection molding machine and inject wax in its paste form. The developed subsystem can be integrated with a wax injection molding machine and can inject wax in its paste form (Medvedovski & Peltsman, 2012).

Initially, a cylinder-based prototype was developed, and experiments were carried out to inject the wax in its paste form (Rezavand & Behravesh, 2007). Based on some of the challenges and issues observed during the experimentation, some design modifications are being made to address these issues and aid in the easy and better injection of wax in its paste form.

2. Wax Injector Prototype Design

The line drawing of the piston-based injector setup used for initial experimentation is depicted in Figure 1. The piston and cylinder configuration had been designed, manufactured, and assembled. The wax injector prototype consists of a piston, cylinder, band heater, temperature sensor, pressure gauge, and motor. The actuating motor generated the rotary motion, which was translated into linear motion using a lead screw, and a lead nut arrangement was connected between the piston and the motor. A combination of band heat, PT 100 RTD sensor, and PID controller worked together to manage the needed temperature for heating the wax, which was subsequently injected by actuating the motor.

A visual representation of the setup described above is shown in Figure 2. During the injection process, the motor activates, driving the lead screw mechanism that pushes the piston forward within the cylinder. As the piston advances, heated wax maintained at a precise temperature by the band heater and controlled by the PID system is forced through the nozzle. This action enables a consistent, controlled flow of wax for injection into the mold cavity.

3. Wax Injector Prototype Testing

The injection testing for the wax injector prototype is shown in Figure 3. This evaluation assesses the prototype's performance under various temperature conditions. The wax was injected in paste form at 55 to 49 °C.

At room temperature, 300 grams of wax are poured into the cylinder. The PID temperature was then set to 55 °C, allowing the wax to heat up before injection. Once the set temperature was reached, the wax was injected by energizing the motor that, in turn, drives the lead screw and pushes the piston forward within the cylinder.

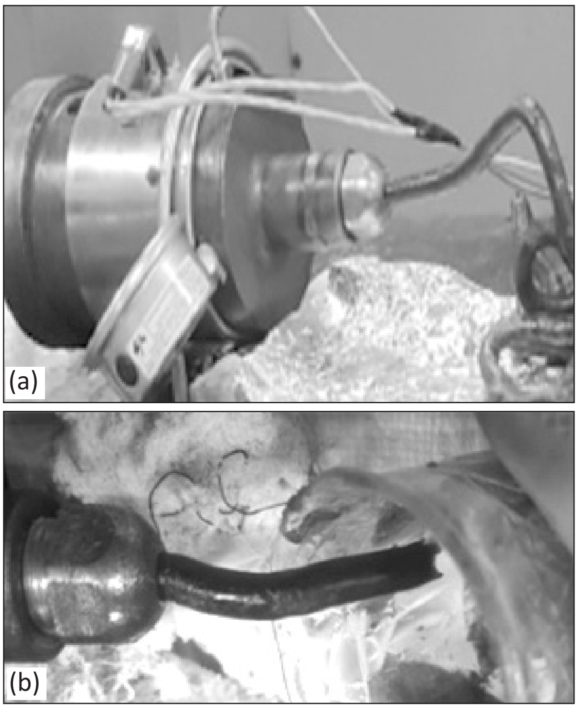

Fig. 3. a) Wax being injected from the cylinder. b) wax is shown as injected from the nozzle.

Table 1
Wax injector prototype test data for injection in different temperatures.

Sl. No.	Set Temp. (° C)	Surface Temp. (° C)	Output Wax Temp. (° C)	Holding Time (min)	Injection status
1	55	55.3	52	12	Injected
2	52	52.5	49	40	Injected
3	50	50.3	46	60	Injected
4	49	49.2	45	75	Injected

The temperature was subsequently reduced in increments of 2 °C, and the cycle was repeated while monitoring the wax's consistency, injection status, wax temperature, and holding time. It was noted that the reduction in temperature was inversely proportional to the holding time of the wax in subsequent cycles; as the temperature decreases, the holding time must be increased before injection can occur. The same has been tabulated below in Table 1.

The wax injector prototype test data for different temperature values are shown in Table 1. It can be observed that as the temperature decreased, the holding time was increased to melt the wax uniformly before injecting. Otherwise, the middle portion of the wax beads used to stick together in the solid form rather than melting and create a block, which restricts the wax passage in the nozzle and halts the injection process.

Also, the band heater was mounted only on the outer surface of the cylinder portion, which led to more time for overall/ uniform melting of wax and also resulted in uneven melting of the wax. The cylinder and nozzle were connected by a nozzle pipe, which caused a sudden reduction in area, resulting in the wax accumulating in the step area. The material used for the fabrication of the cylinder was Mild steel, which had lower thermal conductivity, resulting in a longer holding time for the wax to melt.

4. Design Modification

Based on prototype 1 testing, a few modifications were made to address the issues mentioned above. The cylinder area was gradually reduced

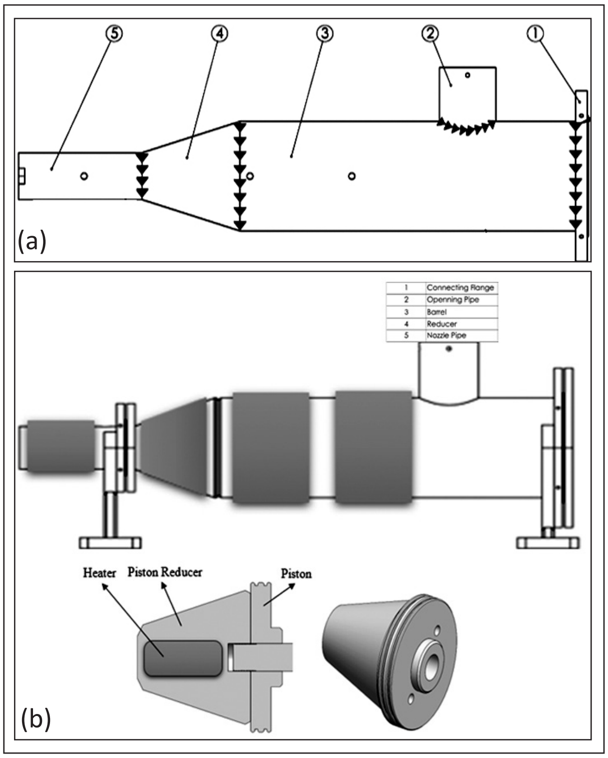

Fig. 4. a) Cylinder with modified design, b) Piston with modified cylinder.

to address the wax accumulating in the step corner. The length of the nozzle pipe was increased, resulting in the core or middle portion of wax being exposed more to heat and aiding in the uniform melting of wax. The heaters are placed throughout the injection process to maintain the required temperature and insulate the system from its surroundings.

Considering all the modifications mentioned above, a new cylinder design was made. The cylinder has three regions, as shown below: A-barrel, B-reducer, and C-nozzle pipe. The cylinder with piston arrangement comprises five heaters, four temperature sensors, and one pressure sensor mounting. The nozzle and its heating element and sensors are attached to the end of the nozzle pipe. Fig. 4a & b shows the cylinder and piston design incorporating all the changes/modifications.

The piston is also modified to house the cartridge heater inside the piston to aid in the melting of wax inside the cylinder.

5. Result and Discussion

A prototype of a wax injector (Prototype-1) equipped with a band heater, temperature sensor, and PID controller was developed to test the injection of wax in paste form. The system's heating behavior, temperature distribution, wax injection characteristics, and overall stability were evaluated. Results showed that while the system could inject wax in paste form, the process became increasingly inefficient as the temperature decreased. Longer holding times were necessary to uniformly melt the wax before injection. Additionally, in several trials, the central portion of the wax beads remained solid, causing them to stick together and form blockages. These blockages restricted the wax flow through the nozzle, resulting in a halt of the injection process.

A key issue identified was the positioning of the band heater, which was mounted only on the outer surface of the cylinder. This design resulted in longer melting times and uneven wax distribution due to incomplete or uneven melting of the wax. Another issue was wax accumulation in the corners where the area between the cylinder and nozzle pipe suddenly decreased, leading to clogging in those regions.

To address these issues, design modifications were made in the subsequent iterations of the wax injector. The improved design featured a single melting chamber operating over a wide temperature range. Wax was uniformly heated at high temperatures in this chamber prior to injection. The revised design enhanced the wax injection process, improving system efficiency by allowing for faster injection in paste form. This modification not only reduced the overall cycle time but also optimized energy consumption, as no additional cooling chambers were necessary. As a result, the wax injection process was made more reliable and efficient.

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A. Palaniappan is working as a Project Associate in the Centre for Smart Manufacturing, Precision Machine Tools, & Aggregates (C-SMPM) at the Central Manufacturing Technology Institute (CMTI), Bengaluru, India. His research area is in new product development.
(E-mail: palaniappan.12.12@gmail.com)

S. N. Vithun is working as a Scientist in the Centre for Smart Manufacturing, Precision Machine Tools, and Aggregates (C-SMPM) at the Central Manufacturing Technology Institute (CMTI), Bengaluru, India. His research areas are Precision and Smart machines, machine aggregates, and precision metrology equipment development.

Prakash Vinod is working as a Joint Director (Scientist-F), Head of the Centre for Smart Manufacturing, Precision Machine Tools, and Aggregates (C-SMPM) at Central Manufacturing Technology Institute (CMTI). His research areas are Design & Development of Precision & Smart machines, machine tool aggregates, Machine tool testing, Noise and Vibration analysis for product development.
(E-mail: prakashv@cmti.res.in)

H. N. Praveen is working as a Project Associate in the Centre for Smart Manufacturing, Precision Machine Tools, and Aggregates (C-SMPM) at the Central Manufacturing Technology Institute (CMTI), Bengaluru, India. He holds a bachelor's degree in Mechatronics. His research interests focus on industrial automation, robotics, and advanced mechatronic systems.
(E-mail: praveenhn87@gmail.com)