Experimental Study of Manufacturing Aluminum Alloy Pistons Using Vertical Centrifugal Casting Process

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Abstract— This work presents an experimental investigation on manufacturing composite pistons from two aluminum alloys, i.e. each alloy form a zone in the piston. Therefore, A336 alloy located at the piston skirt and A242 alloy located at the piston crown. The affecting parameters are the pouring temperature of the alloys, the rotational speed of the casting mold and the casting method. Centrifugal casting and permanent casting methods were used. The effects of various parameters on the mechanical properties such as hardness and wear were measured. It was found that, the centrifugal casting process can be used as a new and effective method in piston manufacturing compared with the permanent casting process. Good results were obtained at 40 rpm casting mold rotational speed and 740 °C alloys pouring temperature.

Index Terms— Piston, Centrifugal Casting, Permanent Casting, Rotational speed, Pouring temperature, Hardness, Wear.

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1 INTRODUCTION

The cast iron pistons were superseded by aluminum alloy piston around the year 1920. Cole and Sherman [1] illustrated that, nowadays the replacement of steel and cast iron in automotive components like pistons with light weight aluminum alloy casting recieved a significant interest to improve their performance and efficiency. Low expansion aluminum–silicon alloys referred by Haque and Young [2] as piston alloys due to their because Al-Si alloys offer the best balance of deriuqer ehtproperties. According to Morishita et al. [3], aluminum based alloy piston provided particularly for diesel cycle engine due to its lower weight and better heat radiation. Chen [4] showed that, light vehicle engine pistons are commonly cast from near-eutectic multi-component Al-Si alloys. These alloys had high levels of copper to upwards of 4-5 wt. % and Ni to about 3 wt. %.

The gravity permanent mold casting considered as the pistons conventional manufacturing method. However, in recent years, new manufacturing methods have emerged. Squeeze casting is one of the new common fabrication routes for pistons fabrication. It was used to reinforce the piston head. Currently, Urquhart [5] and Vijayaram et al. [6] reported that these pistons are manufactured in Japan , Europe and USA.

Ghomashchi [7] and Vikhrov [6] discussed the principles of the squeeze casting process, and Vijayaram et al. [6] produced metal matrix composite pistons reinforced with ceramic fibers using this method. Other researchers including Wang and Tung [8], Wang et al. [9], Taymaz et al. [10] and Xu et al. [11] illustrated that, when the piston surfaces coated with certain ceramic materials their corrosion and wear resistance improved to some extent. Moreover, other new manufacturing methods of pistons have been developed. For example, Liu et al [12] invented a manufacturing method to make partially particle reinforced pistons by centrifugal casting.

Among the above mentioned manufacturing methods, Chirita et al. [13] reported that, the manufacturing of pistons using centrifugal casting process has many advantages such as low cost, easy operation and good fexibility specialy for cylindrical pistons. Moreover, it can be adapted to meet the requirements for variuos mechanical performances at specific locations in the piston. Therfore, centrifugal casting can be considered as a promising manufacturing method of pistons.

Casting mold rotational speed, pouring temperature, mold coating and mold temperature are the most important parameters affecting the centrifugal casting process. Campbell [14] showed that, the main benefit of the centrifugal casting process is that the high force resulting from high rotational speed of the mould which not only assists in mould filling, but may also help to feed the shrinkage during the solidification of the casting. However, this may be partly offset by the very turbulent nature of the mould filling process which may entrain various defects such as bubbles and oxide films.

ASM [15] states that, when the molten metal enters the mold, a pressure gradient is established across the wall thickness by centrifugal acceleration. This causes separatin of constituent due to various densities, with lighter particles such as slags and nonmetallic impurities gathering at the inner diameter.

Ping et al. [16] showed that, the rotational speed of the mold consider as one of the significant process variables which affect the molten metal cooling rate.

Suzuki and Yao [17] showed that, the centrifugal force increased by a square proportion when the rotational speed is increased. This will produce homogenized temperature distribution in the melton materials due to the creation of a strong convection in the liquid pool.

Also, Cumberland [18] mentioned that, factors such as friction, surface tension, inertia, etc. affect the rotational velocity of the molten metal, and thus, it is not possible to calculate the ideal rotational speed of the mold. Morovere, Hall [19] stated that usually the speed of rotation is varied during the casting process.

Singh et al. [20] stated that, pouring temperature exerts an important effect on the solidification mode and needs to be determined partly in relation to the type of structure required. Moreover, ASM [15] mentioned that the pouring process and temperature affect the structure of the resultant centrifugal casting more than the initial mold temperature.

HU et al. [21] showed that, the metal density can be increased by maintaining a lower pouring temperature. Low pouring temperature minimizes the gas absorption and gives fine grain size. However, the minimum temperature is often dictated by casting dimensions and pouring condition.

Davis [22] mentions the delivered process of horizontal centrifugal casting where, the pouring spout is traversed parallel to the axis of rotation and the thickness of the casting is determined by the rate of feeding.

Hall [19] stated that it must be recognized that during the pouring process the direction of movement of the molten metal changes from vertical to horizontal.

McLean and Northcott [23] showed that high pouring temperatures slows solidification from the outer diameter more than it delays freezing from the bore and (presumably) discourages continuous growth of the outer diameter columnar grains.

According to Northcott and Dickin [24], the higher mold temperatures lead to coarse grains, especially for equiaxed grains; however, the influence of mold temperature on the grain structure was minor compared to some of the other parameters. Nevertheless, a low mold temperature can result in a steep temperature gradient during solidification and this can give rise to banding.

Evans et.al [25] stated that molds used in centrifugal casting processes are coated internally with a mold coat, generally of a refractory powder with a binder in the form of slurry. The basic function of this coating is to avoid sticking of the casting to the mold and thus to facilitate casting withdrawal and to protect the mold.

Thornton et al. [26] mentioned that, it can also be used to control the rate of heat extraction. Various types of coatings have been developed. Of these, zircon-based coatings using water as the suspension medium have proved to be effective and are known to give excellent surface finish.

Howson [27] showed that, solidification in centrifugal castings is a similar process to that occurring in static castings i.e. is a change of state phenomena, the rate of which is governed by heat transfer, but there are super imposed effects of the mechanical action.

Marrone [28] showed that, in centrifugal casting, it is very difficult to determine the temperature distribution and solidification time by experimental techniques. Because of this, accurate data on solidification time during centrifugal casting of different materials is not available.

The aim of the present work is to study experimentally the manufacturing of a piston within the standard specifications with improved mechanical properties using centrifugal casting method. The influence of pouring temperature and casting mold rotational speeds on the pistons manufacturing using centrifugal and permenant casting methods will be investigated.

2. EXPERIMENTAL SET-UP

2.1. Materials

Two diffrent aluminum alloys were used in the current study; each alloy forms a specific zone in the piston as shown in Fig. (1). The first aluminum alloy was A336 which located at the piston skirt. While the second aluminum alloy was A242 loacated at the piston crown. Table (1) presents the chemical composition of these alloys.

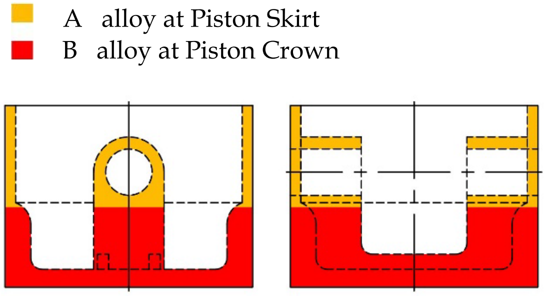


Fig. 1. Schematic drawing of the piston two zones partitions.

TABLE 1

UNITS CHEMICAL ANALYSIS OF ALLOYS USED IN THE MANUFACTURE OF PISTONS

No.	*alloys*	*Element (%)*								
		Si	*Cu*	*Mg*	*Ni*	*Fe*	*Ti*	*Zn*	*Mn*	*Al*
A	*A336*	*11.92*	*1.13*	*1.13*	*2.54*	*0.352*	*0.028*	*0.016*	*0.007*	*Bal.*
B	*A242*	*0.064*	*4.21*	*1.64*	*2.08*	*0.287*	*0.021*	*0.028*	*0.009*	*Bal.*

2.2. Equipment

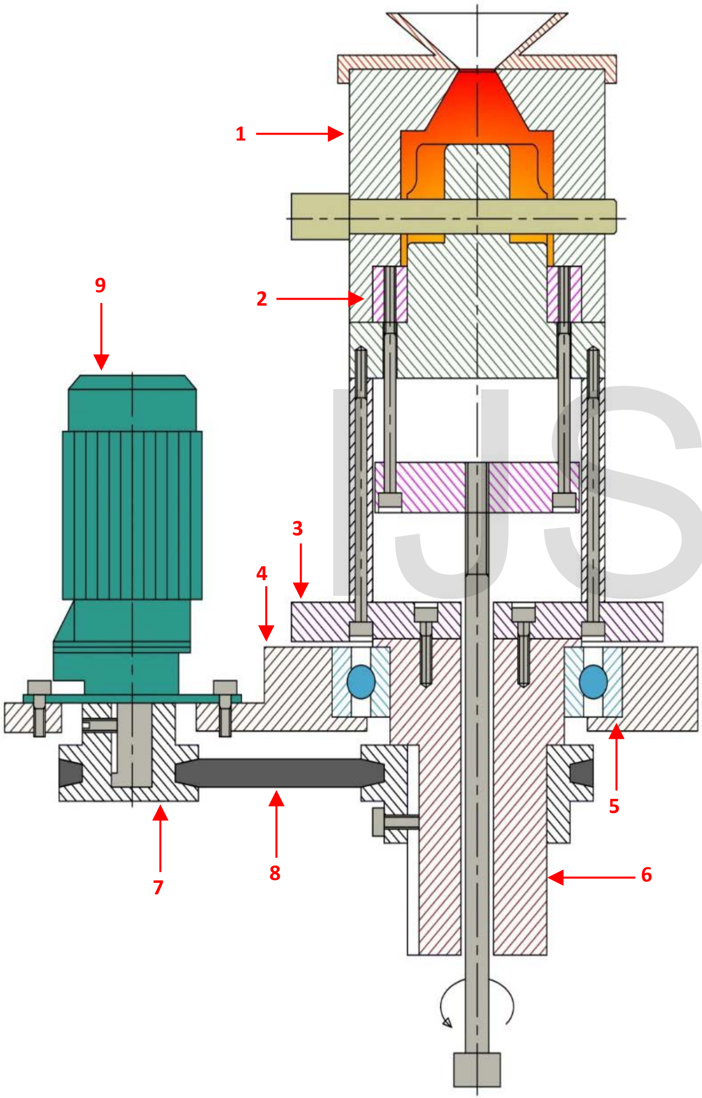
A vertical centrifugal casting machine was designed to carry out the experimental work. Figure (2) shows schematic representation of the experimental arrangement. The casting mold composed of mould, core and pine parts. Rejection system in the centrifugal casting machine facilitates the piston ejecting process from the casting mold after alloys solidification. An electric motor which is fixed on the structure of the machine used to power the system. Moreover, pulleys and belts used to adjust the required rotational speed.During the experimental work, centrifugal casting processes carried out at three different rotational speeds (i.e. 20, 30, and 40 rpm) and two pouring temperatures (i.e. 740 and 780 ^{o}C). While, for permanent casting processes zero rotational speed was applied at the two pouring temperatures. Piston manufacturing processing parameters (i.e. the values of rotational speed and pouring temperature parameters) indicated at table (2).

2.3. Experimental Procedure

1. In the first step in the experimental work the casting mold coated withgraphite material to avoid sticking of the casting piston to the mold and thus to facilitate casting withdrawal after the end of the solidification process which will extend the mold life.

TABLE 2
PROCESSING PARAMETERS OF PISTON MANUFACTURING

Processing	rotational speed rpm	pouring temperature c°
1	Zero	740
2	Zero	780
3	20	740
4	20	780
5	30	740
6	30	780
7	40	740
8	40	780



(1) MOLD CASTING (2) EJECTOR (3) DRIVING FLANGE
(4) TABLE PLATE (5) BEARING (6) SPINDLE SHAFT
(7) PULLEY (8) BELT (9) MOTOR.

FIG. 2 SCHEMATIC ILLUSTRATION OF VERTICAL CENTRIFUGAL CASTING MACHINE.

2. Secondly, the casting mold heated by Ghazi Bonfire fixed at the centrifugal casting machine structure.This syncronatizedwith the alloys melting process in the oven. Figure (3) shows a photo for the vertical centrifugal casting machine and heating process of the casting mold.

FIG.3. A PHOTO FOR THE VERTICAL CENTRIFUGAL CASTING MACHINE.

3. Afterthat, pouring process started by pouringthe first aluminum alloy (A alloy) inside the casting mold cavity then the second aluminum alloy (B alloy) poured. Pouring process carried out during the rotation of the casting mold with the predetermined rotational speed (Fig. 4).
4. When the solidification process completed the piston withdrewfrom the casting mold using the designed ejecting system.
5. Finally, sprues are removed using a turning machine. Then, the casted pistonsare numbered for conducting the tests on them later. Figure (5) is a photo for the pistonsproduced in all cases.

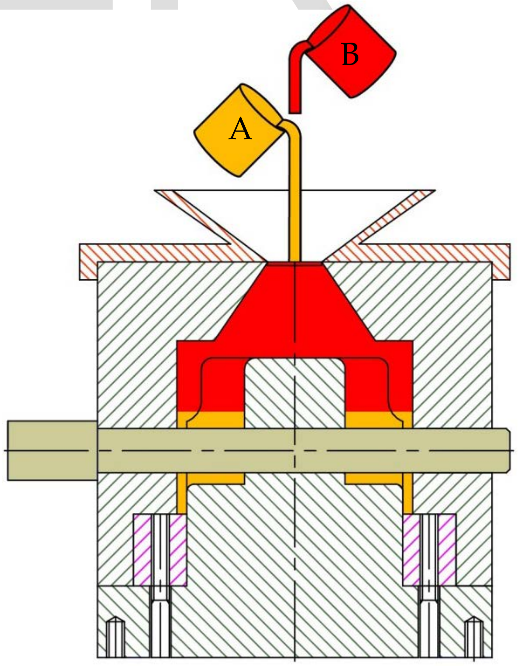


FIG.4.SCHEMATIC REPRESENTATION OF THE POURING PROCESS.

FIG. 5. A PHOTO FOR THE PISTONS PRODUCED IN ALL CASES.

2.4. Testing Procedure

2.4.1. Hardness Test

Vickers hardness test carried out on the fabricated pistons.The load was applied for 15 seconds. Hardness measurements applied on the skirt and crown zones of the piston. Two hardness readings were taken and averaged for each zone. Figure (6) shows locations for hardness tests. Specimens were grinded and polishedbefore testing.

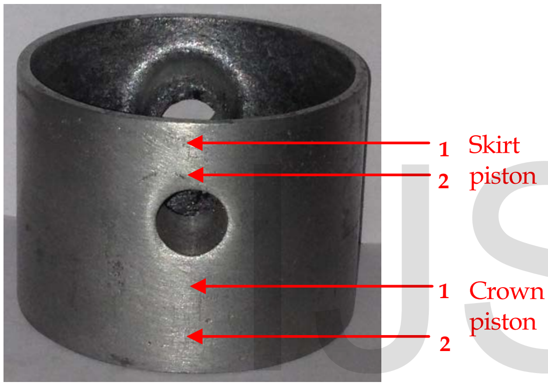


FIG. 6. LOCATIONS FOR HARDNESS TESTS.

2.4.2. Wear Testing

The wear test was measured by weight loss and was performed on Pin-on-Disc apparatus type (model TNO R, The Netherlands), in accordance to the ASTM. In this test the specimendimensionswere 7.5 mm in width, 7.5 mm in Depth and 12 mm length.

An axial load of 40 N was applied witha rotating speed of 520 rpm and a wear period of 15 min using dry friction conditions. The specimens' ends were polished with 1200 grit emery paper and cleaned with acetone.A digital balanewith a 0.1 mg accuracy was used to measure the mass of specimens before and after frication.

3. RESULTS AND DISCUSSION

3.1. Hardness

The average hardness values of the investigated zones (i.e. piston skirt and piston crown) at different pouring temperatures (740 and 780 °C) using different rotational speeds (0, 20, 30 and 40 rpm) are illustrated in Fig. 7 and Fig. 8 respectively.

Average hardness values were directly propational to the casting mold rotational speed. It can be noted that, the average hardness values increased with the increasing of casting mold rotational speed (Figs. 7 and 8). The reason for this is that where the molten metal enters the mold, a pressure gradient is established at the outer diameter (the external surfaces of the piston) by centrifugal acceleration. This causes notlemalloy constituent of various densities to separate, with lighter particles such as slags and nonmetallic impurities gathering at the inner diameter. However, under the same conditions, the average hardness values are inversely proportional to eht increasing of pouring temperature. The reason for this is the occurrence of oxidants in the alloys.

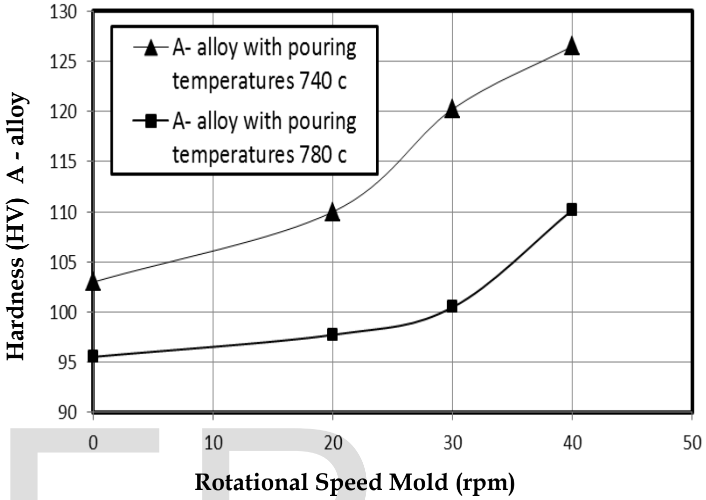


FIG.7. HARDNESS OF PISTON SKIRT AT DIFFERENT ROTATIONAL SPEEDS USING DIFFERENT POURING TEMPERATURES.

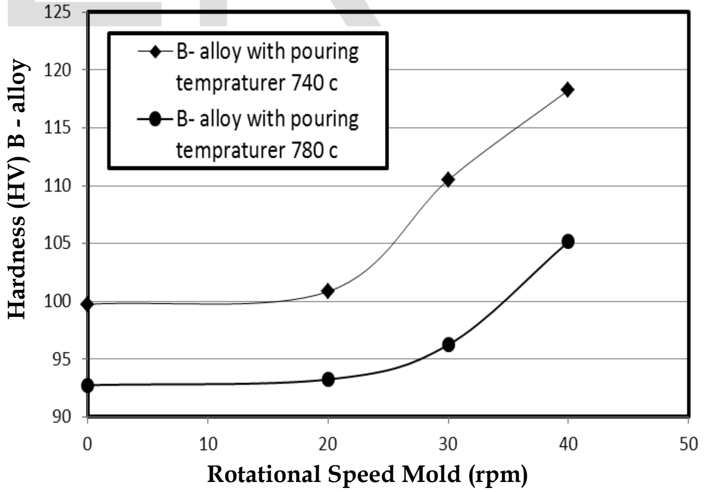


FIG. 8. HARDNESS OF PISTON CROWN AT DIFFERENT ROTATIONAL SPEEDS USING DIFFERENT POURING TEMPERATURES.

Figure (9) illustrates the relation between the average hardness values obtained for piston skirt and crown and the casting mold rotational speed at pouring temperature of 740 °C. It can be noted that, the average hardness values at piston skirt are higher than those of piston crown for the different rotational speeds. This may be due to the presence of silicon element in the A-alloy found at the piston skirt.

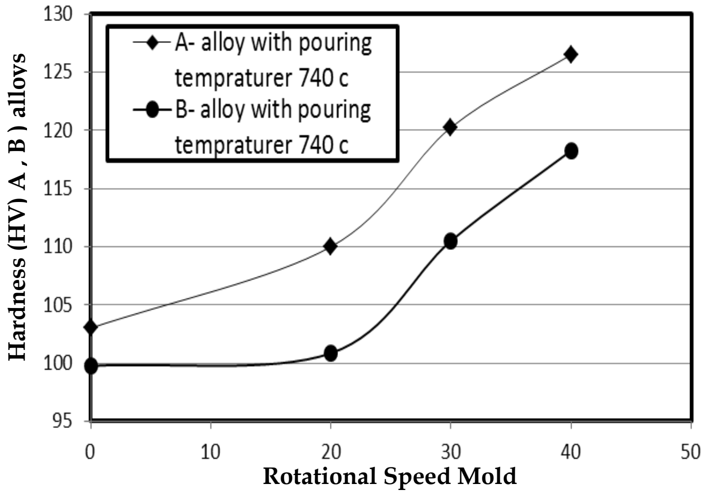


FIG. 9. COMPARISON BETWEEN THE AVERAGE HARDNESS VALUES OF PISTON SKIRT AND CROWN AT POURING TEMPERATURE OF 740 °C USING DIFFERENT ROTATIONAL SPEEDS.

3.2 Weight Loss

Figure (10) illustrates the relation between the weight loss of A-alloy located at the piston skirt with various rotational mold speeds at different pouring temperatures (740 and 780) °C after wear tests.

Weight loss in the A-alloy and mold rotational speed have a inversely relationship. Since, the weight loss reduced with increasing the mold rotational speed. This may be explained by the increase of homogenization in the product surface (piston) with the increasing of casting mold rotational speed (Fig. 10). Furthermore, it can be observed that, the weight loss in the A-alloy at the same mold rotational speed conditions increased with the increasing of pouring temperature.

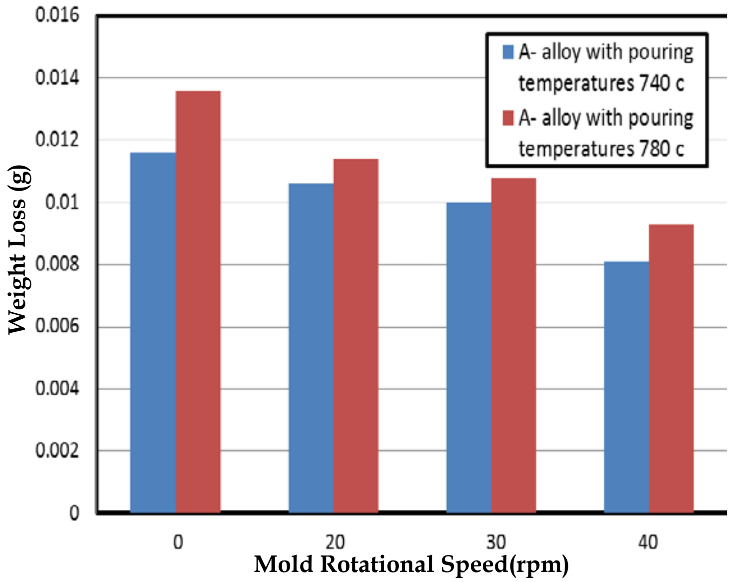


FIG. 10 RELATION BETWEEN THE WEIGHT LOSS AT A-ALLOY WITH VARIOUS ROTATIONAL SPEEDS MOLD AT DIFFERENT POURING

4. CONCLUSIONS

(1) Successfully manufacturing composite pistons composed of two aluminum alloys using centrifugal casting process. This type of pistons contains two types of alloys, which each one of them can meet the piston mechanical requirements such as hardness and wear.

(2) Average hardness values improved with centrifugal casting process compared to the permanent casting process.

(3) Using the centrifugal casting process, average hardness values increased with the increasing of casting mold rotational speed and decreased with the increasing of pouring temperature.

(4) The highest average hardness value found at the piston skirt zone (126.5 HV) using pouring temperature of 740 °C and a rotational speed mold of 40 rpm.

(5) Wear properties were improved using centrifugal casting process compared with the permanent casting process.

(6) The weight loss values decreases with the increasing of casting mold rotational speed and increased with increasing the pouring temperature in the centrifugal casting process.

(7) The weight loss of the piston skirt zone (A- alloy) is less than that of other zones.

(8) Pouring temperature of 740 °C and mold rotational speed of 40 rpm shows the best wear behavior (minimum weight loss value of 8.1 mg).

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