Mechanical Characteristics of Prepared Functionally Graded Cylinder by Centrifugal Casting

Dr. Ali H. Ataiwi
Materials Engineering Department, University of Technology/Baghdad.
Dr. Alaa A. Atiyah
Materials Engineering Department, University of Technology/Baghdad.
Marwan A. Madhloom
Materials Engineering Department, University of Technology/Baghdad.
Email: marwanabbasa@yahoo.com

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ABSTRACT

It is hoped in this paper to use the concept of centrifuging to prepare thick hollow functionally graded cylinder of (Al-TiO_2) alloy. In order to achieve this objective, a vertical centrifugal casting machine was designed and manufactured. The FG cylinders prepared have shown a reasonable linear and the graded hardness value across the thicknesses. FG cylinders exhibit a heterogeneous microstructure in which a high volume fraction of (TiO2) hard particles is clustered on the surface according to the value of pouring temperature and motor force that represented by the mold number of rotations per minutes. It was found that using of pouring temperature of (850˚C) and rotation speed of (2100 r.p.m) would make a better graded hardness value across the thickness especially when (TiO2 weight%) is (10%). It is also found that the clustering of (TiO_2) will weaken the tensile strength of prepared materials but increasing the wear resistance. Results of X-ray diffraction analysis for cylinders prepared with pouring temperature conditions (850˚C) and rotation speed of (2100 r.p.m)shows the development of (TiAl) crystalline phase in all prepared FG cylinders and maximum noticeable intensity was foundin (7.5weight% of TiO_2) FG cylinders.

Keywords: Functionally graded cylinder, Vertical centrifugal casting, and Mechanical characteristics.

الخصائص الميكانيكية لاسطوانة متدرجة وظيفيا بواسطة السباكة بالطرد المركزي

الخلاصة

تم في هذا البحث إستخدام مفهوم التطريد المركزي لتحضير أسطوانة سميكة مُجوّفة مُتدرّجة وظيفياً من سبيكة الألمنيوم- أوكسيد التيتانيوم. ولغرض تحضير هذا النوع من المَواد المُتدرّجة، تم تصميم وتصنيع ماكنة سباكة بالتطريد المركزي العمودي لهذا الغرض. أظهرت الأسطوانات المُتدرّجة وظيفياً المُحَضّرة بأستخدام ماكنة التطريد المركزي قيم صلادة مُتدرّجة بصوره خطيه عبر السمك. كما اظهرت هذه المواد بُنية مجهرية غير مُتجانسة وبكسر حجمي عالي من الدقائق الصلدة من أوكسيد التيتايوم التي تجمّعتْ بدورها على طول السطح إعتمادا على قيمة درجة حرارة الصب وقوة الطرد المركزي التي تم التعبير عنها بعدد دورات القالب لكل دقيقة. كما وُجِدَ أنّ استخدام درجة حرارة الصب (850˚C) وسرعة دوران (2100r.p.m) قد أعطى قيم صلادة مُتدرّجة بصوره خطيه خاصة عندما كانت نسبة أوكسيد التيتانيوم المضافه (10%). كما وُجِدَ أيضاً أن

تجمّع أوكسيد التيتانيوم يُضعِف من مُقاومة الشد لكنهُ يزيد من مُقاومة البلى. ولقد أثبتتْ نتائج تحليل حيود الأشعة السينية للأسطوانات المُحَضّرة بدرجة حرارة الصب (850˚C) وسرعة دوران (2100r.p.m) وجود الطور البلوري (TiAl) بكل العيّنات ولكن كانت أقصى شدة ملحوظة لهذا الطور بالأسطوانة المُتدرّجة ذات نسبة (%7.5) من أوكسيد التيتانيوم.

INTRODUCTION

Functionally graded materials (FGMs) arematerials in which some particular physical properties are changed with dimensions [1]. In FGMs, change of compositions is stepwise or continuously. The step-wise is manufactured by spark plasma sintering (SPS) while continuous is manufactured by the centrifugal casting process[2].

There are many applications of functionally graded materials made of (Al+TiO2) [2]:

1. Components for conventional fuel burning systems.
2. Stealth missiles.
3. Solar receiver system.
4. Rocket and scramjet engines.
5. Components for fuel cells.
6. Cutting tools.
7. Machine parts.
8. Components for optoelectronic systems.

Last years, many researchers want to study the preparation of functionally graded materials by a centrifugal casting process. Pai and Rajan, [3]produced functionally graded cylinder from (Al) matrix and different structures of (SiC, graphite, Si and B4C) by the centrifugal casting process. They concluded that particles of high density such as (SiC) grade towards the external circumference of the cylinder while particles of low density, such as (Si and graphite) grade towards the internal circumference of the cylinder.

Watanabe et al, [4] produced functionally graded cylinders by the addition of fine particles of (TiO2) to (Al) and the addition of (SiC) particles to (Cu) by applying a horizontal centrifugal casting process. The researchers reasoned that the centrifugal force will distribute (TiO2) particles in (Al) matrix gradually and (TiO2) particles are segregated at the outside surface of the cylinder. (SiC) particles are segregated in a copper matrix gradually due to the difference of density between the matrix and the additive particles; they also observed a gradient in hardness values along the thickness of the cylinder.

McKenna, [5]produced functionally graded material (FGM) from (Al-SiC) by using centrifugal casting technique. The researcher concluded that the pressure of centrifugal force pushed the (SiC) particles which take in higher density toward the outer surface of casting while (Al) particles which have the lowest density are concentrated at the inside surface of the mold.

Saad, [6] used a horizontal centrifugal casting method to make a functionally graded material (FGM) and analyzed the effect of the rotation speed of casting mold and overheating temperature on the microstructure and hardness of a hypereutectic (Al-23%Si) alloy. The results showed that the overheating temperature and mold rotation speed affect the grain size and volume fraction of (β-Si) phase, increasing the overheating temperature due to the increasing average volume fraction and decreasing the grain size of primary silicon, but increasing mold rotation speed due to increasing the volume fraction in the inner layer of cylinder thickness and decreasing in the outer layer, also decreasing the grain size of primary silicon. The results showed that values hardness in all layers decreases with increasing pouring temperature.

Experimental Work:

Lab scale centrifugal casting machine was proposed, designed and manufactured to use in preparing of FG cylinder samples under different conditions.

Design lab scale Centrifugal Casting Machine:

All of the major components of a centrifugal casting machine must be designed to ensure efficiency of performance. The motor shaft should be able to withstand applied loadings during operation. The turntable should be able to counterbalance the effect of imbalance associated forces with the mold during spinning action. To restore this imbalance to the axis of rotation, the turntable base diameter is designed to be larger than the mold base diameter. The essential design analysis of the vertical centrifugal force required by the machine, power and torque generated by the spinning section of the machine are considered [7].

Determination of Driven Pulley Speed:

The speed of the driven pulley is determined by [8]:

$$N_2 = \frac{N_{1*}d_1}{d_2} \quad \text{…..……… (1)}$$

Where:

N_2 = Speed of the driven pulley (r.p.m).
N_1 = Maximum speed of the motor pulley (r.p.m) = 3000 r.p.m.
d_1 = Sheave diameter of motor pulley (mm) = 79 mm.
d_2 = Sheave diameter of driven pulley (mm) = 94 mm.

So, $\mathbf{N_2}$ **=2521.27 r.p.m.**

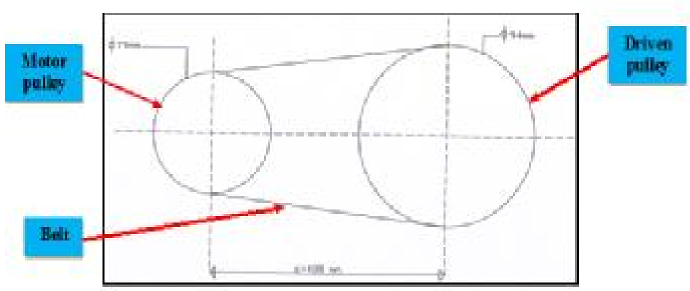


Figure (1): Dimensions of motor pulley and driven pulley.

Determination of Belt Speed:

The speed of the belt is determined by the relation [8]:

$$B_s = \frac{\pi * d_1 * N_2}{1000} \quad \text{..………. (2)}$$

Where:

B_s = Speed of belt (m/min).

So, B_s = 625426.23m/min.

Determination of Belt Length:

The length of the belt of the centrifugal casting machine is determined by [8] :

$$L = 2c + \frac{\pi}{2}(d2 + d1) + \frac{(d2-d1)^2}{4c} \quad \text{……….(3)}$$

Where:

L = Effective outside length (mm).

C = Distance between the two pulleys (mm) = 480 mm.

So,**L= 1231.72 mm.**

Determination of Angular Velocity of DrivenPulley:

The angular velocity of the driven pulley is given by [8]:

$$\omega = \frac{2*\pi*N}{60} \quad \text{..………. (4)}$$

Where:

ω = Angular speed of rotating disc (rad/sec).

N = Speed of driven pulley (r.p.m) = N_2 = 2521.27 r.p.m.

So**, ω = 263.89rad/sec.**

Determination of Angular Velocity of Turntable:

The angular velocity of the turntable is determined by [8]:

$$S_D = \frac{\pi*dp*N}{60} \quad \text{..………. (5)}$$

Where:

S_D = Angular velocity of the turntable (m/sec).

D_P = Diameter of the turntable (mm) = 260 mm.

So,**S_D = 34.306m/sec.**

Determination of the Prepared Cylinder Mass:

The mass of the prepared cylinder is determined by [9]:

$$V = \frac{\pi}{4}\left(D_{oc}{}^2 - D_{ic}{}^2\right) * h_c \quad \text{………….. (6)}$$

Where:

V = Volume (m^3).

D_{oc} = Outer diameter of the prepared cylinder (m) = 0.2 m.

D_{ic} = Inner diameter of the prepared cylinder (m) = 0.18 m.

h_c = Height of the prepared cylinder (m) = 0.07 m.

So,**V = $4.176 * 10^{-4}$ m^3**.

The biggest percentage of the added titanium dioxide is (10) % from the total cylinder size, therefore the size will be as below:

$$V(\mathbf{Al}) = 0.9 * 4.176 * 10^{-4} = 3.758 * 10^{-4}\ m^3.$$
$$V(\mathbf{TiO_2}) = 0.1 * 4.176 * 10^{-4} = 4.176 * 10^{-5}\ m^3.$$
$$M = V * \rho \qquad \ldots\ldots\ldots\ldots (7)$$

$M = V(\mathbf{Al}) * \rho(\mathbf{Al}) + V(\mathbf{TiO_2}) * \rho(\mathbf{TiO_2})$

$M = 3.758 * 10^{-4} * 2700 + 4.176 * 10^{-5} * 3900 = 1.177$ Kg.

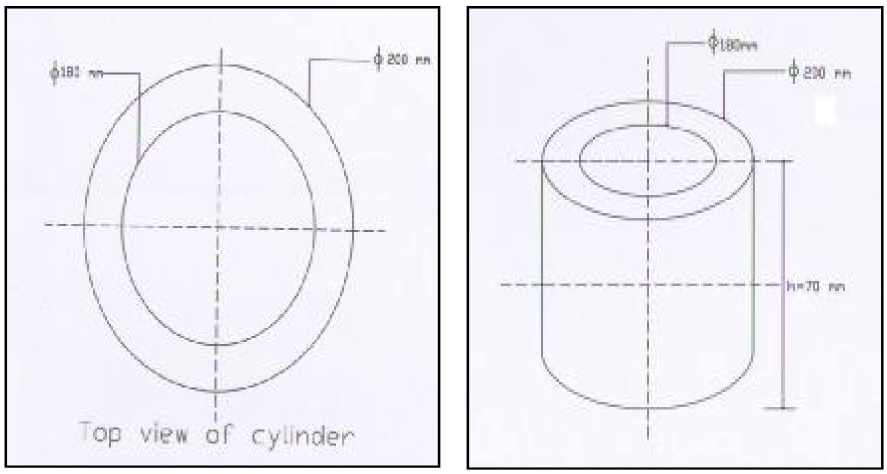


Figure (2): Dimensions of the prepared cylinder.

Determination of Centrifugal Force on the Prepared Cylinder:

The centrifugal force on the prepared cylinder is given by [8]:

$$F = M r_o \omega^2 \qquad \ldots\ldots\ldots\ldots (8)$$

Where:

F = Centrifugal force on the prepared cylinder (N).
M = Total mass of the prepared cylinder (kg) = 1.177 Kg.
r_o = Outer radius of the prepared cylinder (m) = 0.1 m.
ω = Angular speed of rotating disc (rad/sec) = 263.89 rad/sec.
So,**F =** $1.177 * 0.1 * (263.89)^2$ = **8196.384 N.**

Determination of Torque Generated by Machine:

The torque generated by the machine is determined by [8]:

$$T = F * r_D \qquad \ldots\ldots\ldots\ldots (9)$$

Where:

T = Torque generated (N.m).
r_D = Radius of rotating disc (m) = 0.047 m.
So,T**= 385.**
23 N.m.

Determination of Required Power by Machine:

The required power by the centrifugal machine is determined by the relation [8] :

$$P = \frac{2*\pi*N*T}{60} \qquad \text{…..…….. (10)}$$

Where:

P = the required power (Watt).

So**, P = 101659.472 Watt.**

Determination of the Cylindrical MoldMass:

The cylindrical mold mass is determined by [9], using equation (6) above:

$$V = \frac{\pi}{4}\left(D_{oc}{}^{2} - D_{ic}{}^{2}\right) * h_c \qquad \text{………. (6)}$$

Where:

D_{oc} = Outer diameter of the cylindrical mold (m) = 0.215 m.

D_{ic} = Inner diameter of the cylindrical mold (m) = 0.2 m.

h_c = Height of the cylindrical mold (m) = 0.07 m.

So**, $V = 3.406 * 10^{-4}$ m³.**

And equation (7) to calculate the mass:

$$M = V * \rho \qquad \text{………… (7)}$$

So, **M = 2.6566 Kg.**

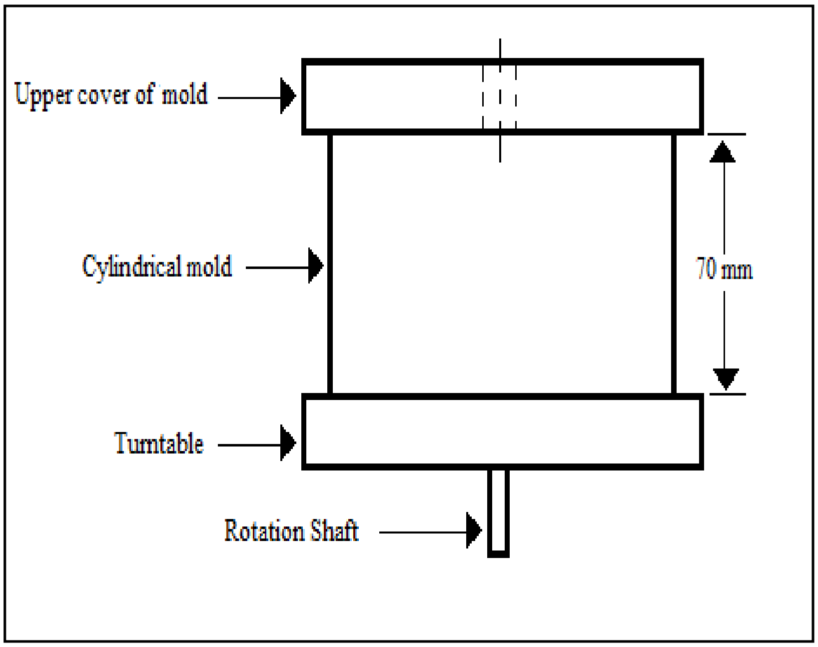


Figure (3): Design of the cylindrical mold, rotation shaft, upper and lower covers of mold.

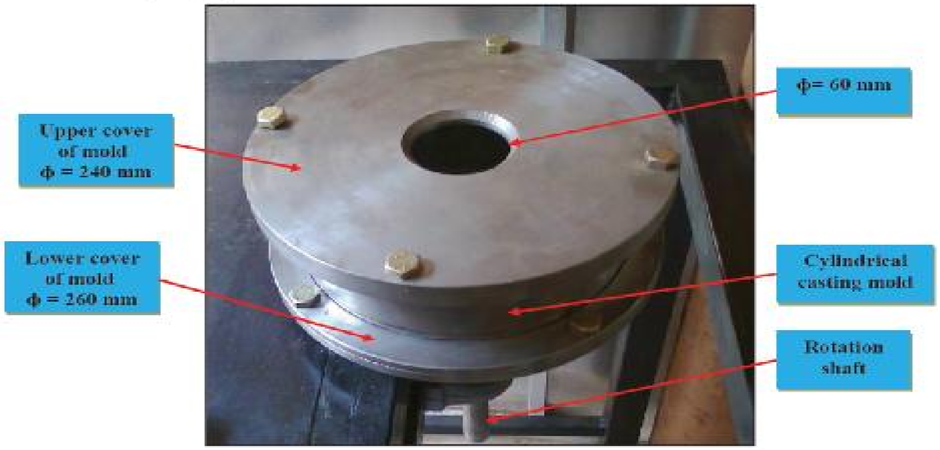


Figure (4): The cylindrical mold, rotation shaft, upper and lower covers of mold.

Determination of the Upper Cover Mass of Cylindrical Mold:

The upper cover mass of the cylindrical mold is determined by using equation (6):

$$V = \frac{\pi}{4}\left(D_{oc}^{2} - D_{ic}^{2}\right) * h_c \qquad \text{………… (6)}$$

Where,

D_{oc} = Outer diameter of the upper cover of cylindrical mold (m) = 0.24 m.

D_{ic} = Inner diameter of the upper cover of the cylindrical mold (m) = 0.06 m.

h_c = Height of the upper cover of the cylindrical mold (m) = 0.0174 m.

$V = \frac{\pi}{4}((0.24)^2 - (0.06)^2) * 0.0174$

$= 0.785\ (0.0576 - 0.0036) * 0.0174 = 7.375 * 10^{-4}\ m^3$.

$$M = V * \rho \qquad \text{..…….. (7)}$$

$M = 7.375 * 10^{-4} * 7800 = 5.7525$ Kg.

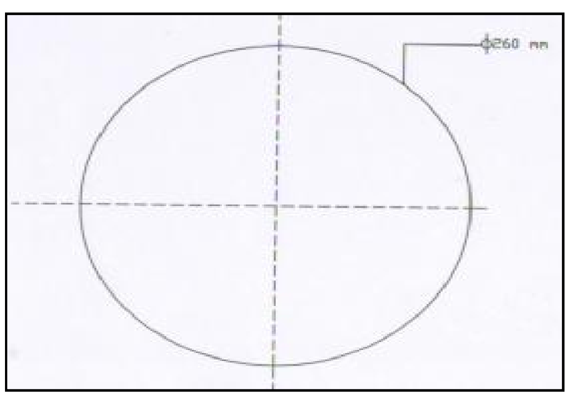


Figure (5): Dimensions of the upper cover of cylindrical mold.

Determination of the Turntable Mass:

The turntable mass is determinate by [9]:

$$V = \frac{\pi}{4} * D^2 * h_c \qquad \text{…………… (11)}$$

Where:

D = Diameter of the turntable (m) = 0.26 m.

h_c = Height of the turntable (m) = 0.0174 m.

$V = 0.785 * (0.26)^2 * 0.0174 = 9.2334 * 10^{-4}$ m³.

$M = V * \rho = 9.2334 * 10^{-4} * 7800 = 7.202$ Kg.

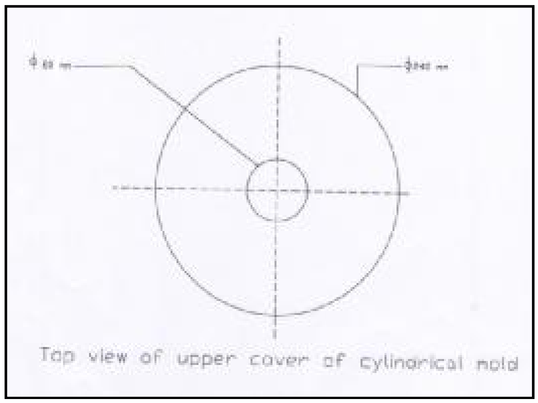


Figure (6): Dimension of the turntable.

Determination of Total Mass forMoldGroup:

The total mass of the mold of the centrifugal casting machine is determined by:

Total Mass = Cylindrical Mold Mass + Upper Cover Mass + Turntable Mass

So**,** Total Mass = 2.6566 + 5.7525 + 7.202 = **15.6111 Kg.**

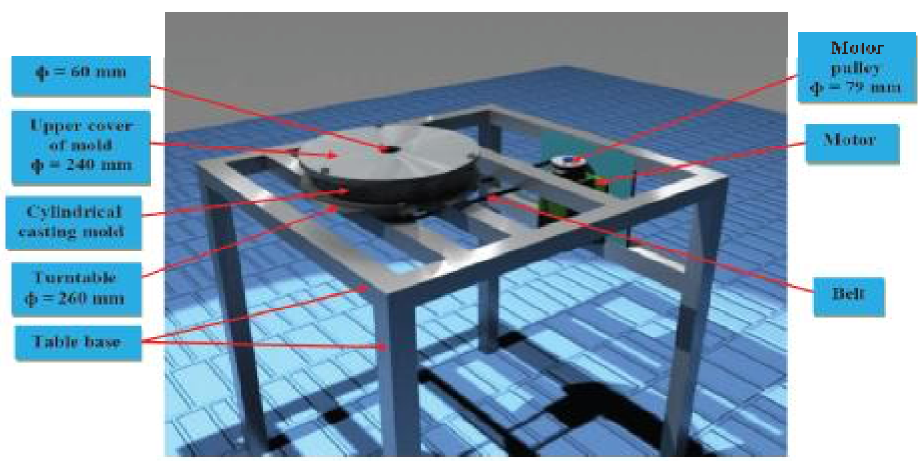


Figure (7): Schematic representation of the designed vertical centrifugal casting machine.

FG samples Preparation

Commercially pure aluminum (99.99 % Al) has been taken from electrical power wires. It has been machinedinto small parts manually. The weight of all quantities istaken by using digital sensitive balance. After that, the electrical melting furnace is prepared. The required melting temperature is controlled by a digital control system. Titaniumdioxide powder (TiO_2) with average particle size (0.421μm) is used as a reinforcement material with (5, 7.5 and 10wt %). There are two parameters studied in this work:

1. Pouring temperature.
2. Rotation speed of mold.

Commercially pure aluminum ismelted into a ceramic crucible using an electrical melting furnace that adjusted to (750˚C). The molten metal was alloyed according to the required percentages of TiO_2 particles that mixed by an electro-mechanical mixer. Then, the slag is skimmed manually.The first mixing process continues for one minute and then the furnace temperature has been adjusted to the required pouring temperature. At thattemperature, the second mixing process is done in two minutes with the same prime mixing rotation speed. The mixture is then poured intothe mold of the vertical centrifugal casting machine.

The vertical centrifugal casting machine is prepared before the starting with the melting process, the required rotation speed is determined through the change of inverter and pulse input unit (Tachometer).

The temperature of the mold is set at (400˚C). After the second mixing stage, the vertical centrifugal casting machine is prepared to work when the temperature of the pouring sprue reaches (300˚C). Pouring process has been done with different rotation speeds (1000, 1150, 1500 and 2100r.p.m) and different pouring temperatures (750, 800 and 850˚C) were used. After pouring process, the mold has been continuing with the rotation for two minutes. The mold is then stopped and the prepared FG cylinder samples have been getting out. Figure (8) shows the set of FG cylinders that prepared in this work. (See appendix (A)).

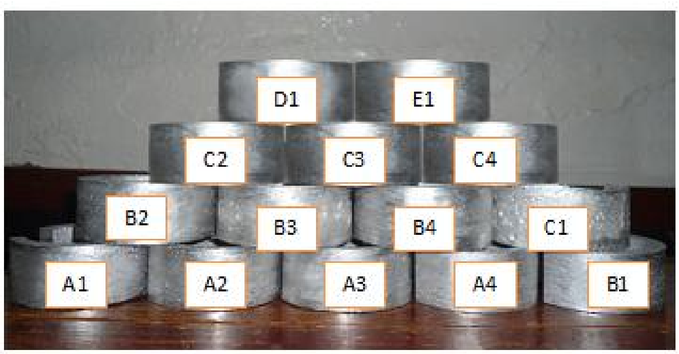


Figure (8): FG cylindrical samples.

FG cylinders Characterization

Manylab tests have been performed to characterize the prepared samples in this work:

Microstructure Test:

After finishing the preparing process, samples are machined from different locations of FG cylinders by milling machine as longitudinal samples with a length (5.8) mm, width (12) mm and thickness (10mm) from each sample. The samples are machined into smaller samples for microstructure investigations. Grinding and polishing and etching were performed on samples according to the ASTM E3-11.Microstructural observations were performed on a photo-microscope pattern type (XJP-H200) attached to a video camera.

Hardness Test:

In order to check the gradation of properties across the prepared FG cylinders, Brinell hardness test is used for that purpose. The test has been performed in accordance with ASTM E8-12. Four readings are taken for each point; the average is taken as a final reading.

Tensile Test:

The universal test machine, type (Instron 1195) is used for tensile testing after preparing samples with standard dimensions. The test was performed in accordance with ASTM E-8.

Wear Test:

FG cylindrical samples were prepared with a diameter (10) mm and length (30) mm from the prepared cylinders. These samples are grinded by using emery papers (320, 400, 600, 800, 1000 and 1200). Wear test is done by using (**Pin-on-disc**) apparatus. This apparatus contains electric motor which has a stable speed of (950) r.p.m and a disc of steel turning with a speed of (278) r.p.m.

The following steps are adopted to perform the wear test method:

1. Calculating the weight of the sample before the test (W_1).
2. Fixing sample with holder.
3. Fixing radius of rotation (r) in (7) cm.
4. Determining the load (5) N.
5. Using test time of (10) minutes.
6. After finishing the test operation, the samplehas calculated its weight for the second time (W_2).
7. Calculating wear rate according to the equation [10] :

$$\text{Volumewearrate}\,(gm/cm) = \Delta W \,/\, (2\pi rn\rho t) \qquad \ldots\ldots (12)$$

$$\text{Volumewearrate} = (W1 - W2) - (2\pi rn\rho t) \qquad \ldots\ldots(13)$$

Where:

W_1 = Weight of sample before the test (gm).
W_2 = Weight of sample after the test (gm).
r = Radius of rotation (cm).
n = Rotation speed of disc (r.p.m).
ρ = Density of material (gm/cm^3).
t = Test time (min).

X-ray Diffraction Test:

X-ray Diffraction (XRD) is a rapid analytical technique primarily used for phase identification. XRD has been obtained at the Ministry of Sciences and Technology-Iraq. X-ray diffractometer is used in this test. This test is taken for (TiO_2) material and FG samplesof rotation speed (2100r.p.m), pouring temperature (850̊C) and amount of TiO_2 (5, 7.5 and 10wt%) respectively.

Results & Discussion:

Hardness is related to components of functionally graded material and amount of each component and its property. Accordingly, the addition of titanium dioxide and the way of its distribution across the FG cylinder has a direct effect on the hardness as well as other mechanical properties. In addition the variables of centrifugal casting process play an important role in the distribution nature of titanium dioxide particles across the thickness. High rotational speeds (i.e. High centrifugal forces) are functioned to push the titanium dioxide particles toward the external surface of the FG cylinder while low rotation speeds encourage titanium dioxide to agglomerate at the internal surface. In other hand, high pouring temperatures will decrease the molten viscosity and support the action of centrifugal force in acceleration of titanium dioxide movement toward the external surface of the FG cylinder samples. It is observed from figure (9), that the minimum increment in hardness with pouring temperature increment is obtained at the titanium dioxide percent of (5) % and rotation speed (1000) r.p.m. Hardness values are (90.3 HB) and (94 HB) at pouring temperatures of (750˚C) and (850˚C) respectively.

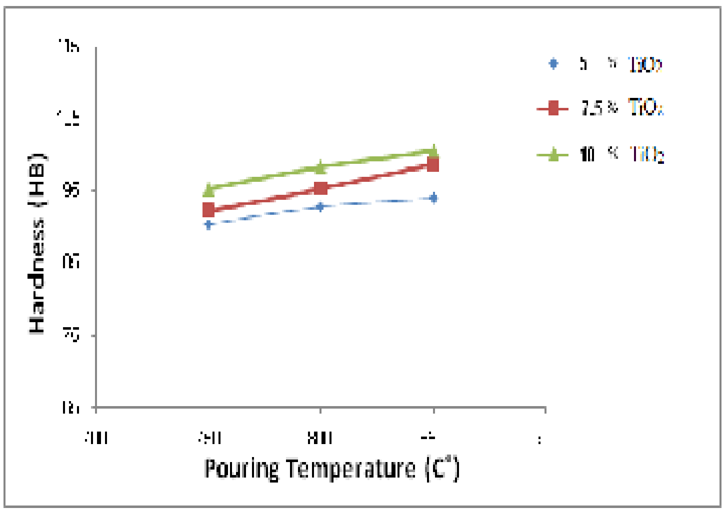


Figure (9): Hardness at different pouring temperatures and titanium dioxide amounts through the rotation speed of (1000r.p.m).

When the amount of titanium dioxide has increased to (7.5) % and the rotation speed steel (1000) r.p.m, higher improvement in hardness is observed as shown in figure (9). At pouring temperatures (750˚C) and (850˚C), the hardness values become (92.2 HB) and (98.6 HB)respectively. When(TiO_2) increases to (10) %, it is shown from figure (9), the hardness is increased dramatically with the increasing of pouring temperature while the rotation speed is still (1000) r.p.m. At pouring temperatures (750) ˚C and (850) ˚C, the hardness values become 95.1 HB and 100.5 HB respectively. The behavior of hardness property across the thickness as shown in figures (10) to (21) is of high importance. Generally, the behavior is almost linear in all samples.

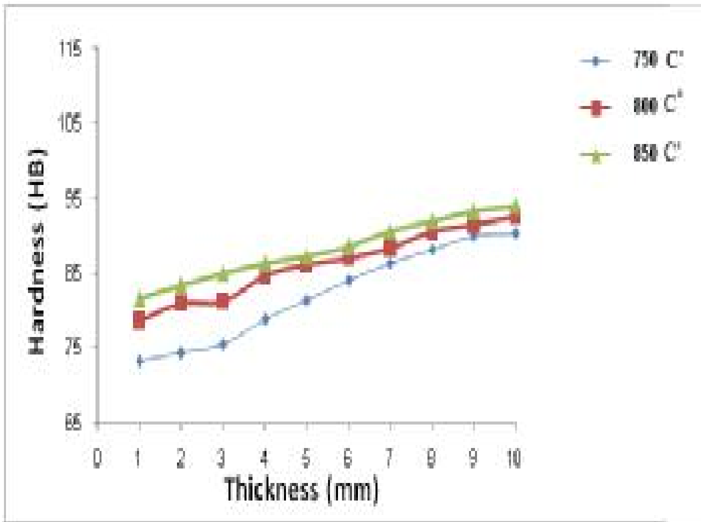


Figure (10): Variation of hardness with FG cylinder thickness and pouring temperature for addition of (5) % TiO_2 and rotation speed of (1000) r.p.m.

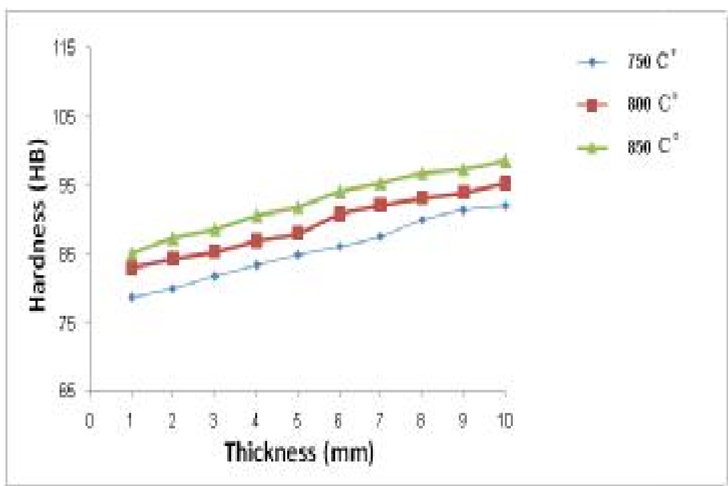


Figure (11): Variation of hardness with FG cylinder thickness and pouring temperature for addition of (7.5) % TiO_2 and rotation speed of (1000) r.p.m.

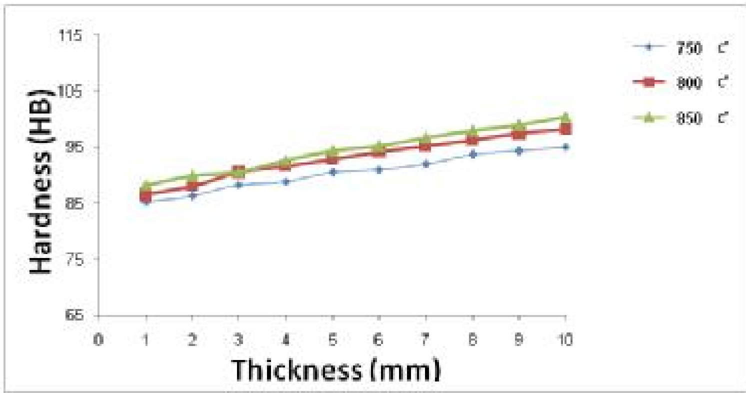


Figure (12): Variation of hardness with FG cylinder thickness and pouring temperature for addition of (10) % TiO_2 and rotation speed of (1000) r.p.m.

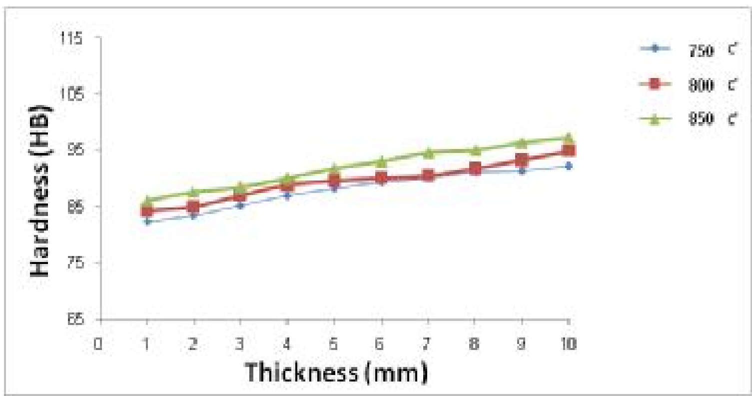


Figure (13): Variation of hardness with FG cylinder thickness and pouring temperature for addition of (5) % TiO_2 and rotation speed of (1150) r.p.m.

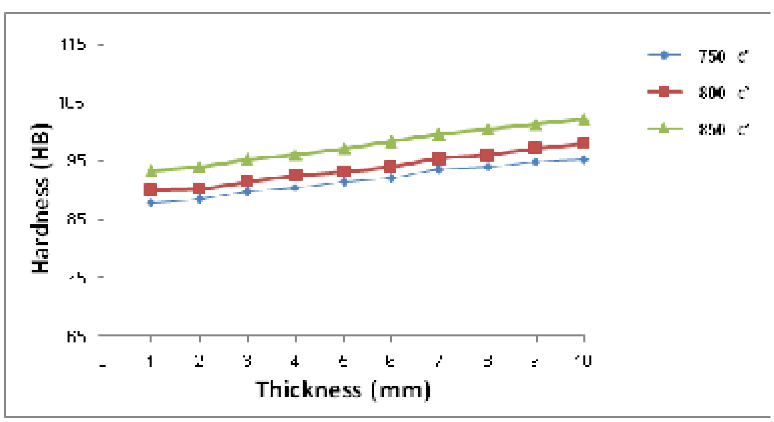


Figure (14): Variation of hardness with FG cylinder thickness and pouring temperature for addition of (7.5) % TiO_2 and rotation speed of (1150) r.p.m.

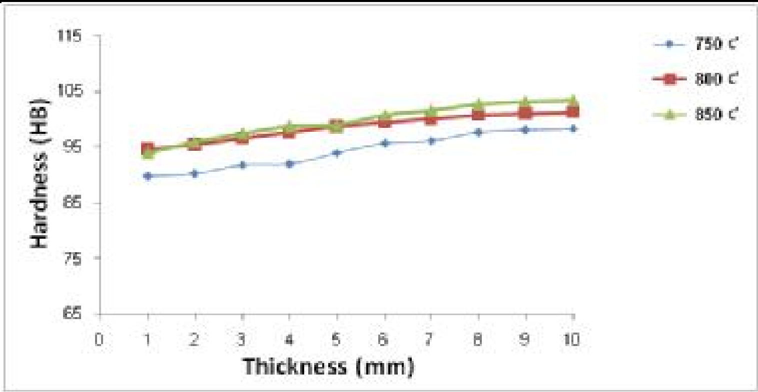


Figure (15): Variation of hardness with FG cylinder thickness and pouring temperature for addition of (10) % TiO_2 and rotation speed of (1150) r.p.m.

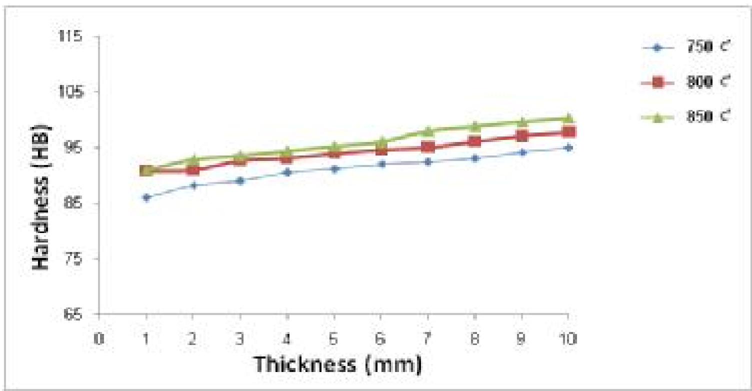


Figure (16): Variation of hardness with FG cylinder thickness and pouring temperature for addition of (5) % TiO_2 and rotation speed of (1500) r.p.m.

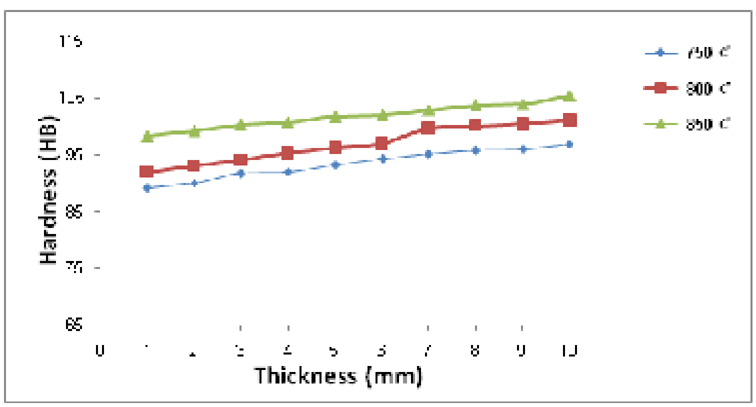


Figure (17): Variation of hardness with FG cylinder thickness and pouring temperature for addition of (7.5) % TiO_2 and rotation speed of (1500) r.p.m.

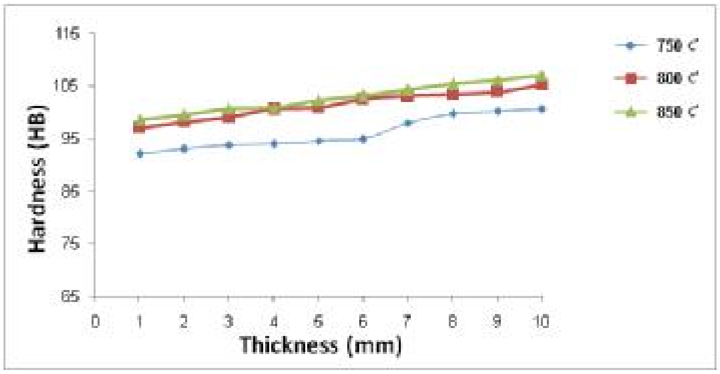


Figure (18): Variation of hardness with FG cylinder thickness and pouring temperature for addition of (10) % TiO_2 and rotation speed of (1500) r.p.m.

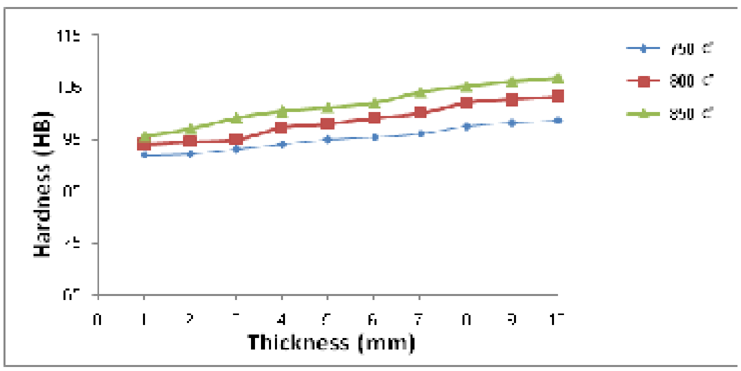


Figure (19): Variation of hardness with FG cylinder thickness and pouring temperature for addition of (5) % TiO_2 and rotation speed of (2100) r.p.m.

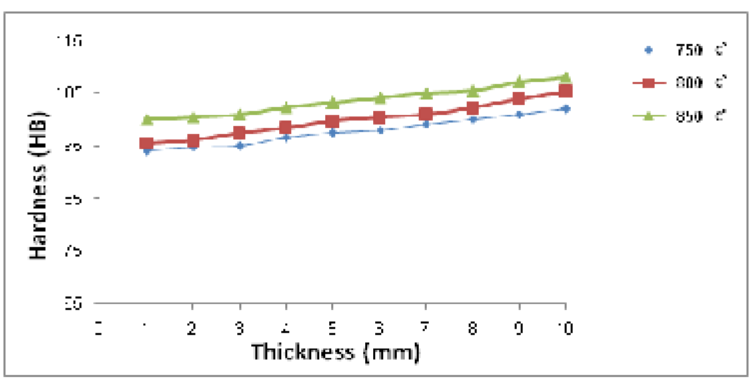


Figure (20): Variation of hardness with FG cylinder thickness and pouring temperature for addition of (7.5) % TiO_2 and rotation speed of (2100) r.p.m.

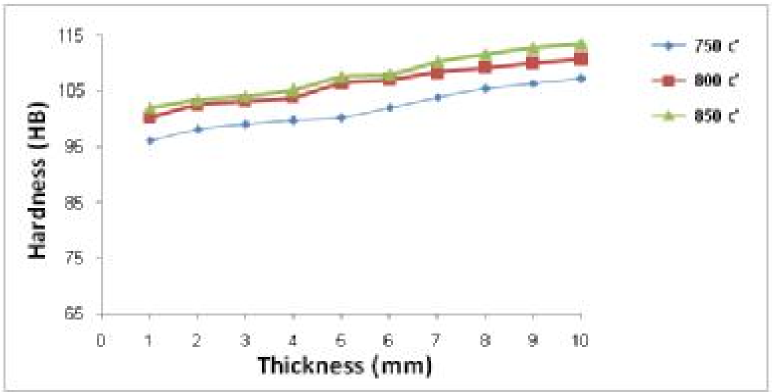


Figure (21): Variation of hardness with FG cylinder thickness and pouring temperature for addition of (10) % TiO_2 and rotation speed of (2100) r.p.m.

At rotation speed of (2100) r.p.m as shown in figures (19) to (21) as the wt% of TiO_2 is increased from 5 wt%, 7.5 to 10 wt%, the hardness linearly jumps by about 5 to 6 % increments. The reason behind such increment is the increasing of TiO2 concentration across the thickness due to the increment in centrifugal force as the rotation radius increased (i.e. increasing of sample thickness).Figures (22) to (25) show the relationship between centrifugal casting variables and tensile strength of FG cylinder samples. It is clear from these figures, that the tensile strength values are decreased generally with these variables.

The effect of (TiO_2), addition to (5) % and rotation speed (1000) r.p.m after pouring at different temperatures, is shown in figure (22). It is shown that tensile strength is decreased continuously with increasing of pouring temperature from (131) MPa to (126) MPa at pouring temperatures (750) ˚C and (850) ˚C respectively.

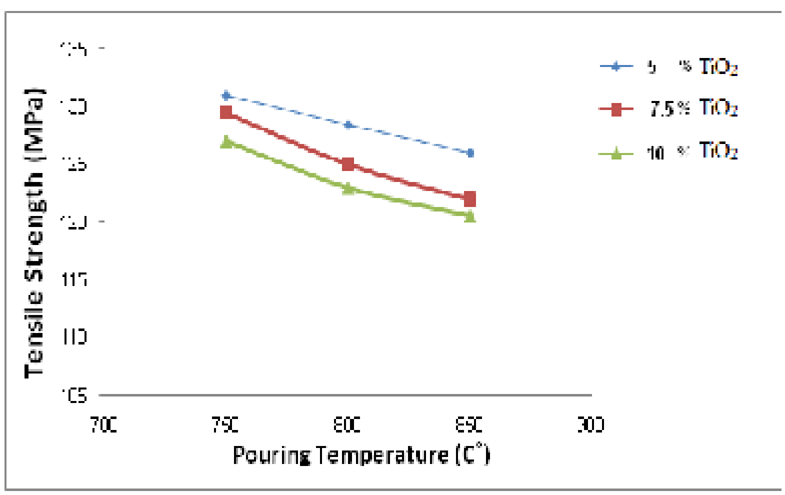


Figure (22): Tensile strength at different pouring temperatures and amounts of titanium dioxide and the rotation speed of (1000) r.p.m.

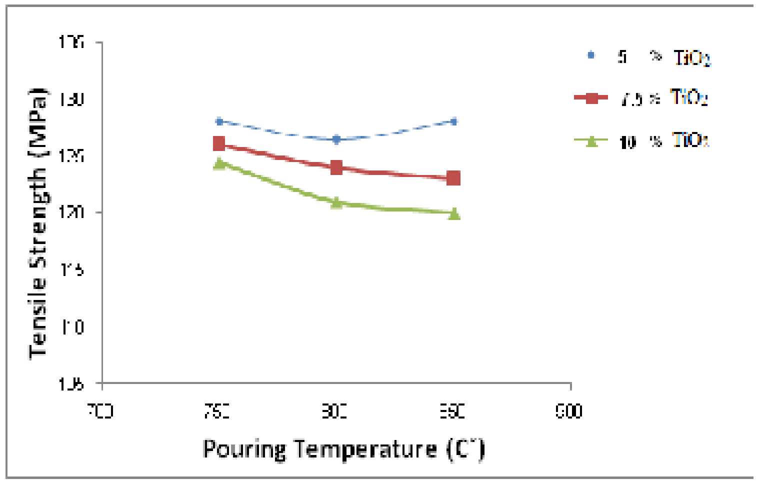


Figure (23): Tensile strength at different pouring temperatures and amounts of titanium dioxide and the rotation speed of (1150) r.p.m.

When the pouring temperature being (850) ˚C and (TiO_2) of (5) %, the tensile strength value is lower than value of tensile strength at (7.5) % because of the non-uniform agglomeration of titanium dioxide throughout the FG cylinder wall. For the same pouring temperature and (TiO_2) of (7.5) %, the tensile strength value is lower than value of tensile strength at (10) % for the same reason.(See figure (24))

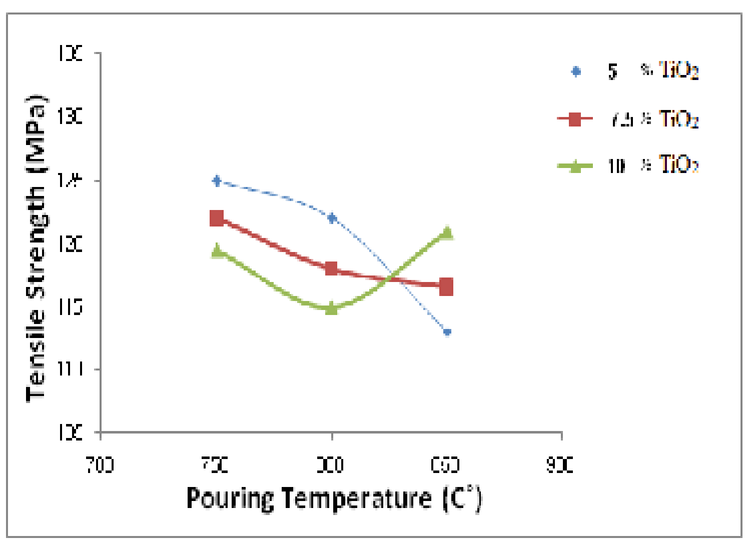


Figure (24): Tensile strength at different pouring temperatures and amounts of titanium dioxide and the rotation speed of (1500) r.p.m.

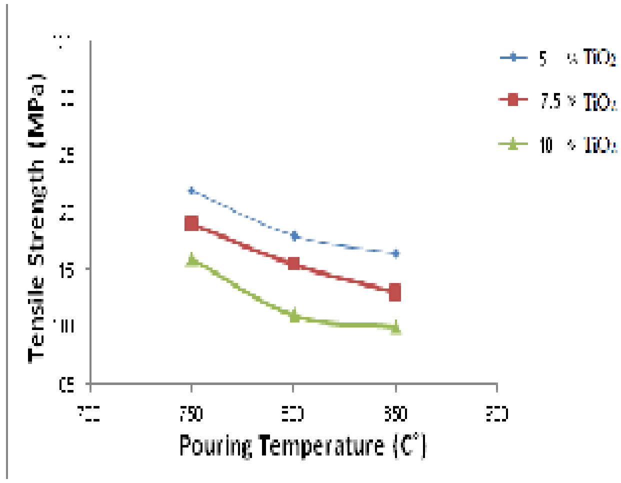


Figure (25): Tensile strength at different pouring temperatures and amounts of titanium dioxide and the rotation speed of (2100) r.p.m.

Figure (26) shows the wear rate as a function of the rotation speed of mold. Wear rate is decreased slightly as the rotation speed is decreased from (1000) to (2100) r.p.m at each of pouring temperature. The reason behind such behavior is the increasing of TiO_2 clustering distribution as the rotation speed increased. The pouring temperature has an impression in this evaluation and clearly a high pouring temperature sample (i.e. 850˚C) have a better wear resistance than that observed in the other pouring temperatures (750 & 800˚C).

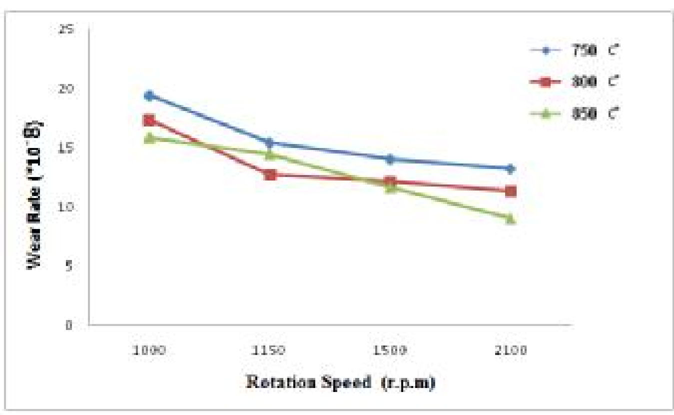
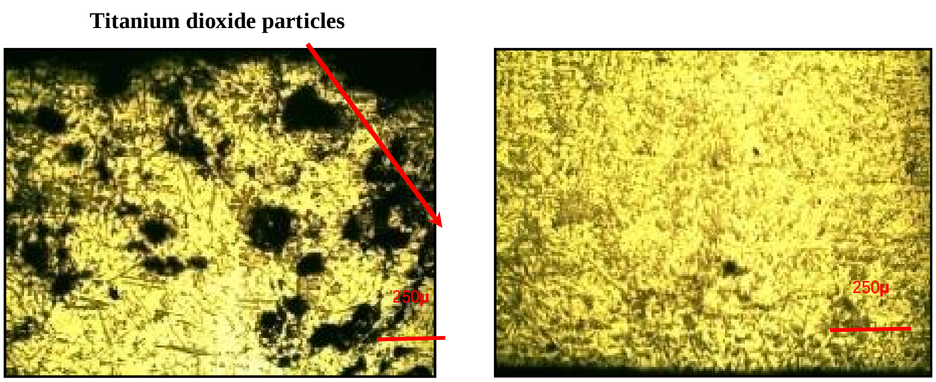
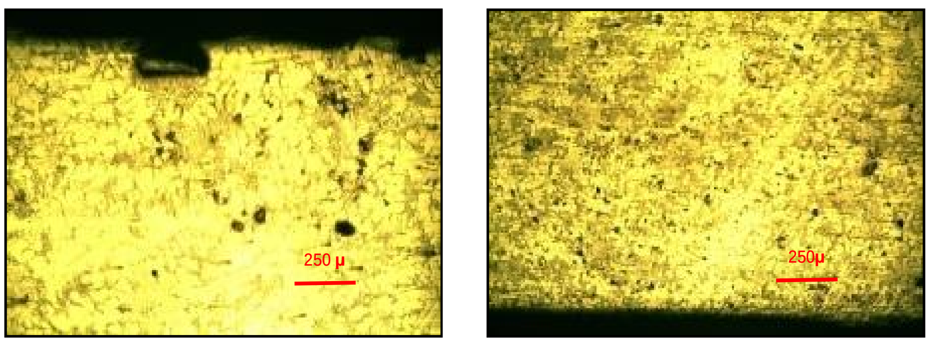


Figure (26): Wear rate at different pouring temperatures and rotation speeds through titanium dioxide percentage of (7.5) %.

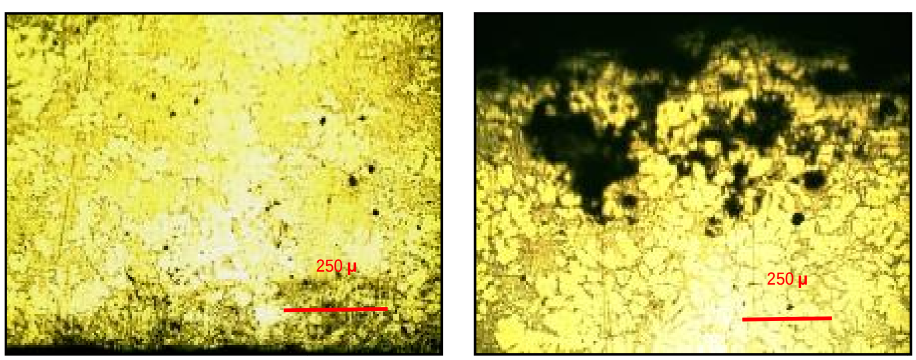
Figure (27) shows the shape of titanium dioxide particle distribution in (Al) matrix at pouring temperature (750) ˚C with titanium dioxide (7.5%) at different rotation speeds.



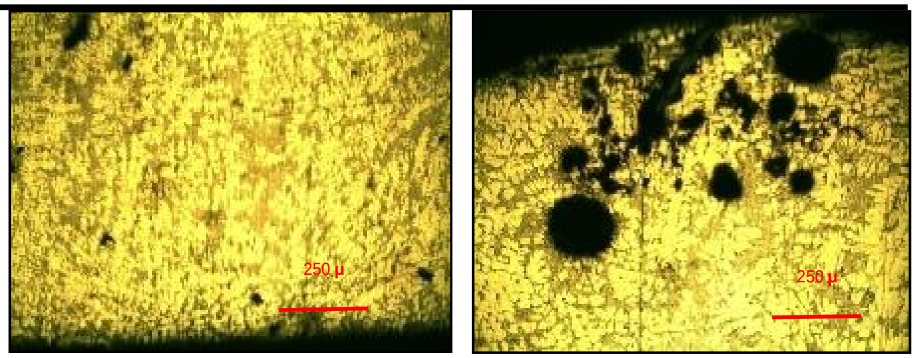
(A) Internal surface of cylinder at rotation speed (1000 r.p.m).
(B) External surface of cylinder at rotation speed (1000 r.p.m).



(C) Internal surface of cylinder at rotation speed (1150 r.p.m).
(D) External surface of cylinder at rotation speed (1150 r.p.m).



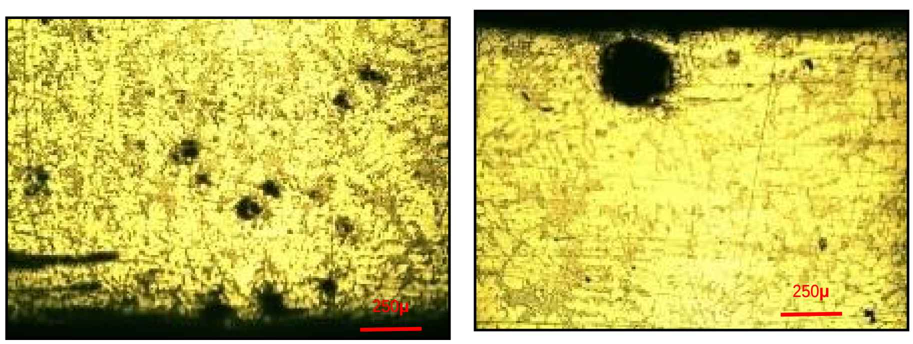
(E) Internal surface of cylinder at rotation speed (1500r.p.m).
(F) External surface of cylinder at rotation speed (1500 r.p.m) .



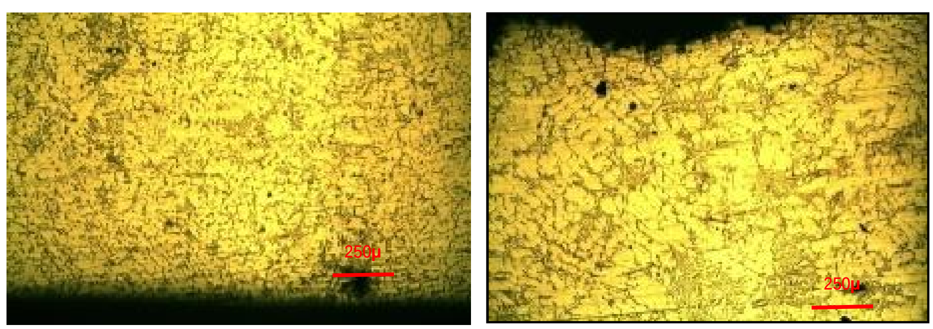
(I) internal surface of cylinderat rotation speed (2100r.p.m).
(J) External surface of cylinder at rotation speed (2100r.p.m) .

Figure (27): Shape of distribution of titanium dioxide particles in (Al) matrix at pouring temperature (750˚C), with titanium dioxide (7.5%) and with different rotation speeds.

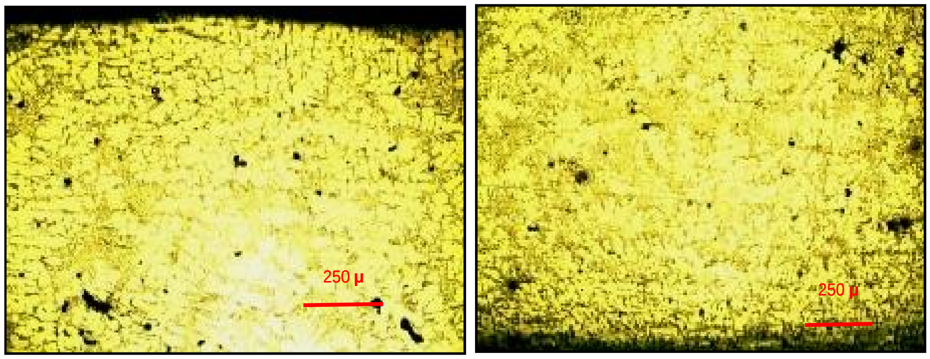
While, figure (28) shows the shape of titanium dioxide particle distribution in (Al) matrix at pouring temperature (750) ˚C with titanium dioxide (10) % and at different rotation speeds.



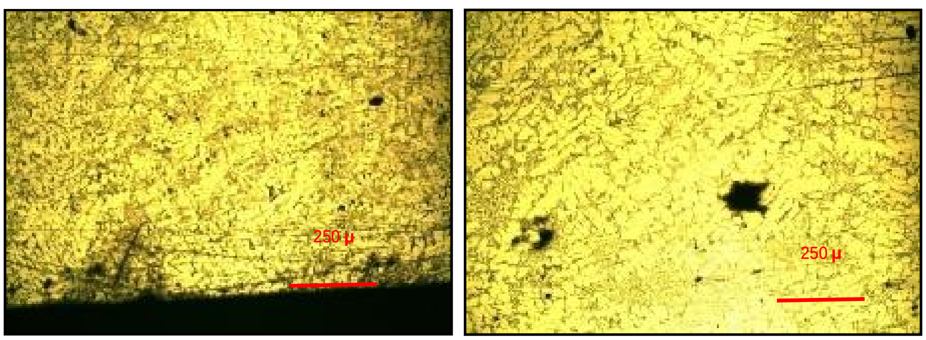
(A)Internal surface of cylinder at rotation speed (1000r.p.m).
(B) External surface of cylinder at rotation speed (1000r.p.m).



(C) Internal surface of cylinderat rotation speed (1150r.p.m).
(D) External surface of cylinder at rotation speed (1150r.p.m).



(E) Internal surface of cylinderat rotation speed (1500r.p.m).
(F) External surface of cylinder at rotation speed (1500r.p.m).



(I) internal surface of cylinderat rotation speed (2100) r.p.m.
(J) External surface of cylinder at rotation speed (2100) r.p.m.

Figure (28) : Shape of distribution of titanium dioxide particles in (Al) matrix at pouring temperature (750˚C), with titanium dioxide (10%) and with different rotation speeds.

The effect of pouring temperature (850) ˚C and rotation speed (2100) r.p.m is analyzed for three samples of FG cylinder using XRD to determine the phase developed as a result of the fabrication process. The XRD patterns of the FG cylinder samples are shown in figures (29, 30 and 31). The following interesting features are noted in each of three FG cylinder samples:

1. A unique crystalline phase is clearly visible (i.e. TiAl) which has a cubic structure at three angles (38.0˚), (43.8˚)& (49.8˚).
2. The absence of additional peaks indicates that no new crystalline phases have been formed except (TiAl) phase.

3. The (TiAl) phase intensity becomes very strong at the samples with (7.5%) TiO_2. (See figure (30)).

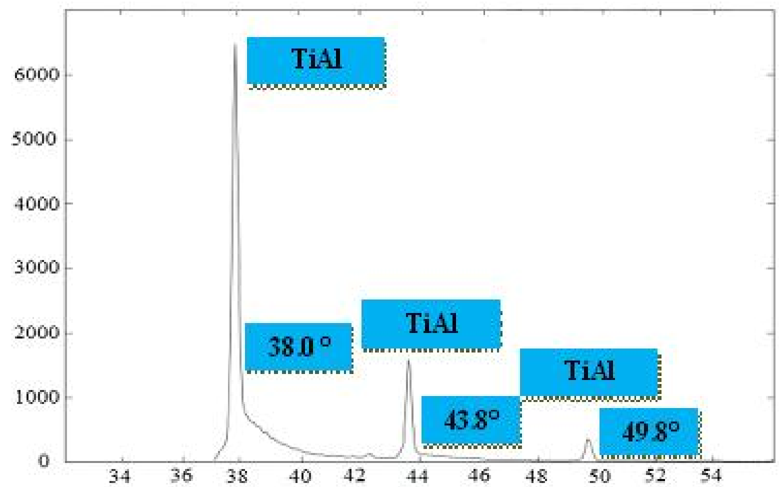
4. 

Figure (29) : XRD result of FG sample of rotation speed (2100r.p.m), pouring temperature (850˚C) and amount of (5%) TiO_2.

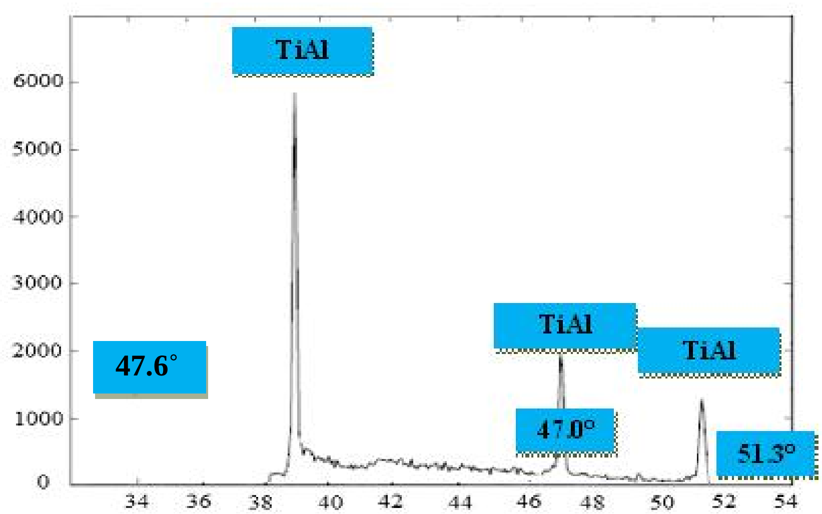


Figure (30) : XRD result of FG sample of rotation speed (2100) r.p.m, pouring temperature (850˚C) and amount of (7.5%) TiO_2.

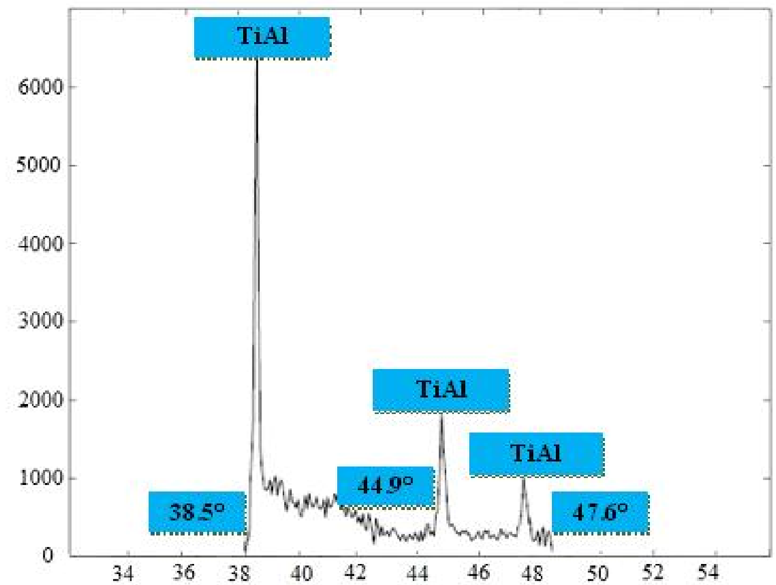


Figure (31): XRD result of FG sample of rotation speed (2100) r.p.m, pouring temperature (850˚C) and amount of (10%) TiO_2.

CONCLUSIONS

According to the results, the following points can be concluded:

1. High rotational speeds (i.e. High centrifugal forces) are very important to push titanium dioxide toward the external surface of the FG cylinder while low rotation speeds encourage the titanium dioxide to agglomerate at the internal surface.
2. Adding titanium dioxide (TiO2) to commercially pure aluminum increases the hardness values while it decreases the tensile force and wear rate.
3. Increasing of pouring temperature leads to increasing the hardness values while it decreases the tensile strength and the wear rate due to Hydrogen dissolving in the melt.
4. Titanium dioxide clusters are diminishing tensile strength too much. These clusters are worked as stress concentration areas and forming shrinkage and gaseous porosities among these clusters.
5. Decreasing the difference between pouring temperature and mold temperature leads to produce sound FG cylinder, with minimum defects and vacancies especially at the outside surface of the cylinder.
6. The increment in pouring temperature leads to decrease in wear rate for all rotation speeds.
7. Better graded hardness across the thickness of FG cylinder are obtained at rotation speed = 2100 r.p.m, pouring temperature = 850˚C and TiO_2= 10 %.
8. (TiAl) phase has been developed in each of FG cylinder samples poured at 850˚C and rotated with (2100 r.p.m). (TiAl) phase becomes so clear with high intensity in sample with (7.5 %) TiO_2.

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Appendix (A)

FG cylinder Symbol	Rotation speed (r.p.m)	Pouring temperature (˚C)	TiO_2 %
A_1	1000	750	5
A_2	1150	750	5
A_3	1500	750	5
A_4	2100	750	5
B_1	1000	800	5
B_2	1150	800	5
B_3	1500	800	5
B_4	2100	800	5
C_1	1000	850	5
C_2	1150	850	5
C_3	1500	850	5
C_4	2100	850	5
D_1	1000	750	7.5
E_1	1000	750	10