

Analysis of Micro Cracks and Die Erosion in Die Casting

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Analysis of micro cracks and die erosion in die casting

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Abstract:

Die soldering is a challenging issue on die life and casting quality in High Pressure Die Casting (HPDC) Industry. It increases die down time which causes increasing production cost per piece. Die soldering can be tackled by surface heat treatment operations like gas nitriding and other PVD coatings. Used and scraped die is selected from the die casting industry for investigation of die soldering issue. Chemical distribution of elements and surface condition of affected die soldering zone is investigated. The study reveals that, there are abundant micro cracks, micro holes and micro cavities at soldering portion. The radius of micro holes is about 0.25 μm and the radius of macro holes is about 8 μm . The die inserts are made up of H13 die steel and LM24 Aluminum alloy is used for casting operation. At the die soldering cross section region, distribution of aluminum and die soldering mechanism and its causes studied. The die soldering mechanism is classified as chemical, physical, mechanical and mixed soldering. The soldering phenomena have been researched based on die temperature and its chemistry, metal temperature and its chemistry, injection pressure and its velocity, and die surface roughness. The spread and formation of die soldering on used and scraped die is also discussed in this article.

Keywords: chemistry; die casting; die surface roughness; erosion; injection pressure; soldering; temperature.

Introduction:

The production cost per piece depends on the die life. Studies show that normal die life varies from 25000 cycles to 250000 cycles depending upon the design and complexity of the die (1) (2) (3) (4) (5). The production cost per piece can be reduced by increasing the die life. Die life is considered as total number of castings produced before its failure. Die may fail due to any one or combination of the following reasons like heat checks, chemical attack, soldering, mechanical erosion, thermal fatigue and mechanical stresses. Heat checking and die soldering are the two major factors which result in die failure (6) (7) (8) (9). Numerous past works have targeted principally on the heat checks (10) (11) (12) (13) (14). However, with the event of die casting trade, more and more consideration is being given to die bonding for a notable decrease in potency and productivity of die casting process. Recently some researchers have begun to review soldering mechanism by experimental work (15) (16) (17) (18) (19). However, die casting experiments in agreement with the particular production facilities will be terribly future and costly, so that some researchers have implemented many efficient experimental ways for work the attachment and the other phenomena within the facility (20) (21) (22) (23) (24). These strategies will be classified into 3 types: accelerated tests; friction welding and hot dip aluminizing. From the output of research work, the conclusions will be created that there are intermetallic compounds are produced within the die steel.

Different metallic element aluminum alloys presents a distinct bonding tendency towards the steel die. The bonding tendency of the casting to a given steel die will increase with the number of casting cycles (25) (26) (27) (28). Soldering increases simply with rise in metal temperature, die temperature, injection velocity, injection pressure and failure of die surface coatings (29) (30) (31) (32) (33). Die surface treatments and PVD coatings will effectively scale back the incidence of soldering (34) (35) (36) (37). However the data of die soldering remains sensor activity. No theoretical approach has been finalized to investigate the consequences of method parameters on causing soldering problem.

In this article, the surface conditions of the die and the distribution of chemical elements of soldering zone have been studied to analyze the soldering mechanism. Theoretical analysis of the results of method parameters on inflicting soldering are administrated by connected theory. Finally, the generation and unfold of soldering in a given die portion with the die casting process have additionally been investigated.

Experimental and Results:

Used and scraped die from the die casting company is taken to investigate the characteristics of the die soldering region. The die was employed to cast aluminum filter cover. The process parameters of the die are as follows:

Aluminum alloy grade: LM 24
Metal temperature : 670-720°C
Die temperature : 200-250°C
Gate velocity : 35-40 m/sec
Injection pressure : 80-100 MPa
Solidification time : 10 seconds
Die coat/lubricant : Chem. trend water base die coat (1:100) ratio.

The die portion with soldered aluminum is cut off from the die to study the surface condition of the soldered die. The solder die part is dissolved with 15% Caustic soda solution for 20 hours. Figure 1 (a) depicts the surface conditions of the soldered die at general position and (b) depicts the surface state near the gate location.

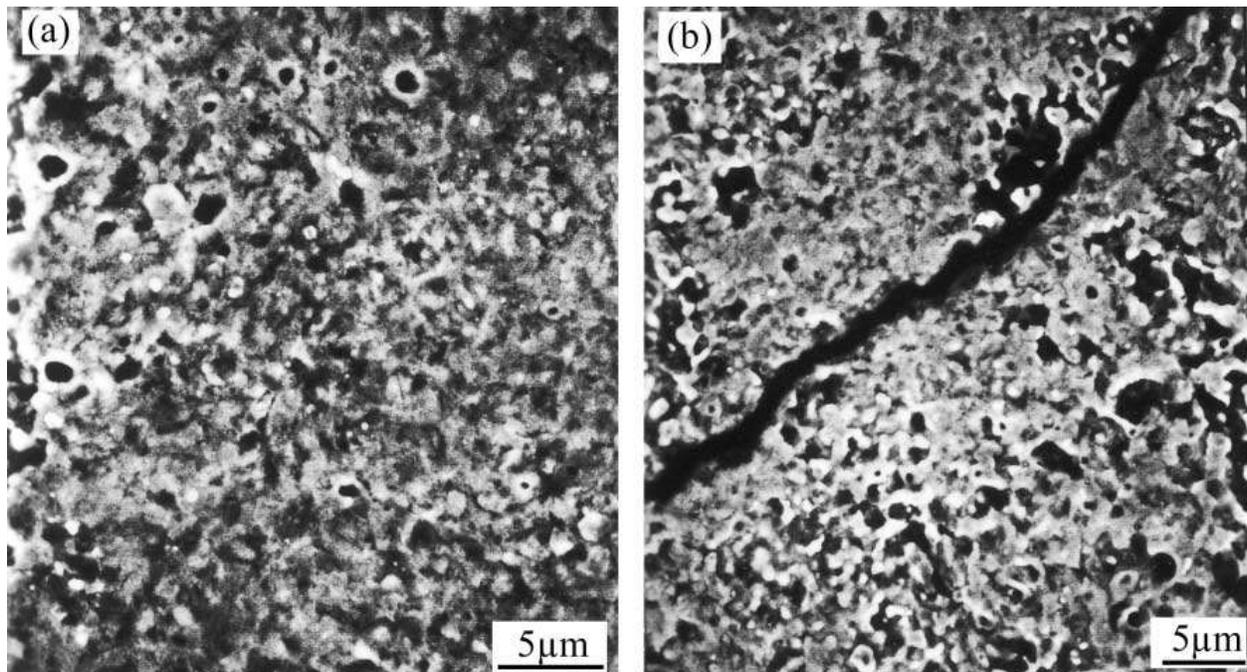


Figure 1. The surface condition of the soldered die: (a) general position in the die: (b) position near to gate location.

It is observed from Figure 1(a) that there exist various micro holes and micro cavities on the die surface. The radius of the tiny micro holes is about $0.25\ \mu\text{m}$ and the radius of large macro holes is about $8\ \mu\text{m}$. so the micro holes represents the character that intermetallic layers separates the die surface and therefore the micro cavities represents the character of small erosion. Die erosion near gate location is high while compare with general position in the die. There exist some cracks near the gate location as shown in Figure 1(b). Scanning electron microscopy (SEM) reveals the microanalysis of the soldering region as shown in Figures 2 and 3. Figure 2. Depicts that there exit a straight interface between the die and soldered aluminum. It indicates the chemical reaction between the casting and the steel die. The soldering is predominantly physico- chemical bonding. When the liquid metal enters and solidifies curved cracks present in the die, strong mechanical interaction takes place and results in mechanical soldering as depicts in Figure 3. However, the cracks with tiny sizes are flared, the mechanical interaction caused by micro

cavities and cracks are not strong enough that soldering occurs both chemical and mechanical action. Therefore soldering is classified as mechanical, physico- chemical and mixed soldering based on mechanism of soldering.

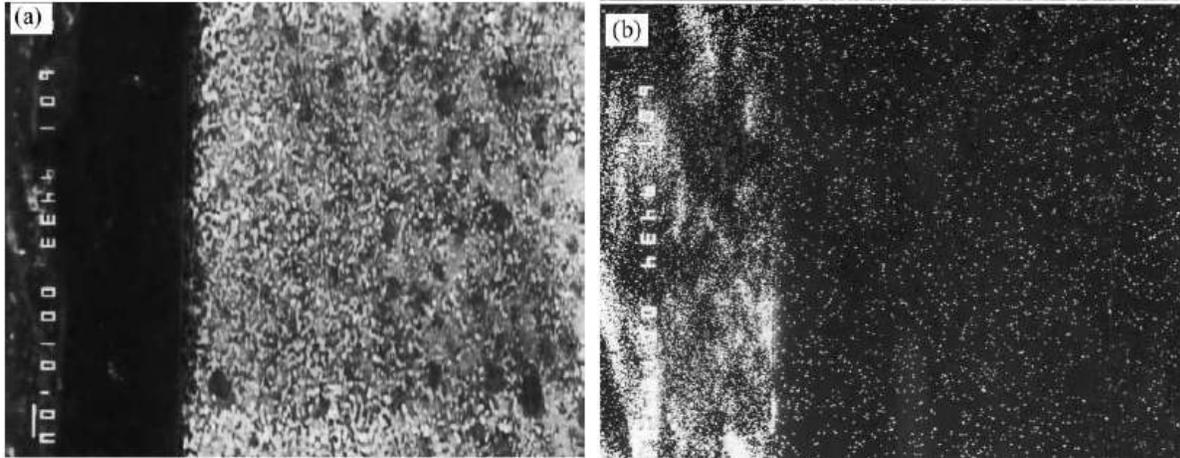


Figure 2. SEM analysis of physico- chemical soldering: (a) back scattered electron image (b) X-ray mapping of Al.

It is also noticed that most die surface parts with rich aluminum transition layers. The transition layer consists of intermetallic compounds which are the results of diffusion mechanism. The transition layer plays a vital role in soldering occurrences.

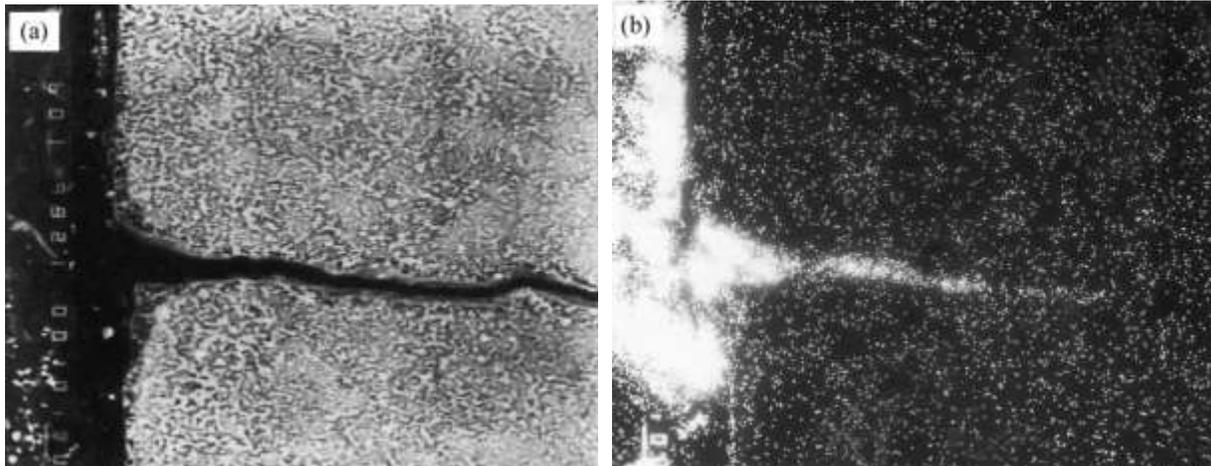


Figure 3. SEM analysis of Mechanical soldering: (a) back-scattered electron image: (b) X-ray mapping of Al.

During casting operation, molten metal is injected into the die cavity under high pressure and velocity. This activates atoms presents on the die surface and leads to breakage of atomic bonding. This result in aluminum atoms diffused with die atoms and forms atomic bonding. It is observed that most metallic bonds formed at high temperature still exist after solidification. Joint area is formed between the casting and die after casting cycle. Metallic bonds are produced, when there is interaction between atoms of molten aluminum and atoms of die steel. The atoms which gain constant activation energy are participated in bonding process. According to Maxwell-Boltsman law, the fraction of atoms in activation state to all interfacial atoms can be derived as:

$$f = \exp\left(-\frac{\Delta U}{RT}\right) \quad (1).$$

Where ΔU = constant activation energy of interaction.

f = fraction of atoms. It is sure that fraction of atoms (f) is directly proportional to the ratio of real contact area and apparent contact area between the casting and die surface.

That is $f \propto A_r/A_a$;

$$\text{Now equation (1) becomes } \frac{A_r}{A_a} = A_0 \exp\left(-\frac{\Delta U}{RT}\right) \quad (2).$$

When $\frac{A_r}{A_a} = 1$, A_0 can be obtained as:

$$A_0 = \exp\left(-\frac{\Delta U}{RT_0}\right)$$

Where T_0 = critical temperature, at which the casting bonds with the die. Then the equation (2) becomes

$$\frac{A_r}{A_a} = \exp\left\{-\frac{\Delta U}{R}\left(\frac{1}{T} - \frac{1}{T_0}\right)\right\} \quad (3).$$

The temperature of the liquid metal rises when it is injected on die surface under high velocity. An assumption is made that molten metal is injected on to the die surface at an angle of β and velocity of u . The vertical component of the velocity of metal is known as kinetic energy. This energy with a given mass (m) is change into heat energy of the metal. The rise in temperature of the liquid metal due to increase in kinetic energy is given as:

$$\Delta T = \frac{U^2 \cos^2 \beta}{2C_m} \quad (4).$$

Where C_m = specific heat of liquid aluminum. The gate area is constant for given die casting condition. The relation between injection pressure and filling velocity of liquid aluminum metal is expressed by Darcy equation:

$$u = C_d \sqrt{\frac{2P}{\rho_M}} \quad (5).$$

Where p = injection pressure

ρ_M = density of aluminum

C_d = coefficient for cold chamber die casting and is equal to 0.8.

The casting and die interface temperature can be expressed by the equation as:

$$T_i = \frac{b_M T_M + b_m T_m}{b_M + b_m} \quad (6).$$

Where T_M = Melt temperature

T_m = Die temperature

b_M and b_m = heat accumulation coefficient

The rise in interface temperature ΔT_i can be expressed as:

$$\Delta T_i = \frac{b_M}{b_M + b_m} \Delta T \quad (7).$$

Considering equations (5)-(7), equation (3) can be written as

$$\frac{A_r}{A_a} = \exp\left[-\frac{2c\rho(b_M + b_m)\Delta U}{2c\rho R(b_M T_M + b_m T_m) + R b_M C_d^2 \cos^2 \beta P} + \frac{\Delta U}{RT_0}\right] \quad (8).$$

Soldering of aluminum metal to the die surface is considered as adhesion of two different metals under pressure. The metallic bonds are formed by inter atomic forces exist between two metallic atoms caused by adhesive forces. The energies $\gamma\alpha$ and $\gamma\beta$ are required to break metallic bonds that exist between two solid metals α and β in contact on unit area, whereupon the interfacial energy is recovered. The energy needed to create die soldering can be expressed as (38).

$$\frac{A_r}{A_a} \geq \frac{2\gamma\alpha}{\gamma\alpha + \gamma\beta - \gamma\alpha\beta} \quad (9).$$

According to this expression, the ratio between real contact area and the apparent contact area between the casting and die is desperate factor which influences the soldering formation.

Figure 4. Depicts the effects of activation energy and temperature on A_r/A_a where $\Delta U_1 < \Delta U_2$. It is observed that the activation energy is vital element that influences the value of A_r/A_a , which is responsible for die soldering according

to the energy criterion of soldering. At the same interface temperature, a rise in activation energy tends to reduce in number of atoms in the activity station and a tremendous reduction in the value of A_r/A_a . Therefore, a rise in activation energy causes to decrease in soldering effect of the casting to the steel die. This can be used to explain the effect of alloy composition and die surface chemistry which results in soldering. Because the activation energy of interaction of Al-Fe is more than that of Al-Al. Increasing aluminum concentration on die surface results in increasing number of atoms that participated in soldering. Addition of iron (Fe) upto 1.3 wt% in the aluminum alloy reduces soldering tendency during casting process. The reason behind that is the activation energy of Al-Fe < than that of Fe-Fe. The separation of iron atoms from the liquid aluminum surface results in high concentration of iron atoms. The diffusion of iron atoms from die steel surface to the molten aluminum alloy can be prevented by high concentration of iron atoms in the alloy itself. Similarly, the activation energy of the interaction of Al-Fe is less than that of Al-Mo. The critical temperature T_0 is much greater than the die temperature. Therefore the soldering resistant ability can be obtained by laser melted molybdenum coating on the die surface.

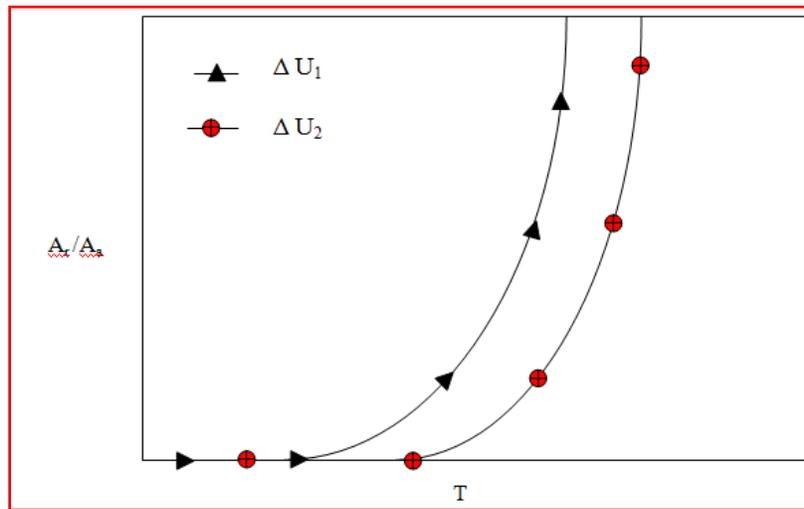


Figure 4. Effect of temperature (T) and activation energy (ΔU) on A_r/A_a .

It is observed from Figure 4. The interfacial temperature is vital factor that influences the value of A_r/A_a . At starting, the value of A_r/A_a is small with respect to temperature (T). However, when the temperature increases to meet the critical temperature T_0 , the value of A_r/A_a increases suddenly. The temperatures of both the die surface and the interface depend on liquid metal pouring temperature and the heat transfer condition. The soldering occurs rarely, when the die temperature is low. Soldering occurs easily at hot spots, where the die temperature is very high. This has been verified during casting process.

Injection pressure is one more factor that aggravates the soldering formation. The effects of injection pressure on soldering occurrences include two parts namely chemical action and mechanical action. High pressure and velocity of injected molten metal on to the die surface causes partial wash out of coating material on the die surface. This result in direct attack of molten metal with die steel surface. The mechanical action of injection pressure increases the value of A_r/A_a . High injection pressure increases the alloy energy and the number of active atoms that causes soldering formation. Therefore the value of A_r/A_a rises with the chemical action of the injection pressure.

Figure 5. Demonstrates the effect of injection pressure on A_r/A_a where P_2 is two times as greater as P_1 . It is evident that the value of A_r/A_a is more at high pressure at the same temperature. So die soldering occurs very easily under high injection pressure.

The wetting process of liquid metal happens on the die surface due to surface tension, when the liquid metal is injected in to the die cavity. The wettability is always demonstrated by contact angle θ . The wettability is perfect, when the contact angle is zero. However, the solid surface is completely dry, when the contact angle is 180° . The solid surface is partially wetted, if the contact angle is in between $0-180^\circ$. The smaller contact angle results in better wetting. The value of contact angle between the die steel surface and the liquid aluminum represents the soldering tendency of the aluminum with the steel die.

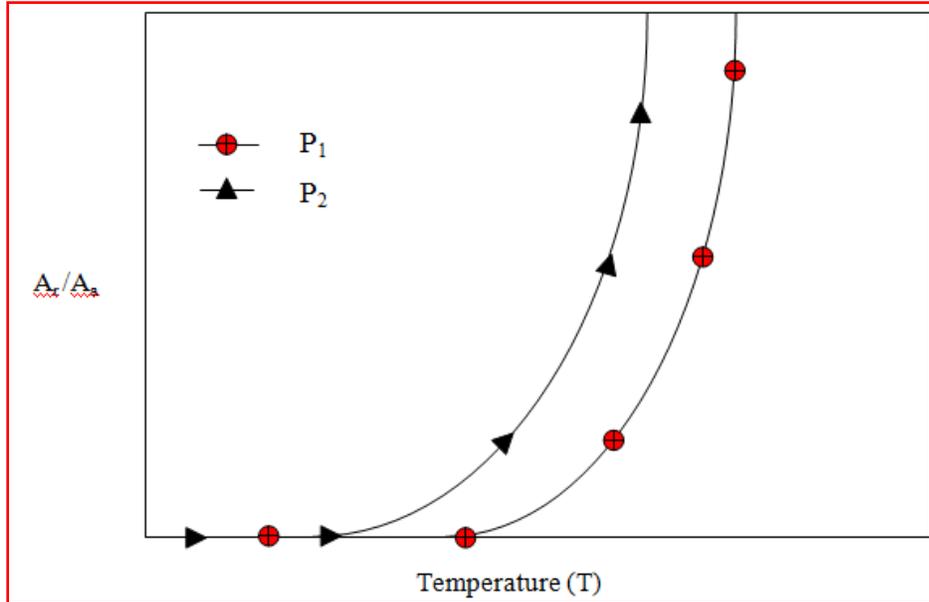


Figure 5. depicts effect of injection pressure on the value of A_r/A_a .

In aluminum die casting, there is a contact angle hysteresis between the die surface and the molten aluminum. The major factors that affects hysteresis contact angle are solute deposition on the die surface, surface roughness and molten metal. A contamination point still exists, even if the die lubricant is partially washed out from the die surface. It has been experimented (39) (40) that the influence of surface contamination on the contact angle hysteresis is equal to that of a rough surface. The contact angle hysteresis of a random rough surface of the die by molten aluminum metal and the wettability is discussed here. The roughness coefficient (r) for the rough surface is defined as the ratio of the real contact area to the apparent projective area. The relation between the apparent contact angle θ_a and the real contact angle θ_c is given by Wenzel as:

$$\cos \theta_r = r \cos \theta_a \quad (10).$$

A rough surface consists of small pieces of different materials is consider as a compound surface. By assuming that the die compound surface consists of two kinds of flat surfaces with the fractions to the apparent projected area are f_1 and f_2 respectively. The apparent contact angle is expressed as:

$$\cos \theta_c = f_1 \cos \theta_1 + f_2 \cos \theta_2$$

Where θ_1 and θ_2 are the real contact between the two kinds of flats and the liquid. Gas always obstructs the large size holes on the die steel surface by the liquid aluminum metal. This cannot occur by the smaller size holes on the die surface due to surface tension. If f_2 is the fraction that cannot contact with the molten aluminum, θ_2 is equal to 180° and the expression changes into the following form:

$$\cos \theta_c = f_1 \cos \theta_1 f_2 \text{ and considering } f_2 = 1 - f_1, \text{ the equation can be obtained as:}$$

$$\cos \theta_r = r f_1 \cos \theta_1 + f_1 - 1 \quad (11).$$

When $f_1 = 1$, that is the die surface contacts with liquid aluminum perfectly without obstructing gas, the result of the surface roughness on the apparent contact angle between the iron and the liquid aluminum or WC-Co and the molten aluminum is depicts in Figure 6(a). If $f_1 = 0.8$, when the liquid aluminum obstructs gas on large size valleys, the relation between the surface roughness of the two contact systems and the apparent contact angle is depicts in Figure 6(b). The apparent contact angle is less than 90° , when the die contacts with the liquid aluminum. It is observed that the apparent contact angle decreases with increase in the surface roughness coefficient. The apparent contact angle between WC-Co and liquid aluminum is more than 90° and increases with increase in the surface

roughness coefficient. However the soldering tendency with WC-Co coated die is less than when compared to steel die.

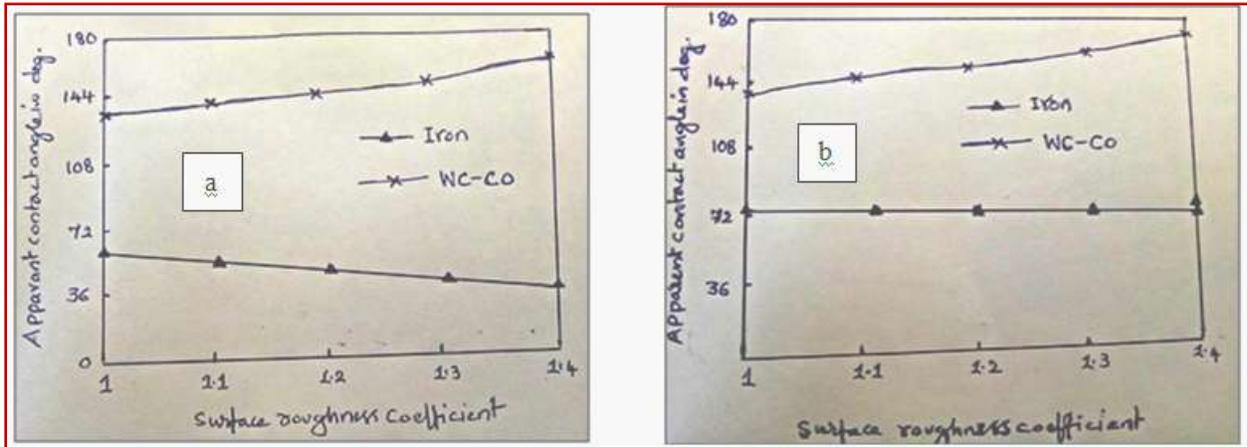


Figure 6. Apparent contact angle between solid surface and aluminum melt vs. surface roughness coefficient: (a) $f_1 = 1$; (b) $f_2 = 0.8$.

Comparing Figure 6 (a) and (b), It is noticed that the apparent contact angle of obstructing gas is higher than that of full contact even though the roughness coefficients are the same. This demonstrates that the contact angle hysteresis increase with increasing number of micro cavities and micro holes on the die steel surface.

An experiment is conducted in the die casting plant with high gate velocity of 150 m/sec and high pouring metal temperature of 750°C. In this experiment soldering takes place after only one or two shots to H13 steel die without any coating and die lubrication agent. This reveals that the interfacial temperature is very near to the critical temperature T_0 . This causes strong chemical reaction between the steel die surface and molten metal. The soldering occurs after second shot due to the oxide films on the die surface have been washed out by the first shot. But in actual practice, the gate velocity, pouring molten temperature and the die temperature is lower and die is also protected by die lubricant which form thin layer on die surface. This thin layer acts as barrier between the die surface and molten metal and thus prevents occurrence of die soldering. On the other hand, if there is any hot spot in the die, the lubricant layer is detached / washed off from the die and causes direct contact of molten metal with die surface. This results in die soldering formation. This is demonstrated in the Figure 7. At the beginning no soldering occurs at the die surface. As the number of casting cycles keeps on increasing, the aluminum atoms from the liquid metal diffuses into the die surface and the iron atoms from the die dissolves in the melt. The aluminum atoms concentration on the die slowly increases. When it reaches a threshold value, chemical reaction will occur between the die and molten metal and leads to soldering. An intermetallic compounds are formed and grown, which are washed out by high pressure of molten metal. Micro cavities and micro holes are formed and grown by erosion of the liquid metal. With the continuation of die casting process, heat checks are formed on the die which results in mixed soldering. This heat checks grows and leads to crack propagation. This crack propagation causes die failure and finally withdrawn from the production service.

The formation and spread of soldering in the die with protective coating is different from the die without protective coating. Figure 8. Demonstrates the condition of the die with protective coating. The coating is so strong and cannot be washed out easily with the injection pressure of the metal. According to energy analysis [18] the chemical reaction between the molten metal and the die with coating is very low and hence the tendency of soldering formation is very low or nil. However with increasing casting cycles, micro cracks are produced in the coating. Once these cracks are propagated into the die, the coating detached from the die. This result in the die cannot be used for further production and finally withdrawn from the service.

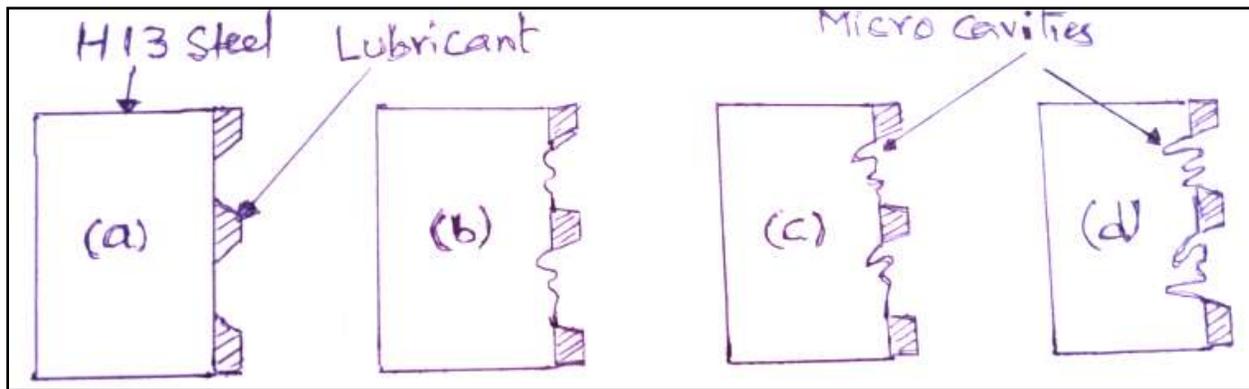


Figure 7. Shows the surface state change of the die without die coatings (PVD) in die casting process.

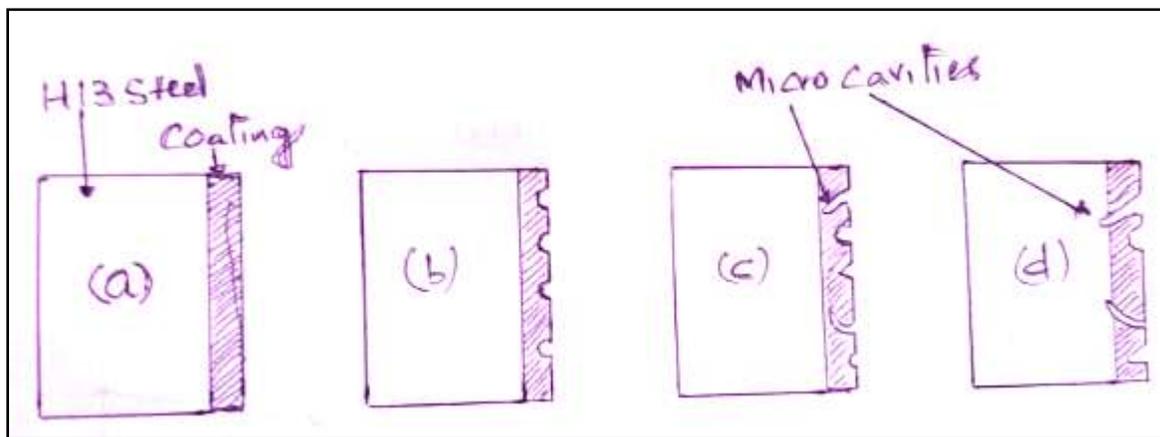


Figure 8. Shows the die surface state with coatings (PVD) in die casting process.

Conclusions:

- Large number of micro cavities, micro holes, micro cracks are observed at soldering portion of the die steel surface. These surface imperfections are responsible for mechanical action between the molten metal and the die and causes chemical reaction at the given apparent contact area.
- Soldering is grouped into three types namely mechanical, physico-mechanical and mixed soldering based on mechanism of soldering.
- The activation energy of interaction between the die and the casting and the interfacial temperature strongly influence the value of A_r / A_a .
- Die with special protective coatings are less affinity to soldering formation.
- The roughness coefficient of the die surface increases w.r.t increase in number of casting cycles. This results in decrease in the apparent contact angle between the die and the liquid metal.

Declarations:

- List of abbreviations:
Not applicable
- Availability of data and materials

- Not applicable
- Competing interests
Not applicable
- Authors contributions
M.Bhaskar- carried out original work
Tamil Nalluswamy- editing and drafting

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Figures

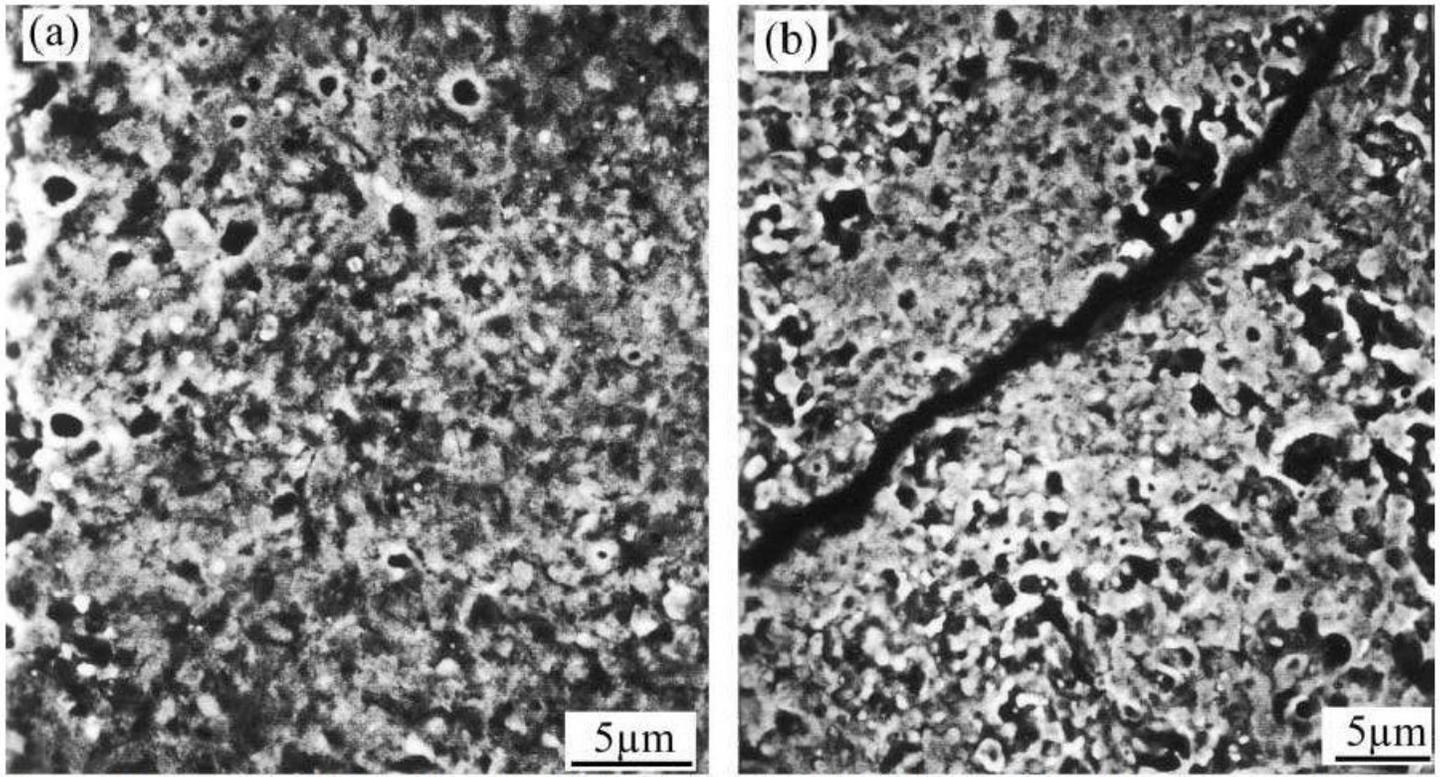


Figure 1

The surface condition of the soldered die: (a) general position in the die: (b) position near to gate location.

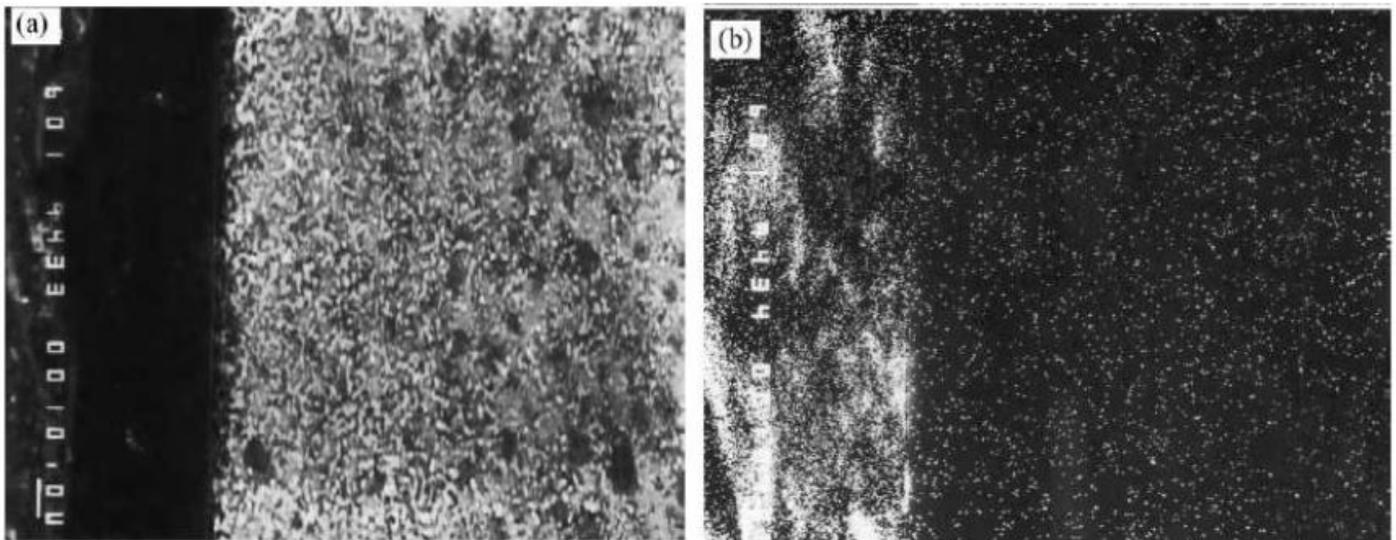


Figure 2

SEM analysis of physico-chemical soldering: (a) back scattered electron image (b) X-ray mapping of Al.

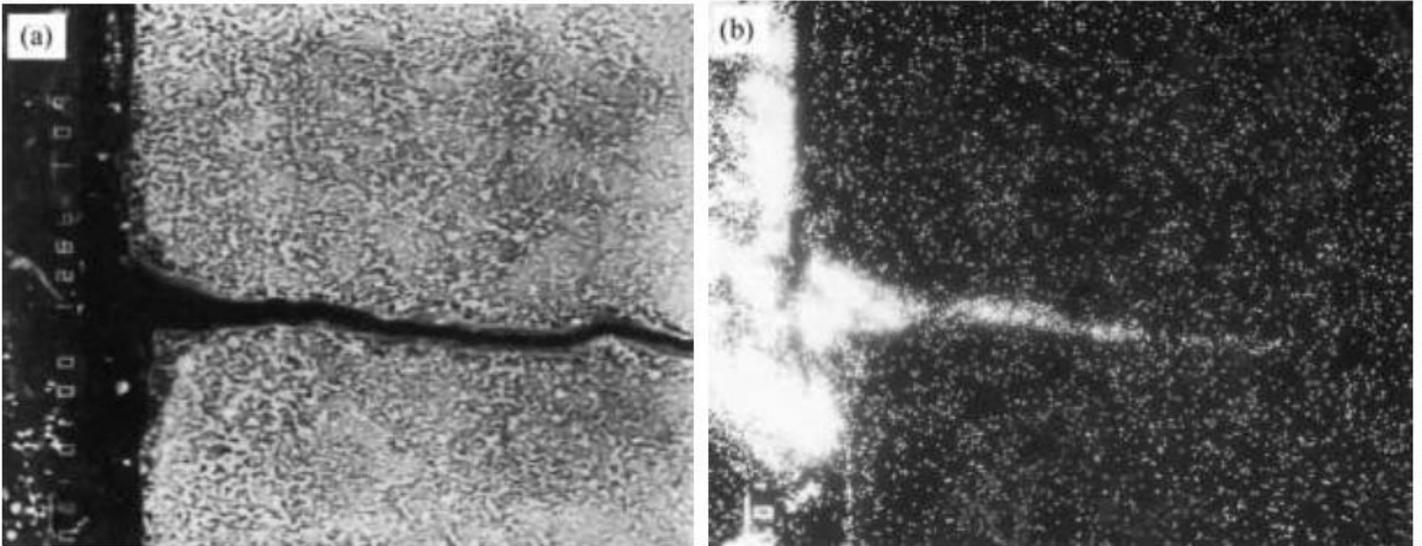


Figure 3

SEM analysis of Mechanical soldering: (a) back-scattered electron image: (b) X-ray mapping of Al.

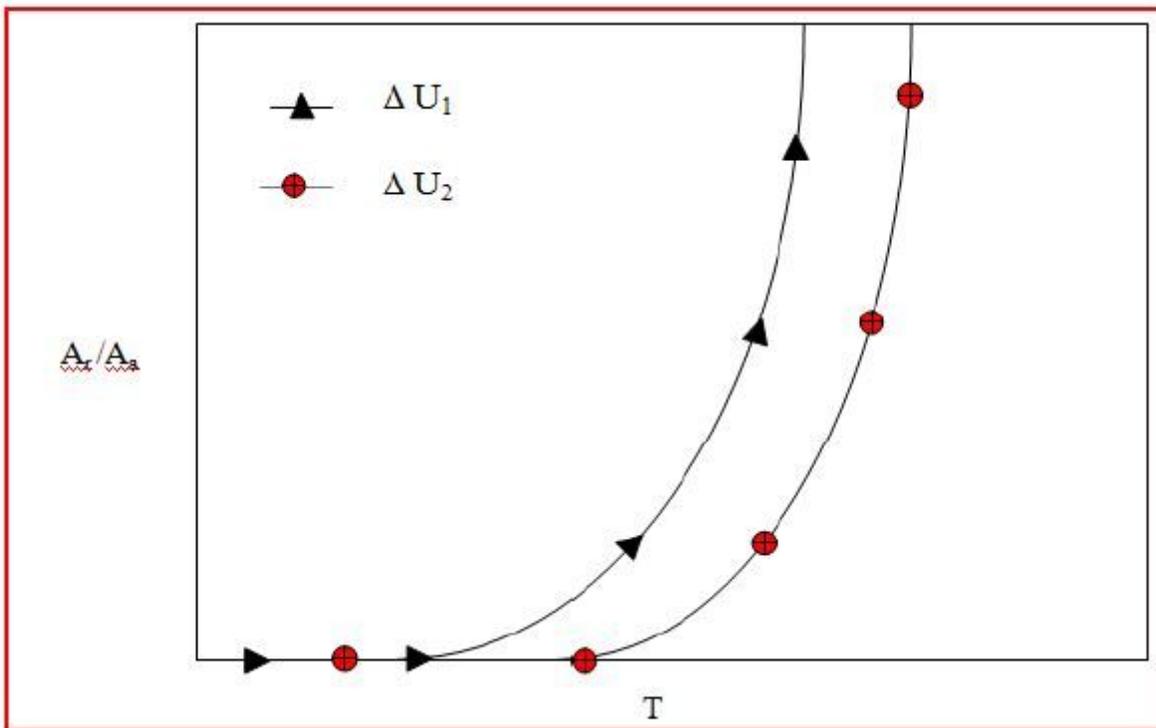


Figure 4

Effect of temperature (T) and activation energy (ΔU) on A_x / A_a .

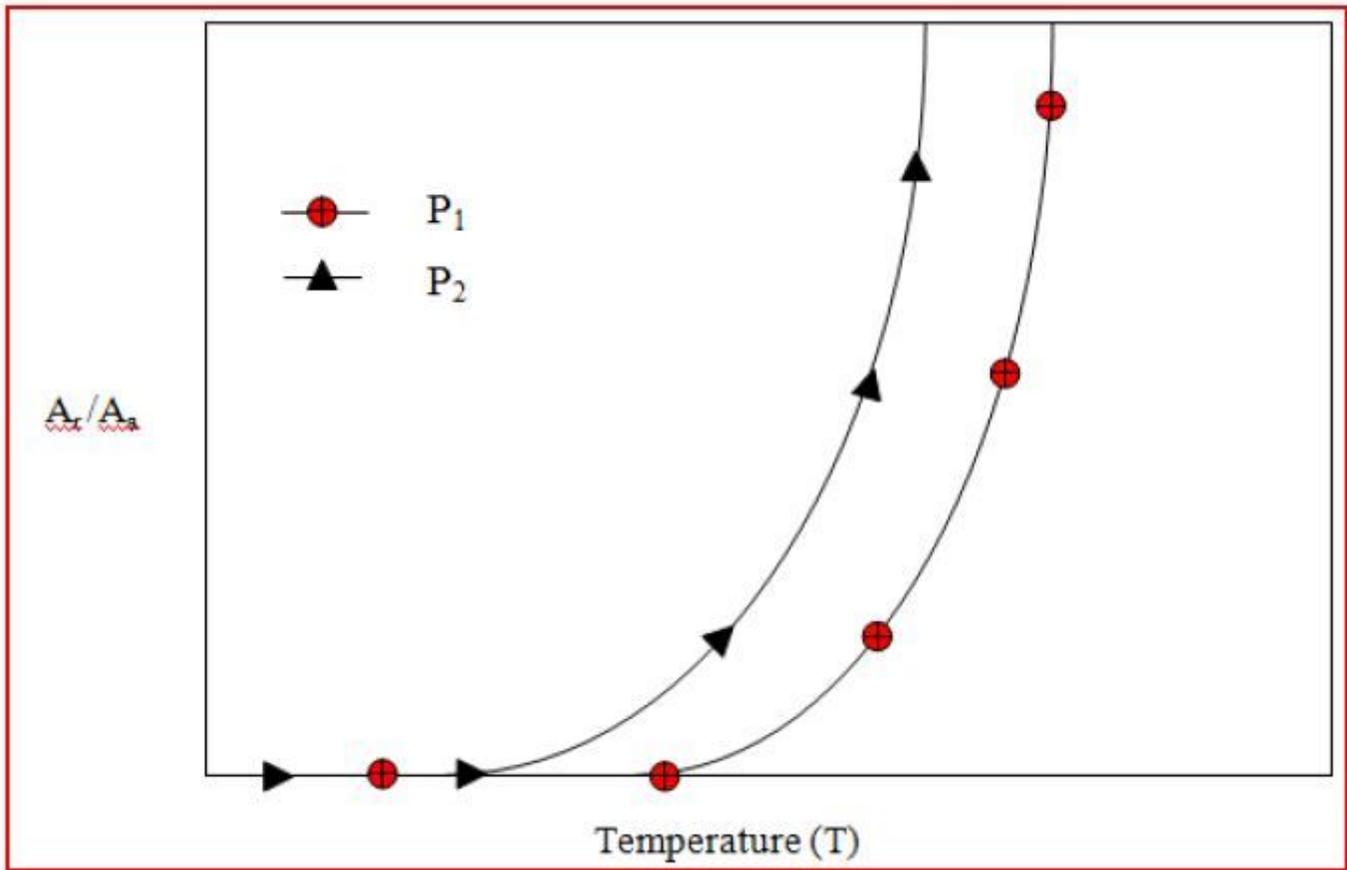


Figure 5

depicts effect of injection pressure on the value of A_r/A_a .

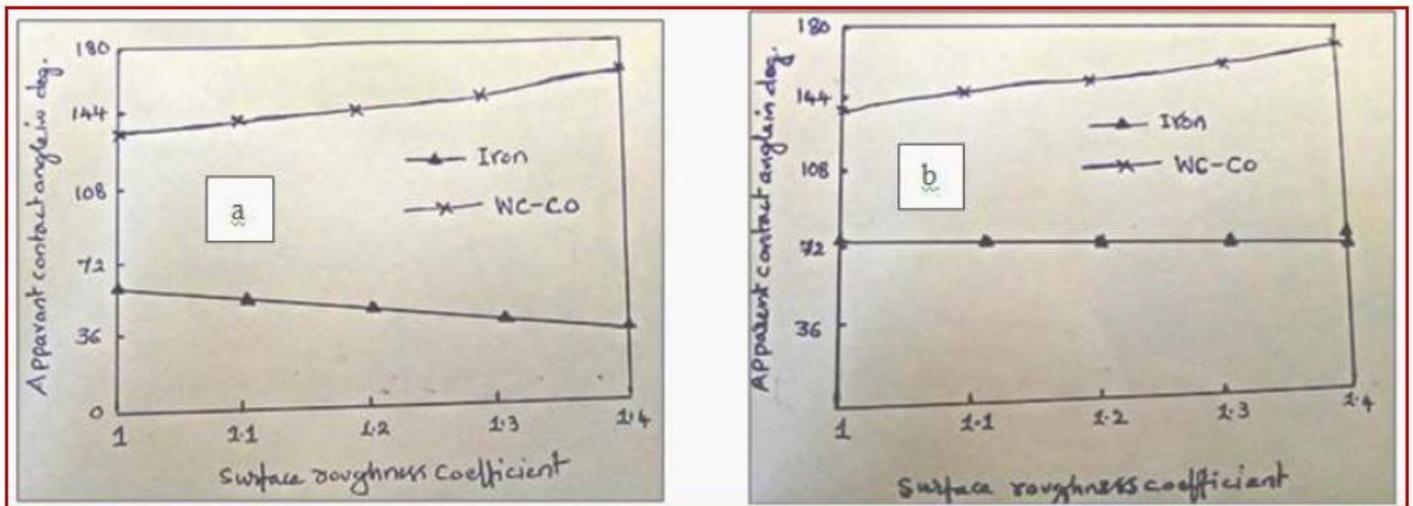


Figure 6

Apparent contact angle between solid surface and aluminum melt vs. surface roughness coefficient: (a) $f_1 = 1$; (b) $f_2 = 0.8$.

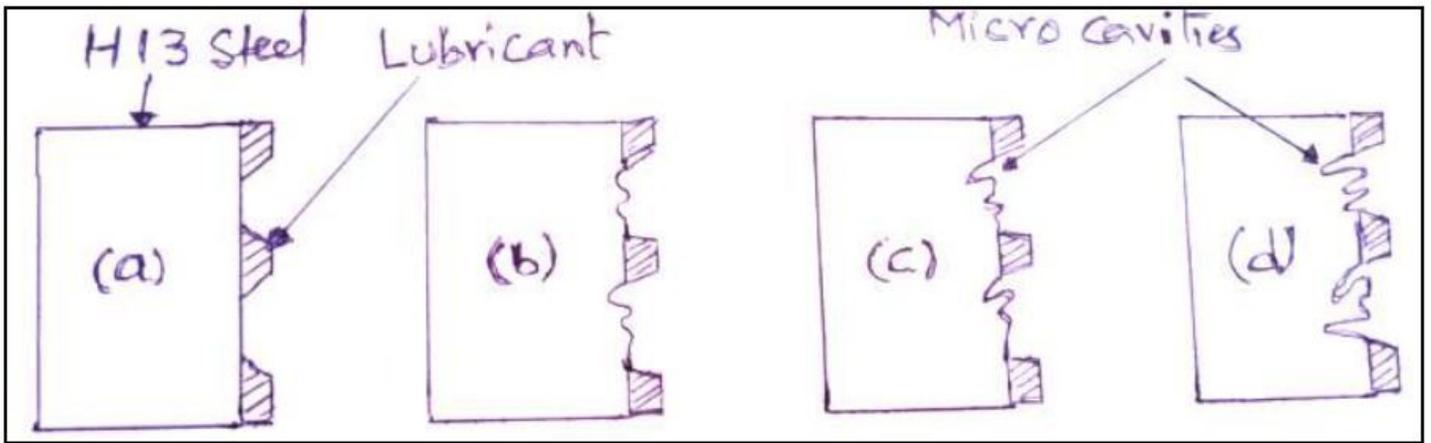


Figure 7

Shows the surface state change of the die without die coatings (PVD) in die casting process.

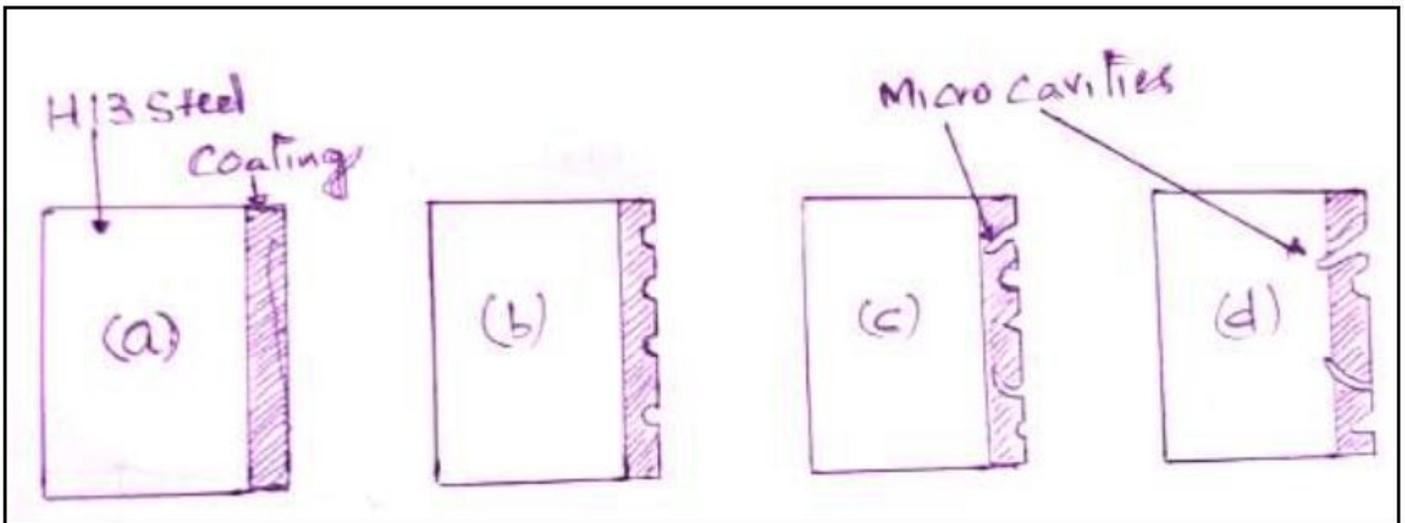


Figure 8

Shows the die surface state with coatings (PVD) in die casting process.