

DIE CASTING TECHNOLOGY FOR THE NEW CENTURY



Presented by:
North American Die Casting Association

SOLDERING TENDENCIES OF ALTERNATE NON-FERROUS DIE MATERIALS

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ABSTRACT

Soldering of aluminum alloys to the die components during die-casting is a problem that faces all die casters and results in substantial losses of time and money. Consequently, various efforts have been made around the world aiming at mitigating this problem. In this work, a special apparatus has been designed and used to test the resistance of several ferrous and non-ferrous die materials to soldering. The die materials tested include H-13, Anviloy® 1150, CermeTi-C-10®, CermeTi-C-5® and TZM.

The results shed light on the physical mechanism underlying die soldering and show that die soldering can be effectively mitigated by using the appropriate die material.

INTRODUCTION

A very dominant mode of die failure in aluminum die casting is die soldering; wherein the cast aluminum alloy sticks to the die and remains there after the ejection of the part, thus rendering the die unfit for further cast cycles.

The primary mechanism of soldering is that of diffusion. When aluminum comes in contact with the ferrous die material, the iron and the aluminum atoms diffuse into each other resulting in the formation of a series of intermetallic phases over the die material. Initially iron and aluminum react with each other to form binary iron-aluminum intermetallic phases. Subsequently, these phases react with the molten aluminum to further form ternary iron-aluminum-silicon intermetallic phases [1,3]. Iron and aluminum have a great affinity for each other and the root cause for soldering is this high reaction kinetics between iron and aluminum. Once the initial binary and ternary intermetallic phase layers are formed over the die material, the aluminum sticks to the die due to the abnormally low thermal conductivity of the intermetallic phases and favorable interface energies between the intermetallic layers and aluminum.

Almost all die casting operations in the US use tool steels for die materials. Premium Grade H-13 and modifications of H-13 and H-11 are examples of some of the ferrous

die materials used in aluminum die casting. Several approaches have been employed to alleviate soldering. Die coatings, die lubricants and surface engineering methods have been effective in increasing die life, however they are not permanent solutions.

A possible permanent solution to the soldering problem lies in the use of an effective non-ferrous die material. Some basic property requirements for a die material are: resistance to formation of reaction products with aluminum, good thermal conductivity (comparable to tool steels), resistance to thermal fatigue cracking, good machinability and formability, high surface hardness and uniform surface properties.

In this paper, four potential non-ferrous die materials have been tested for soldering tendencies. They include Anviloy®1150, CermeTi-C-10®, CermeTi-C-5® and TZM. The reference die material was H-13, and 380.1 aluminum alloy was used. All the above non-ferrous die materials are manufactured via powder metallurgy. Surface finish on all of the candidate die materials can be tailored to the surface specifications.

BACKGROUND

The mechanism of die soldering and the rationale for selecting the candidate non-ferrous dies is given below.

Mechanism of Soldering

Past researchers on die soldering [2,3,4], have explained the operative mechanism of soldering through the following stages.

STAGE I ⇒ Erosion of grain boundaries on the die surface

STAGE II ⇒ Pitting of the die surface

STAGE III ⇒ Formation of binary iron-aluminum compounds

STAGE IV ⇒ Formation of “pyramid” shaped structures of ternary iron-aluminum-silicon phases

STAGE V ⇒ Adherence of aluminum onto the “pyramids” of intermetallic phases

STAGE VI ⇒ Flattening of erosion pits and intermetallic phases.

The vital stages in soldering include the initial erosion of the die material by the molten aluminum and the subsequent formation of the intermetallic compounds (Stages I through III). In ferrous die materials, there is very little time lapse between these stages, due to the rapid reaction kinetics of the formation of the binary iron-aluminum compounds after pitting. The mechanism of erosion pit formation is by both mechanical impingement of the incoming aluminum melt on the die surface and intergranular corrosion of the die surface by aluminum. The latter is the more dominant cause for pitting [3]. The mechanical erosion depends greatly on the strength and hardness of the die material. Whereas, the intergranular corrosion depends on the chemical composition and the microstructural consistency of the surface of the die material. In ferrous die materials, pitting primarily occurs because the aluminum melt reacts with the softer regions in the surface microstructure. In H-13 these areas are generally the areas in-between the hard martensitic plates on the surface of the die [2,3].

Once pitting occurs and the intermetallic compounds are formed, the aluminum instantly sticks to the die surface. Hence, a good measure for the tendency of the die material to solder would be the thickness of the intermetallic layers that forms on the die surface. There are two primary regions in the die where soldering occurs. One is the region around the gate where we have impingement soldering, and the other is the region right opposite the gate area where deposition soldering takes place. The experimental apparatus designed at WPI is capable to evaluate both these soldering tendencies.

Non-Ferrous Die Materials

Understanding the mechanism of soldering has helped us narrow down the window of solutions to mitigate the problem. One such solution is the use of an alternate non-ferrous die material. Important properties to look for in a die material to effectively resist soldering are:

- Material should be inert to corrosion and erosion by molten aluminum
- Kinetics of formation of reaction products between the die material and aluminum must be slow
- Assure compositional and microstructural consistency on the surface of the die material, and
- Minimize thermal fatigue cracking of the die surface.

The following are the key properties that were considered in selecting the die materials studied.

- Thermal Conductivity
- Material Strength
- Room Temperature and high temperature hardness

Table 1 shows the various properties of the selected materials compared to H-13 tool steel.

(see Table 1)

Casting a die material create large variations in compositions, microstructure and mechanical properties. Powder metallurgy processes tend to create a high integrity net shape part with minimum variations in material properties. In addition, these parts can attain 99%, or greater values, of theoretical densities.

ANVILOY® 1150 is a material developed by powder metallurgy process, specifically, for its high temperature strength and excellent thermal conductivity. Simplicity of tooling manufacture (no heat treatment), low erosion, and excellent resistance to thermal cracking make it a premium choice for applications where H-13 and similar grades might be used [5]. CermeTi-C-10® and CermeTi-C-5® are metal matrix composite (MMC) materials containing Ti-6Al-4V matrix and 10% and 5% of TiC particles respectively. The patented materials are produced through a proprietary CHIP processing [6], where the part is produced by a three step powder metallurgy process of cold isostatic pressing (CIP) followed by a vacuum sintering process, and a hot isostatic pressing operation (HIP). The material exhibits good machinability, good wear resistance, high fracture toughness and high corrosion resistance. CermeTi MMC materials have been evaluated as a liner for shot sleeves where they have demonstrated considerable improvement in life than H-13 tool steel [7]. TZM is also a P/M part, which has high ductility. It is an established molybdenum alloy that provides excellent service in applications requiring high strength, creep resistance and ductility.

EXPERIMENTAL PROCEDURE

An experimental apparatus was built to simulate a die casting environment. Prior to designing the apparatus, a thorough similitude analysis was performed to attain geometric, kinematic, thermodynamic and mechanical similarities between the laboratory experiment and the die casting process [8]. Figures 1 and 2 are a schematic diagram and photographs of the test apparatus, respectively. The melt is held in a 200 lb. electric crucible over which an unistrut rig carries a motor driven shaft that holds the die material test pins. The test pins are rotated in the melt at a minimum of 5000 rpm to simulate the drag forces experienced by a die cast die in operation. The cylindrical design of the pin enables it to experience various levels of drag forces and melt turbulence at various points along its circumference [8]. The time of rotation can be varied to evaluate the resistance of the material to soldering. The aluminum alloy used was a standard industrial grade 380.1 with 1.1 % iron. The initial melt temperature before the run was maintained at 625°C and the final melt temperature after the run was about 600°C. Table II details the variables and the constants used in the experimental runs.

(see Figure 1)

(see Figure 2)

(see Table 2)

The factorial method was utilized in these experiments. Each run was repeated twice to ensure R&R. The dependant variables in the experiments were the thickness of the intermetallic layers, and the area of the pin surface soldered. Three inches of the pin surface were immersed in the melt.

After each experimental run, the die material pins were quenched in cold water to arrest any further reaction between aluminum and the die material. The pins were later sectioned at appropriate locations to perform metallographic analysis. Sectioned samples were hot mounted and taken through successive grinding steps (60 mesh to a 600 mesh SiC grinding papers). Subsequently, the samples were polished with a 1 μ m water based diamond polishing suspension on an automatic polisher for a couple of weeks to ensure a smooth and continuous interface between the die material and the soldered aluminum.

RESULTS

The percentage area soldered and the thickness of the intermediate layer between aluminum and die surface for each of the die materials in this study is given in Table III

(see Table 3)

Figures 3 and 4 show the percentage area soldered and the thickness of the intermediate layers, respectively. The lines through each set of data points in Figure 4 are the result of a linear fit by regression analysis.

(see Figure 3)

Metallographic analysis of the soldered interfaces revealed that intermediate layers were also formed in the non-ferrous die materials. These layers grew out of the die surface and the aluminum soldered on top of the intermediate layers. In addition, erosion pits were also observed in all the die materials, before the intermediate layers began to grow on the die surface. Erosion pits began to appear in Anviloy®1150 only after the 150s rotation time.

DISCUSSION

It can be observed from the results that Anviloy®1150, CermeTi-C-10® and CermeTi-C-5® are far better candidates for die materials than the conventional H-13 in resisting die soldering. TZM was also consistently better than H-13 but failed to reach the performance of the other three non-ferrous materials.

The growth of the intermediate layer in all the die materials follows a parabolic rate law. This is evidence that the layers grow by a diffusion mechanism. Hence, it can be concluded that for both ferrous and non-ferrous die materials, die soldering is a diffusion-controlled process. The growth rates of the intermediate layers in the soldered microstructure were calculated, and are shown in Figure 4. The equation is of the following form.

(see Figure 4)

where,

y = Thickness of the Intermediate Layer

t = Time of rotation in aluminum melt

c = constant

k = Rate constant

The rate equations in Figure 4 show the respective values of K and c for all the die materials.

In Figure 4, the intercept (t_0) of the linear fit lines and the x-axis is a significant term; it defines the time elapsed before the material starts to form erosion pits, and when the intermediate layers begin to grow. In case of H-13, this time is quite small. H-13 begins to form erosion pits in less than 4 seconds. Once the pits are formed in H-13, the intermetallic layers begin to grow almost instantaneously.

In the case of CermeTi® and Anviloy® the time before pitting on the die surface was quite considerably longer than H-13. CermeTi® began to pit after about 80 seconds, and pitting began in Anviloy® after about 140 seconds. In CermeTi®, the intermetallic layer began to grow as soon as the pits were formed. Whereas, in Anviloy® pitting occurred after 150 seconds of rotation in the aluminum melt, however, the intermediate layers were observed only after 240 seconds. This observation might suggest that the erosion pits in the case of Anviloy® is more due to mechanical erosion of the die surface by aluminum rather than the chemical corrosion by the melt. Another observation is that in Anviloy®, aluminum soldered to the die material on the pits after 150 seconds, without any intermediate layer formation. This is mostly due to interface energy effects.

The rate of growth of the intermediate layers in CermeTi and H-13 are quite similar but the incubation time, t_0 , before the growth process begins is greater in CermeTi. Anviloy® has a smaller growth rate than the other materials, and TZM has the largest growth rate. TZM however has a greater t_0 than H-13.

CONCLUSIONS

The following conclusions are based upon laboratory tests. However, most of the results with the test apparatus have been successfully validated in the industrial sector. The validation demonstrates the benefit of performing an extensive similitude analysis.

- Anviloy®1150 and CermeTi® are superior die materials than H-13 in resisting die soldering.
- The resistance to soldering demonstrated by TZM ranged between CermeTi® and H-13.
- Soldering in both ferrous and non-ferrous die materials is a diffusion-controlled phenomenon.
- The mechanism of soldering in ferrous and non-ferrous die materials consists of three major steps in the following order of occurrence.
 - Pitting of the Die Surface
 - Formation of intermediate phase layers
 - Soldering of aluminum onto these intermediate layers
- Pitting is the most critical step during soldering. Materials that have greater resistance to pitting have shown greater resistance to soldering in aluminum melt.
- The rate equation for the formation and growth of the intermediate layers between the die material and the soldered aluminum was calculated. In addition, the incubation time, t_0 , before soldering begins was calculated for each material.

REFERENCES

1. Sumanth Shankar and Diran Apelian, "*Die Soldering-A Metallurgical Analysis of the Molten Metal/Die Interface Reactions*", Proceedings of the 19th International Die Casting Congress, NADCA Transactions, November, 1997, pp. 245-251.
2. Sumanth Shankar and Diran Apelian, "*Investigation of Die Soldering in Aluminum Die Casting*", Progress Report, Aluminum Casting Research Laboratory, 99-3, MPI - WPI, Worcester, MA 01609, Dec. 1999.
3. Sumanth Shankar, "*A Study of the Interface Reaction Mechanism Between Molten Aluminum and Ferrous Die Materials*", Doctoral Dissertation, WPI, Worcester, MA 01609, April 2000.
4. Sandhya Gopal, Anup Lakare and Rajiv Shivpuri, "*Soldering in Die Casting: Aluminum Alloy and Die Steel Interactions*", Die Casting Engineer, vol.44, n.3, May/June 2000, pp.70-81.
5. James R.Woodruff, CMW Inc., Private Communication.
6. Susan M.Abkowitz, Dynamet Technologies Inc., Private Communication.
7. S.M. Abkowitz, A. Laitinen, D. Apelian, "*Shot Sleeve Life Extension with New MMC Material*", Light Metal Age, 57, 1, 2, pp 114-116, 1999.
7. Sumanth Shankar and Diran Apelian, "*Investigation of Die Soldering in Aluminum Die Casting*", Progress Report, Aluminum Casting Research Laboratory, 97-2, MPI - WPI, Worcester, MA 01609, May 1997.

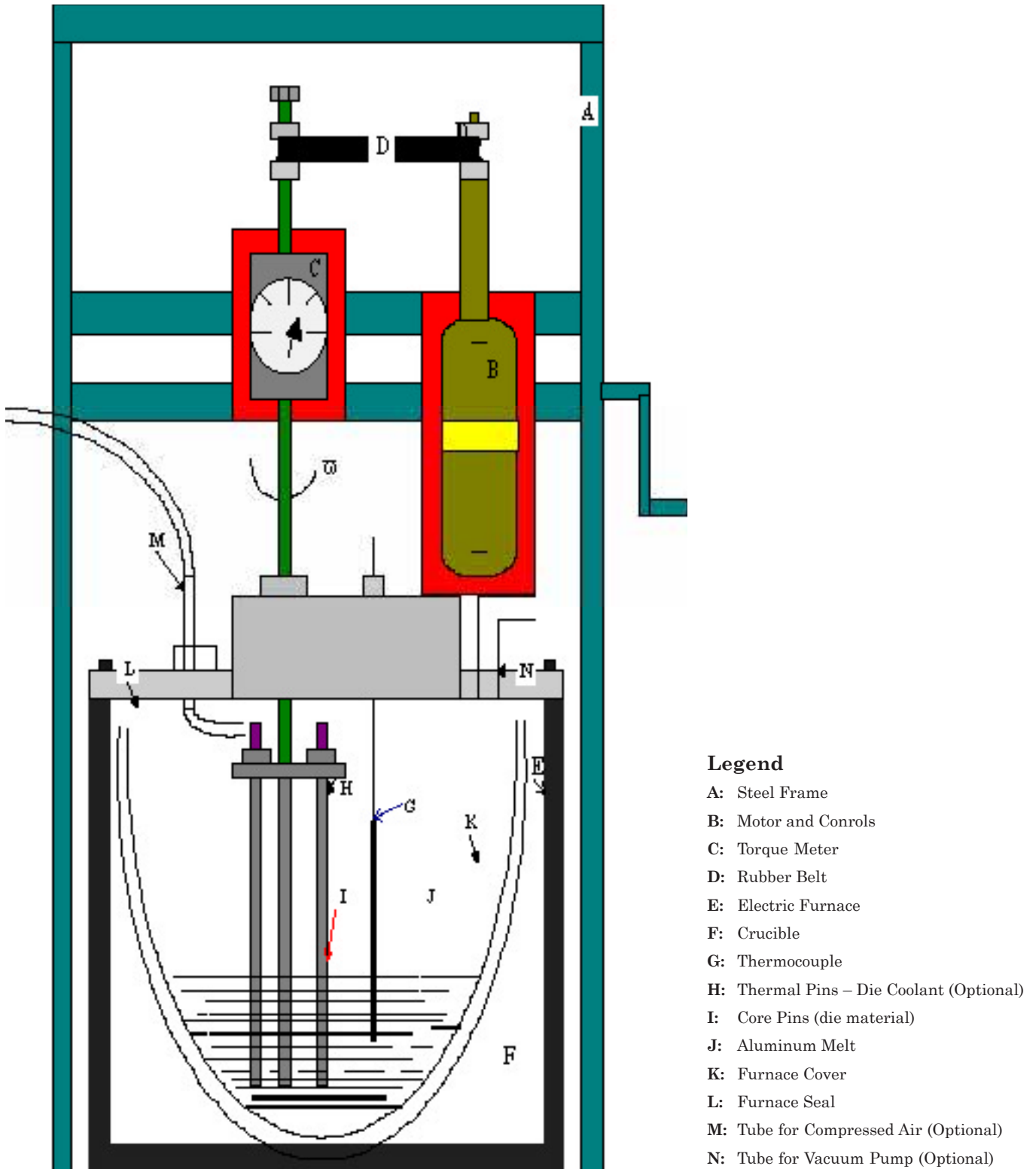


Fig. 1: Schematic of the experimental setup to test soldering tendencies in die materials.

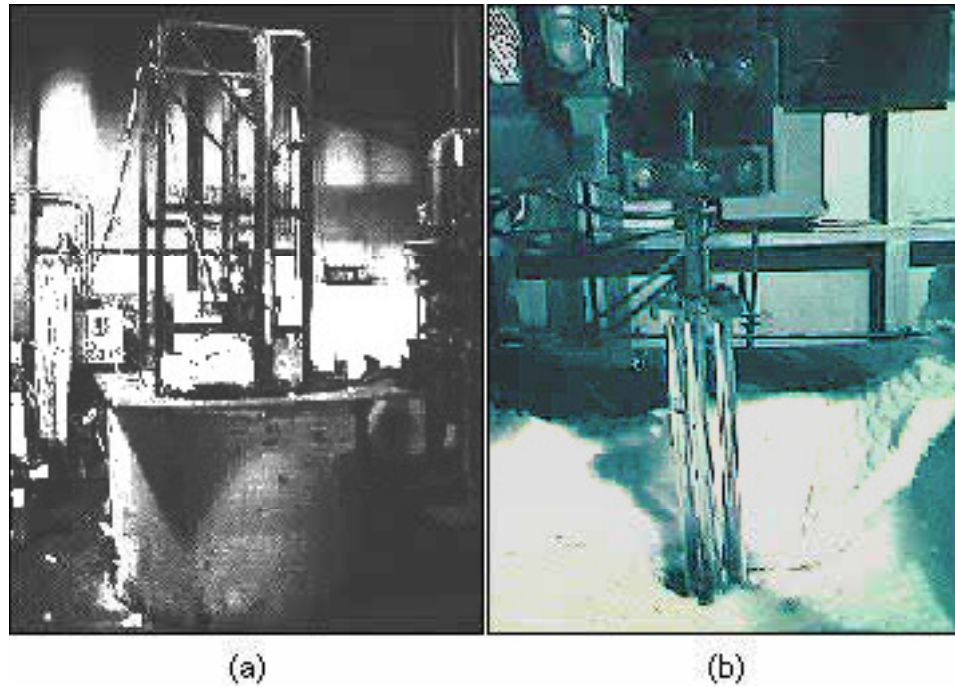


Fig. 2: Experimental apparatus – (a) Electric furnace and a unistrut construction holding the die material pins arrangement and the motor to rotate the pins, (b) a close-up view of the die material pins arrangement dipped in molten aluminum.

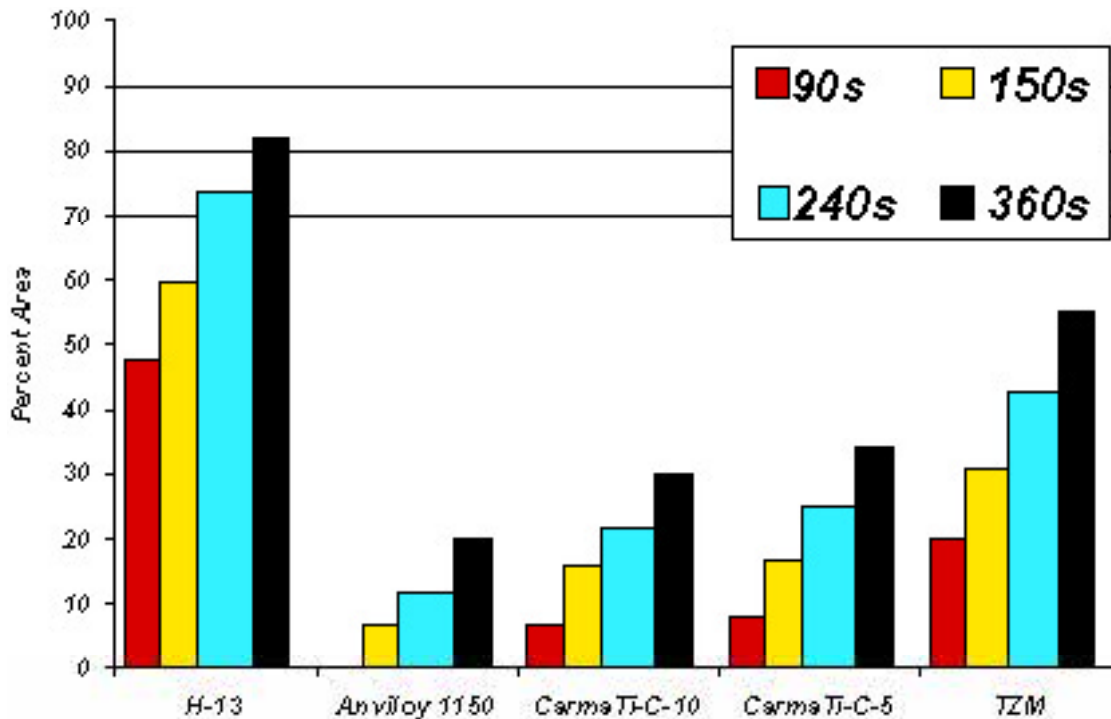


Fig. 3: Percentage area soldered for all the tested die materials at various times.

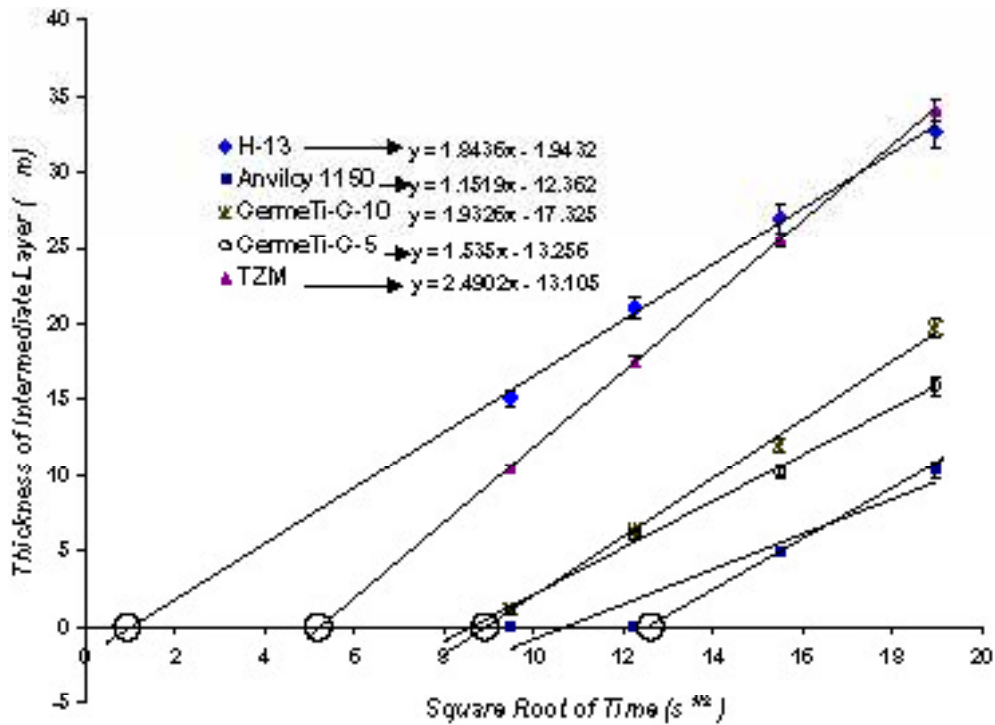


Fig. 4: Thickness of the intermediate layer at various rotation times. The lines represent the linear fit of the respective data points and the equations in the legend indicate the equations for the respective linear fits. In addition, the incubation time (t_0) before which pitting and the formation of intermediate layers start is shown for each material. t_0 Values are noted by circles on the ordinate.

Table 1: Properties of the Chosen Non-Ferrous Die Materials

MATERIAL	ANVILOY	CemeTi	TZM	H-13
PROPERTY				
<i>Composition</i>	4%Ni, 4%Mo, 2%Fe, 90%W	MMC of Ti-6Al-4V and TiC	0.5%Ti, 0.1%Zr, 99.2%Mo	0.35%C, 0.35%Mn, 1%Si, 5%Cr, 1.2%Mo, 1%V
<i>Hardness (HRC)</i>	34	40	$R_B - 260$	52
<i>Thermal Conductivity (W/m K)</i>	128	8	120	28
<i>UTS (MPa)</i>	945	1000	1000	1730
<i>Elongation</i>	3%	3%	10%	13%

Table II: Experimental Matrix

VARIABLES		CONSTANTS	
<i>Factor</i>	<i>Levels</i>	<i>Factor</i>	<i>Levels</i>
Die Material	Anviloy 1150	Melt Temperature	625 C
	CermeTi-C-10		
	CermetTi-C-5	Speed of Rotation	5000 RPM
	TZM		
	H-13	Die Pre Heat	325 C
Time	90 s	Die Surface Finish	#320 grit
	150 s		(longitudinal)
	240 s		
	360 s		

Table III: Percentage Area Soldered and Thickness of the Intermediate Layers

<i>Die Material</i>	<i>Percentage Area Soldered (%)</i>				<i>Average Thickness of Intermediate Layer (nm)</i>			
	90 s	150 s	240 s	360 s	90 s	150 s	240 s	360 s
H-13	45	57	71	82	15.10	21.07	27.00	32.67
Anviloy 1150	0	4	9	20	0.00	0.00	4.95	10.34
CermeTi-C-10	4	13	19	30	1.23	6.35	12.00	19.73
CermeTi-C-5	5	14	22	34	1.10	5.98	10.24	15.92
TZM	17	28	40	55	10.43	17.48	25.55	34.07