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Selectively reinforced squeeze cast pistons

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1. SQUEEZE CASTING

A process which is a combination of gravity die casting and closed die forging. The technique in which metal solidifies under pressure within closed die halves. The applied pressure and the instantaneous contact of molten metal with the die surface produces rapid heat transfer that yields a porous free casting with mechanical properties approaching the wrought product . Squeeze casting offers high metal yield, nil or minimum gas or shrinkage porosity, excellent surface finish and low operating costs.

Squeeze casting (also known as extrusion casting, squeeze forming, liquid forging) was developed to produce high quality components. In this process, pressure is applied on the solidifying liquid metal. Due to the intimate contact between the liquid metal and the mold and hence higher rate of heat removal across the metal mold interface, premium quality castings are obtained. The patent on this process seems to be that of James Hollingrake in 1819 from Manchester. The steps involved in this process are : (i) pouring of metered quantity of liquid metal with adequate super heat in to the die cavity, (ii) application of pressure on the liquid metal and maintaining the same till the solidification is complete and (iii) removal of the casting and preparation of he die for the next cycle. These steps are illustrated schematically

The process is basically divided into two types: direct and indirect. What is shown is the direct process, where the squeeze pressure is applied through the die-closing punch itself, whereas in the indirect process, the squeeze pressure is applied after closing of die, by a secondary ram

SPECIFIC FEATURES OF SQUEEZE CASTING OVER CONVENTIONAL GRAVITY DIE CASTING:

a. Solidification under pressure enhances internal soundness, thereby increasing the suitability potential for critical applications.

b. Squeeze casting results in a high degree of refinement in the structure of the alloy. Grain size reduction to the extent of 50% of that of the conventionally gravity cast alloy is usually possible finer microstructure.

c. In general, material formed by squeeze casting has a fine equiaxed grain structure and exhibit higher toughness than materials formed by gravity casting.

d. Absence of gas/shrinkage porosity.

e. Near net shape, high degree of surface finish and dimensional accuracy.

f. Significant improvement in mechanical properties due to finer microstructure.

g. Faster cycle times.

h. In conjunction with high quality reusable dies and thin die coatings, good dimensional reproducibility is possible, matching that of pressure die casting.

i. In the absence of running or feeding system, a high metal yield approaching 95% can be achieved because all the metal poured into the die is used to form the components.

j. Casting alloys as well as wrought alloys can be squeeze cast to finished shapes; castability and fluidity of the material are of little concern. Suitable for long freezing alloys too.

k. Components of forging quality can be produced by squeeze casting.

l. Fibre and particulate reinforcement can be incorporated with advantage in squeeze casting.

m. Recycled scrap material can be used for components which would conventionally require a more expensive high quality primary alloy

Table lists mechanical properties squeeze cast Vs chill cast and forging. The mechanical properties of squeeze cast components are superior to that of conventional casting.

Alloy	Chill Cast		Squeeze cast	
	UTS (MPa)	Elongation (%)	UTS (MPa)	Elongation (%)
LM5	230	10	250	14
LM18	150	6	187	13
LM 24	200	2	233 368(T6)	272
LM 25	310 (T6)	3	331(T6)	7
A 357	313(T6)	7	347(T6)	9
FORGING				
A 6061 - Forging	262	10%	292	10

Some of the Squeeze Cast components being made worldwide are in the following table.

Piston	Motor Support
Engine Block	Disc Brake Caliper
Cylinder Head	Turbo Charge Impeller
Connecting Rod	Brake Drum
Brake Disk	Brake Pedel
Wheel	Track shoe
Pulley	Piston Pin
Pull Arm socket	Valve Rocker Arm
Track Hub	Exhaust Manifold
Bushes	Differential Clutch compartment
Flange Hub	Cylinder Liner
Gear Housing	Pinion Gear

3. ALUMINIUM MATRIX COMPOSITES

Composites are materials composed of more than one constituent. One of the constituent is the metallic matrix and the other a reinforcement. The matrix holds the reinforcement together.

Aluminium matrix composite refer to a class of material where aluminium is the metal matrix reinforced by materials like SiC, Al_2O_3 ,TiC, TiB_2, Graphite and certain other ceramics.

Apart from the reinforced material, the morphology of the reinforcement too is of importance. The three major morphologies are Continuous fiber, Chipped fiber or Whisker and particulate. With further options like Reinforcement Volume Fraction and reinforcement orientation and aluminium alloy composition and heat treatment , a wide range of materials and resultant properties are feasible.

The automotive piston components that are currently under development using Aluminium matrix composites by various automotive manufactures are listed below:

Reinforcement	Component	Manufacturer
SiC (particulate)	Piston	Dural, Martin Marietta, Lanxide
Al_2o_3 (fibre)	Piston Ring Groove	Toyota
Al_2o_3 (fibre)	Piston Crown	FM, JPL, Mahle and others
SiC (particulate)	Cylinder liner, Pistons	FM
Al_2O_3 – SiO_2-C	Cylinder liner	Honda

The most widely used reinforcements in the case of aluminium matrix composites for automotive applications have been graphite and silicon carbide, both in the form of particulates and fibers. The development that have taken place in the recent years are

a. Aluminium-Graphite composites

Initially, cast Al/Gr (p) composites were developed through liquid metallurgy route for automotive antifriction applications. The primary advantages of this material were less cost, easy machinability and improved damping capacity which is essential for automotive applications. These composites have been used to fabricate many automotive components like pistons, liners and bushings using permanent mould casting, squeeze casting, centrifugal casting and pressure die casting.

The pistons of Al/Gr (p) composites tested in diesel engines led to reduced wear of the pistons and rings, reduced loss of frictional horsepower and freedom from seizure under adverse lubrication conditions. The specific fuel consumption is observed to have decreased. Similar results have been obtained by using these pistons in gas-line engines.

FM reports that 4% graphite dispersed in Al-18Si alloy improves its scuffing resistance by a factor of two. The liners from these alloys have been evaluated by them in two-stroke and four-stroke engines in collaboration with Ferrari, Hiro and Alfa Romeo. It has been observed that the power generated improved by 10%. Also, negligible wear with no friction marks or scuffing has been observed and power ratings were found to be close to highest levels achievable.

b. Aluminum-Silicon Carbide composites

These composites show excellent specific strength, specific modulus and wear resistance. The coefficient of thermal expansion decreases linearly with increase in SiC content. Dural has been manufacturing this material since 1986. These materials are supplied in the form of ingots which can be remelted and cast into desired components. Conventional casting processes like sand casting, permanent mould casting, investment casting and squeeze casting have been used to make automotive

components. The automotive components that are manufactured using these composites include pistons, brake rotor, cylinder sleeves and drive shafts.

The Piston Division of Karl-Schmidt Unisia(Germany) have introduced a squeeze-cast aluminium alloy (HD-339-P) piston reinforced with a 80% alumina-20%silica perform in the crown and combustion bowl region for tractor-trailer diesel engines. It is observed that high temperature (300^o C – 400^{o}C) yield strength and stability were markedly increased in the critical piston regions, increasing the thermal gradients generated by high output diesel engines. Although the perform was slightly heavier that the matrix alloy, overall weight penalty was trivial because the perform was confined to a small region (17% by volume).

Summing up, in automobile applications, the Aluminium Metal Matrix composites offer the following benefits relative to the conventional metal / alloys.

Weight saving.
Increased specific stiffness
Enhanced Wear resistance
Reduced Coefficient of Thermal Expansion.
Elevated temperature strength
Fatigue strength
Improved creep resistance
High surface durability.
Reduced emission

4. DEVELOPMENT OF SQUEEZE CAST PISTONS

IPL and IIT, Madras have worked together to develop squeeze casting and an Aluminium Metal Matrix composite piston.

SQUEEZE CASTING MACHINE

An indirect type squeeze casting machine (Fig) was designed to fulfill the requirements to cast the composite piston.

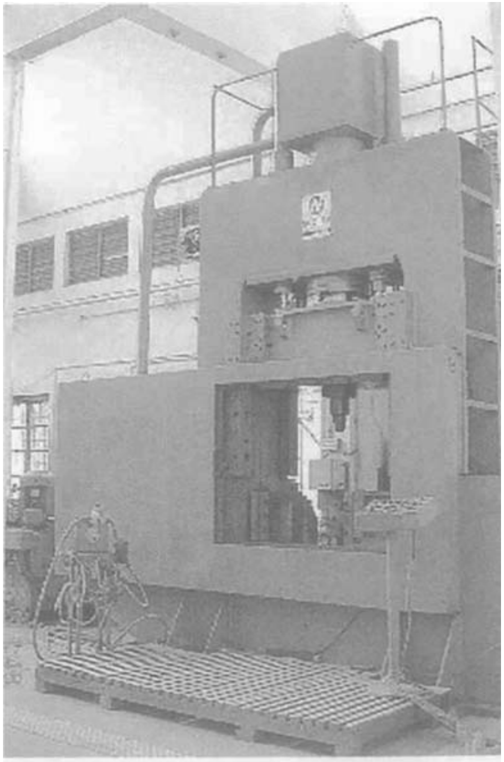
The salient features :

(i) Hydraulic Press , C/H frame type construction (day light – 1000 mm, pate size – 1000 x 500 mm)

(ii) Die locking cylinder (Capacity 200T , stroke – 300mm)

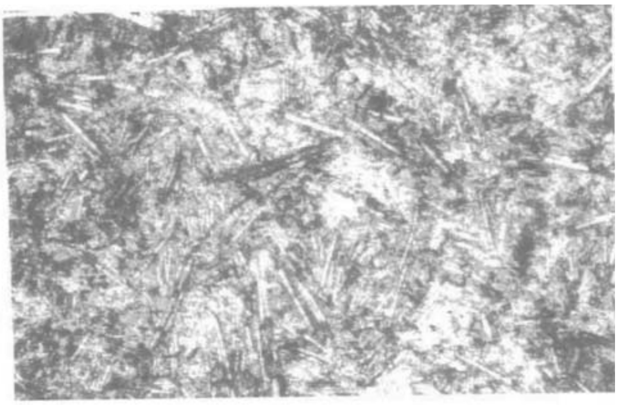
(iii) Top closing cylinder (Capacity 150T, stroke – 700 mm, speed – 200 to 5m/s, variable)

(iv) Squeezing/Ejection Cylinder(Capacity 20T, , stroke – 150 mm, programmable pressure control)



Squeeze Casting Machine

Selectively Reinforced Squeeze Cast Piston



Optical Micrograph of Composite Magnification - 200

Piston after Engine Testing

(v) Options for manual and auto-cycle operations.

In auto-cycle of mode, the following sequence of operations will take automatically (with operator intervention at step No.2)

1. Die locking cylinder moves fast forward, slows down after tripping limit switch, locks the die halves and develops the set load (max. 200T). The cylinder is isolated using check valve.
2. Operator places the preform in the die cavity and presses the button, which activates the auto ladle.
3. Auto ladle pours the desired quantity of metal.
4. Return motion of the ladle activates the die closing cylinder.
5. Die closing cylinder moves fast forward, changes over to slow speed after tripping limit switch, closes the die.
6. Squeezing cylinder ram, held in position with back-pressure, moves backward to accommodate the excess metal, as the die closes in step 5.
7. Die closing cylinder develops the set load (max. 150 T) and gets isolated using check valve.
8. Squeezing cylinder moves forward, develops the set pressure ramp rates, as programmed in PLC.
9. The liquid metal solidifies under pressure for a specified time, set on the panel. At the end, the squeeze pressure is reduced to the back pressure level.
10. Dwell timer gives signal to the die closing cylinder to retract in slow-fast motion to the set position.
11. Die locking cylinder retracts in slow-fast motion to the set position.
12. Squeeze cylinder moves forward, ejecting the component and the pressure is reduced to the back pressure level at home position.
13. Component pick-up, die cleaning and coating done manually

AUTO LADLE:

Pouring of metered quantity of liquid metal into the die cavity is essential for castingthe near-net-shape components. This necessitates the inclusion of auto-ladle in the system. This is integrated with the squeeze casting machine.

Specifications:

Ladle range	:	0.5 – 2.0 Kg
Arm traverse range	:	1500 mm
Average cycle time	:	15 Sec
Metering accuracy	:	+/- 2%
Control system	:	2 axes servo DC, user control of cycle speeds (variable within a cycle) and metering, detection of pouring problem and return of molten metal to crucible, motion controller interfaced to a pendent with 2 line 16 char. LCD display and key board, windows 95 based application software for configuring and controlling the system.

FURNACES:

Two furnaces, one for melting the alloy, viz., aluminium – 12% silicon alloy and the other for heating the composite before placing into the die cavity.

Aluminium Melting furnace:

Electrical resistance heated Capacity : 300 Kg

Power rating : 72 KW

Max temp. : 1000^0C

Preform Preheating Furnace:

Double chamber construction +/- 180^oC rotation

Electrical resistance heating Max. Temp : 1000^0C

MOBILE DEGASSING UNIT:

The MDU is used for in the removal of dissolved hydrogen from the melt, before starting the casting operations.

Specification :

Gas flow rate: 0 – 10 lpm
Gas pressure : 2 bar
Sleeve speed range : 80 – 650 rpm

5. PRODUCT DEVELOPED

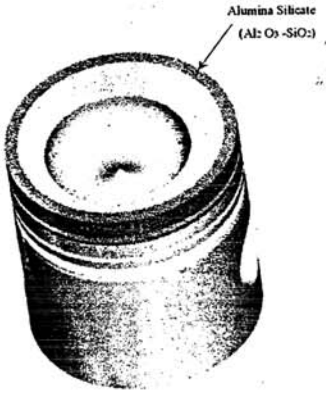
The diesel engine piston (Simpson Model No.S3/25) was taken up for development. Presently this is made by conventional process, viz gravity casting and is not reinforced with fibers. The present design in use is an alfin piston 88.9mm diameter and 100mm height made by gravity die casting process

The intention was to make this piston by squeeze casting process with Alumina-silicate fiber reinforcement in the top ring groove area. The necessary die set, consisting of two vertically split halves, top punch (the shape matching with that of inside contour of piston) and the bottom pad was designed and fabricate. The ceramic insert in the form of ring, preheated to 500^0C was placed on the bottom pad. The die was locked with a locking force of 150T. The aluminium – 12% Si melt with super heat of 750^0C was poured in the die cavity. The die was closed with the top punch (Load = 100T). Immediately after closing, the squeezing operation started automatically according to the programmed sequence. The maximum pressure applied was 75 MPa in 5 ramps and the pressure was maintained for 60s. Initially the castings were examined visually by cutting into several pieces and subsequently the uncut castings were examined by NDTs. The casting was heat treated to T6 condition and machined to the exact dimensions.

PROJECT:DEVELOPMENT OF SQUEEZE CAST MMC PISTON

Comparison of Wear between Composite & Ni-Resist Cast Iron (IP 13)

	Composite Ring Material-IP18		Ni-Resist C.I Ring Material-IP 18	
Test-1	Composite	IP 18	Composite	IP 18
Initial weight(gm)	99.4790	6.4123	90.2944	6.4078
Final weight(gm)	99.4870	6.4043	90.2928	6.4057
Wear	+0.0080	-0.0080	-0.0016	-0.0021
Test-2	Composite	IP 18	Composite	IP 18
Initial weight(gm)	99.4726	6.7792	90.2928	6.4057
Final weight(gm)	99.4780	. 7702	90.2913	6.4041
Wear	+0.0054	-0.0090	-0.0015	-0.0016



Squeeze Cast Piston with Ring Groove Reinforcement

Thermal expansion coefficients of Composite & Al-12.5% Si alloy

Temp °C	Composite $\alpha \times 10^{-6}$ °C^{-1}	Alloy $\alpha \times 10^{-6}$ °C^{-1}
66	---	21.2
90	21.8	---
116	---	23.2
125	22.2	---
140	22.8	24.6
170	23.3	---
180	---	27.2

Comparison of Experimental & Theoretical Densities of Squeeze Cast Composite

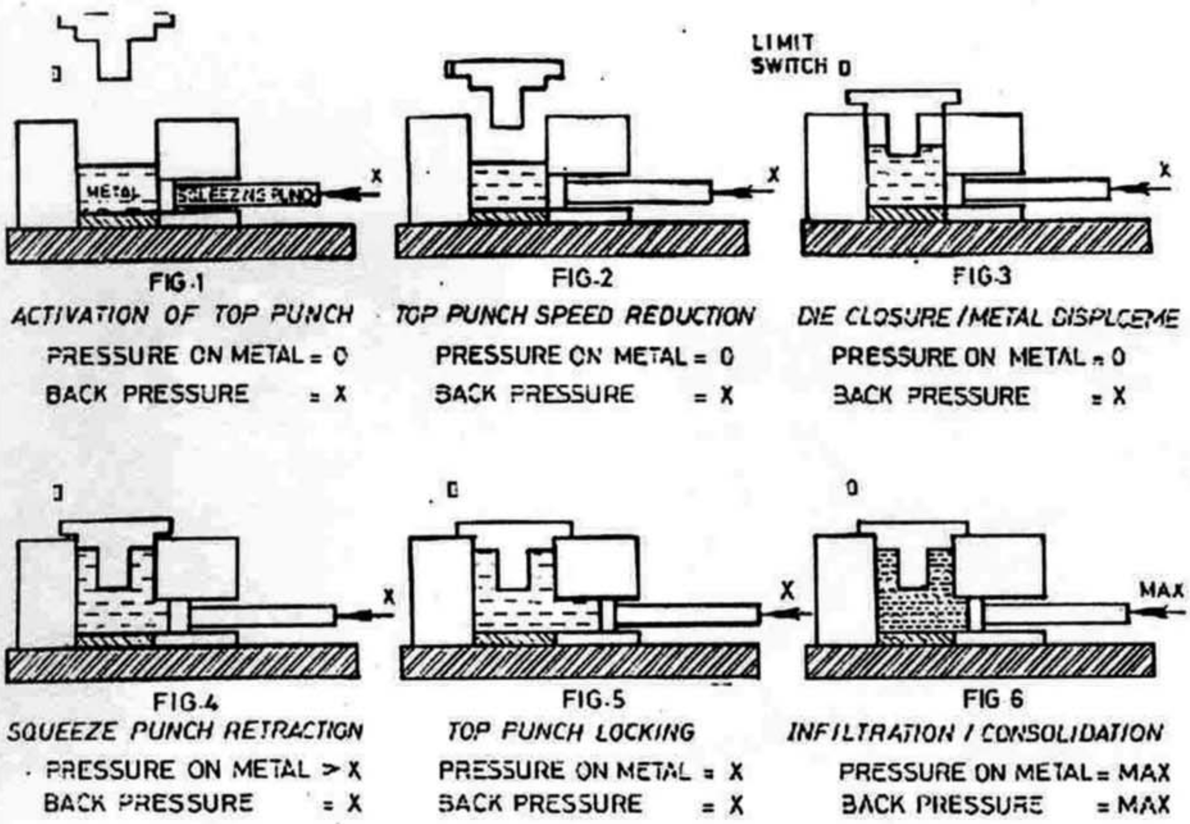
Material	Theoretical Density (gm / cc)	Measured Density (gm / cc)
Al.12.5 Si alloy	2.710	2.693
10% V_f Composite	2.699	2.691
15% V_f Composite	2.693	2.687
20% V_f Composite	2.688	2.685
25% V_f Composite	2.682	2.673

Comparison of alfin & composite pistons in engine test

Parameter	Standard Alfin Piston	Composite Piston
Power at rated speed (Ps)	36.3 Ps	37.0 Ps
BSFC (gms/hp/hr)	176	173
L.O.C.(gms/hr)	10.5	11.2
Blowby at rated speed (Lpm)	12 at start 9 at 100 hrs.	6 at start 5 at 100 hrs.
Top groove wear		
Cyl.1	0.010 mm	0.002 mm
Cyl.2	0.012 mm	0.002 mm
Cyl.3	0.012 mm	Nil
Top groove wear		
Cyl.1	0.010 mm	0.005 mm
Cyl.2	0.005 mm	0.005 mm
Cyl.3	0.005 mm	0.003 mm

Fatigue Strenghs of Reinforced Squeeze Cast & Unreinforced Gravity Cast Materials

Type of Material	Frequency RPM	Torque Applied Nm	No.of Cycles x 105
Aluminium Silicon Alloy gravity cast	5000	14.375	1.49
Composite	5000	14.375	9.50



Sequence of Squeeze Pressure Application

In the present development, material system consisting of Alumina –Silicate flake at 15% volume fraction

(V_f+15%) and eutectic Al-Si alloy forms the Metal Matrix composite.

These MMC pistons are evaluated for physical and mechanical properties like wear, density, fatigue strength, tensile strength, hardness, microstructure etc.

EVALUATION OF MATERIAL PROPERTIES:

DENSITY :

The density indicates the quality of the castings produced. The density of the squeeze cast base alloy and composites were measured using Archimedes principle. These values are given in Table. The Theoretical densities are obtained by rule of mixtures. The density values of the matrix and the fibre are assumed to be 2.71 and 2.6 gm/cc respectively. The results indicate marginal decrease in composite density with increasing fibre volume fraction. The measured densities are greater than 99.5% of the theoretical density. This indicates that the squeeze casting process produces denser castings indicating minimal porosity and the infiltration is complete in the case of composites.

TENSILE STRENGTH

Tensile strength tests were conducted on sample specimens from MMC portion and unreinforced portion of squeeze cast piston. Fiber reinforced portion shows higher tensile strength at 290 N/mm^2 against 260 N/mm^2 recorded by unreinforced portion.

MICROSTRUCTURE

The samples were taken from reinforced portion and un-reinforced portion of squeeze cast piston and the microstructure was studied at 200X. In the reinforced area uniform distribution of Alumina-Silicate fiber in the matrix of Al-Si eutectics is seen. Polygonal primary silicon particles in Al-Si eutectic matrix is observed in unreinforced region.

HARDNESS

Hardness of the reinforced area is found to be slightly lower (104 BHN) when compared to un-reinforced area (128BHN). It may be attributable to volume fraction as well as solidification kinetics influenced by ceramic fiber.

7. ENGINE TESTING

A S3-24 Simpson diesel engine 88.9 x 127 mm 3 cylinder 2.4 litre naturally aspirated Direct Injection diesel engine was assembled with the composite piston and dynamometer tested at full load rated speed for a duration of 1000 hours after running in. All performance parameters were measured including power, fuel consumption, oil consumption, blow-by and smoke. Standard three ring pack was used in the test for comparison, consisting of Top Ring: Inlaid chrome, internally beveled, Barrel periphery comp., ring 2nd ring: Internally stepped, taper periphery IP18, uncoated comp., ring 3rd ring: Chrome conformable oil ring

Wear : Wear tests were conducted on specimens of two materials; fibre reinforced squeeze cast and Ni-resist cast iron against standard top ring material in the conventional pin-on-disc type wear testing machine. The tests were conducted under similar conditions, viz, disc speed, lubrication and duration. The results are given in table. It may be seen that there is no wear in the case of composite and there is a wear in the case of Ni-resist material. The composite gains weight, 0.0080 gm, by removal of material from the ring. On the other hand, the Ni-resist cast iron loses weight, 0.0016 gm. In both cases, the ring material loses weight.

Thermal Expansion : The measured values as functions of temperature are given in the table.

CONCLUSION

1. An alternative process of squeeze casting using selective reinforcement at the top groove and land area provides a superior alternative to the conventional method of gravity die-casting and forging.
2. Indirect squeeze casting machine designed and developed as a collaborative project between IIT Chennai and India Pistons has successfully been used to produce such an alternative piston
3. This piston has been subjected to static and dynamic tests to establish its superiority in terms of strength, wear resistance and fatigue.

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REFERENCES

1. V.M. Playatskii, 'Extrusion Casting of Aluminium', Primary Sources, New York, 1965
2. Lynch, R,F., et al., 'Squeeze Casting of Aluminium', American Foundrymen Society Trans., 1975, pp.569-576.
3. Okada, S., et al., 'Development of Fully Automatic Squeeze Casting Machine', American Foundrymen Society Trans,1982, pp.135-146.
4. Franklin, J.R. and A.A.Das, 'Squeeze Casting - a Review of the Status', British Foundryman, 1984,pp. 135-146
5. R.Mahadevan,V.Vijayaprasad, R.Palaninathan, M.Singaperumal 'Development of Selectively Reinforced Squeeze Cast Pistons" 2nd International SAE Mobility Conference Chennai India