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DEVELOPMENT OF SILICON CARBIDE REINFORCED ALUMINIUM METAL MATRIX COMPOSITE FOR HYDRAULIC ACTUATOR IN SPACE APPLICATIONS

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ABSTRACT

An actuator is a mechanical device that takes energy created by air, electricity, liquid and converts it into motion. In the present study, the design of actuator cylinder using 15-5 PH (H-1025) stainless steel is considered. The dilation, weight, time and cost of fabrication of current design is high. The final component when incorporated into the destination adds weight as a whole due to its density. The present work focussed on replacing the existing material with a SiC particle reinforced aluminium metal matrix composite to reduce weight, dilation and fabrication cost of the actuator. To achieve these objectives two step-mixing method of stir casting technique has been adopted and subsequent property analysis has been made. Aluminium alloy 6061 and silicon carbide (500 grit size) has been chosen as matrix and reinforcement material respectively. T6 heat treatment also improves the material properties. The material properties are then validated using transient structural analysis in ANSYS Workbench and the design is found successful in reducing weight of actuator. Cost analysis is conducted and actuator cylinder with Al-SiC composite material came out to be a potential substitute for the existing design.

KEYWORDS: Hydraulic Actuator, 15-5 PH (H-1025) Stainless Steel, T6 Heat Treatment, Transient Structural Analysis

INTRODUCTION

Engine gimbal control system used in launch vehicles possess hydraulic actuator in it. Currently, 15-5 PH stainless steel actuator cylinder serves the purpose. Multiple hydraulic actuators are being used together in launch vehicles for engine gimbaling. Due to high density (7.8 g/cc) of 15-5 PH stainless steel, the weight of actuator cylinder is high. The precipitation hardened stainless steel is hard to machine and results in increased fabrication cost and machining time. Besides, the actuator cylinder is machined from a block and is also creating huge material wastage summing up the fabrication cost. The present work focusses on replacing the existing material with a SiC reinforced aluminium metal matrix composite to reduce weight, fabrication cost and time consumed keeping its structural integrity intact.

Aluminium alloy 6061 and silicon carbide particulates (25% weight fraction, 500 mesh) are selected as matrix and reinforcement. Stir casting being the most economical and proven method is selected for composite fabrication. T6 heat treatment consisting of solutionizing, quenching and aging is also conducted on the cast specimen to improve its mechanical properties. The experimental results obtained after material testing were in good agreement with the expected results and heat treated specimen gave better mechanical properties. Scanning Electron Microscope (SEM) and microstructure studies of the material were conducted to study the homogeneity in casting, effect of heat treatment and to analyse the type of failure during tensile loading.

Finally, transient structural analysis of the cylinder is done and s compared with the existing design. The maximum input pressure to which the cylinder can be subjects to is 21MPa. The variation of pressure from minimum to maximum is assumed to take place in the maximum operating frequency. This is the worst case loading condition for the cylinder. Al-SiC composite possess a density of 2.69g/cc compared to 7.85 g/cc of stainless steel. Mass of the actuator cylinder came down from 2.1435 kg to 0.73452 kg. It is observed from transient structural analysis of the cylinder that the dilation of the cylinder is within permissible limits and the maximum stress developed is less than the yield strength of the material. In addition to weight saving attributes, total fabrication cost and time consumed can also be reduced by replacing the existing design with Al-SiC composite. Redesigning the cylinder with added stiffeners and other members can reduce the total stress developed inside the cylinder upon pressure loading. Besides actuator cylinder, the end caps, reservoir, accumulator and the fixturing tools can be replaced with the suggested material and it undeniably saves considerable amount of weight that can be used for added devices in the vehicle..

STIR CASTING

Stir casting can be regarded as a popular process for manufacturing AMCs for research applications. The process is usually carried out in a stir casting furnace with the matrix and reinforcements added to the furnace and then stirred continuously. A stir casting machine consists of mainly the following parts.

- Control and Display Unit
- Stirring mechanism
- Main Casting furnace
- Pre-heating furnace

Composites with up to 30% volume fractions can be suitably manufactured using this method. The dispersal of the particles in the final solid depends on strength of mixing, wetting condition of the particles with the melt, rate of solidification and relative density. Geometry of the mechanical stirrer, position of stirrer in the melt, melt temperature, and the properties of the particles added governs the distribution of particles in molten matrix.

TWO STEP MIXING TECHNIQUE

The matrix material is heated above its liquidus to ensure complete melting. It is followed by cooling to keep the temperature in between its liquidus and solidus. The preheated reinforcement particle is then added to this semisolid matrix material and manual mixing is carried out. Manual mixing was used because it was very difficult to mix using automatic device when the alloy was in a semi-solid state. The slurry is again heated to a fully liquid state and mixed thoroughly by using mechanical stirrer. The potency of this two-step mixing method is mainly due to its ability to break the gas layer around the particle surface which otherwise impedes wetting between the particles and molten metal. Thus the mixing of the particles in the semi-solid state helps to break the gas layer because of the abrasive action due to the high melt viscosity

EXPERIMENTAL DETAILS

The stir casting machine at Karunya School of Mechanical Sciences, Coimbatore have been used for this purpose. The dimensions of the mold used for casting was 100x100x10 mm. The raw material requirements were as follows

- Metal matrix-Aluminium alloy -Al-6061)
- Particle reinforcement - Silicon carbide particles (500 mesh)
- Surfactant- Magnesium powder
- Degassing Tablets
- Crucible- Graphite (size no. 6)

Table 1: Stir Casting Furnace Specifications

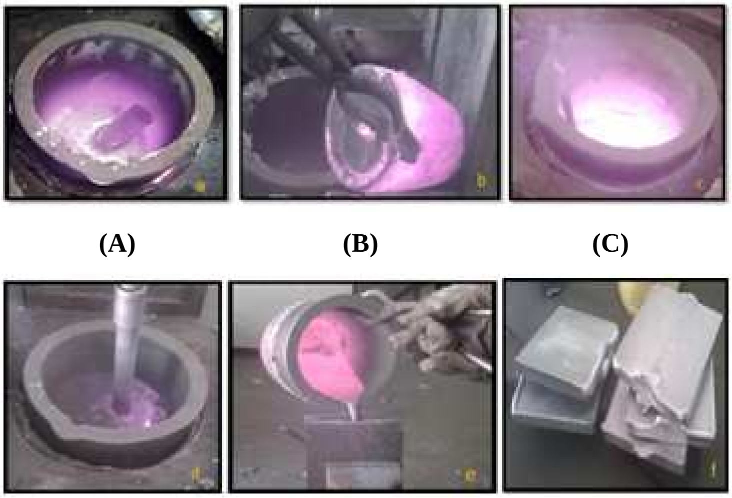
Make	SWAMEQUIP
Capacity	2 kg
Operating temperature	100-1200°C
Operating voltage	440 V, 3 phase

Aluminium rods of diameter 32 mm were cut into rods of smaller lengths so that they could be fed into the crucible for casting. Silicon carbide particles was weighed in a weighing machine and appropriate amount of silicon carbide was taken in a smaller crucible and was kept in the pre-heating furnace. The maximum temperature to be attainedin the pre-heating furnace was set to 930oC. The aluminium rods being bigger than the matching crucible were allowed to melt in a high-temperature furnace, and after melting completely, were transported over to the stir casting furnace.When the temperature reached around 650-660o, aluminium matrix was at a molten state. The temperature was again increased to more than 700oC for melting the matrix completely. Al6061 alloy (1.41 kg) melts at a temperature of 756°C in a graphite crucible in melting furnace and degassing was carried out using hexachloroethane degassing tablets.

Silicon carbide reinforcement (470g) is preheated at 930°C for one hour. Magnesium metal powder (18g) is added to the molten matrix material kept at semisolid state just before reinforcement addition to improve wettability. The molten slurry is first manually stirred during SiC addition and is then mechanically stirred using a 3 bladed stainless steel stirrer continuously for 7 minutes at 900 rpm. After continuous stirring the molten material is poured on to a permanent mould and the cast is removed after 2 minutes.

Table 2: Process Parameters during Stir Casting

Stirring Speed	900 rpm
SiC preheat temperature	930°C
Stirring temperature	630°C
Stirring time	7 minutes



(A) (B) (C)

(D) (E) (F)

Figure 1: Casting (A)Melting of Aluminium (B)Addition of Sic (C)Manual Mixing (D)Mechanical Mixing (E)Pouring in to Die (F)Final Cast Specimens

T6 HEAT TREATMENT FOR Al-SiC COMPOSITE

T6 heat treatment is generally used for aluminium alloys for improvement in their mechanical properties. Since aluminium alloy 6061 is the major content in the composite, T6 heat treatment is carried out for SiC reinforced aluminium metal matrix composite to study its mechanical properties. T6 heat treatment comprises of two steps- Solution heat treatment and artificial aging. Solution heat treatment is carried out primarily where the composite is kept at 530°C for one hour such that its composing elements gets dissolved in solid solution. It is followed by quenching where the specimen is dipped in water kept at 30°C in order to prevent the composing elements from precipitating on cooling. When this solution heat treated quenched specimen is kept at room temperature, it becomes T4 heat treatment. When aging is done at elevated temperature, at 205°C for 3 hours, it becomes T6 heat treatment. The tensile, impact and hardness specimen are initially cut on wire-cut EDM and then heat treated followed by testing procedures as explained earlier.

TRANSIENT STRUCTURAL ANALYSIS

Transient structural analysis is conducted on the hydraulic actuator using Al-SiC composite as the cylinder material and the results are studied using ANSYS workbench v15.0. The three dimensional model of the hydraulic actuator is completed using SOLIDWORKS 2014.

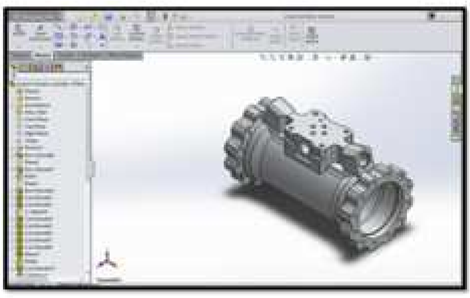


Figure 2: Model of Actuator Cylinder

INPUT LOAD AND BOUNDARY CONDITIONS

The pressure acting inside the hydraulic actuator is given as the input load. However in case of transient analysis, the pressure load varies with respect to time and the input tabular data is provided below. This is a conservative type of analysis considering the worst condition inside the cylinder considering a transition from minimum pressure to maximum pressure at maximum operating frequency 4Hz.

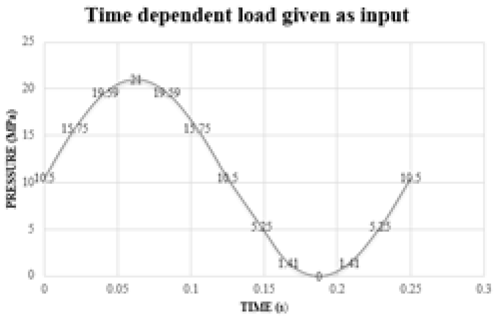


Figure 3: Input Load (Pressure)

RESULTS AND DISCUSSIONS

Mechanical tests like tensile, hardness and impact and microstructure studies of the composite is done at Microlab, Chennai accredited by National Accreditation Board for Testing and Calibration Laboratories (NABL), an autonomous body under the Department of Science & Technology; Government of India providing laboratory accreditation services to laboratories that are performing tests/calibrations in accordance with ISO / IEC 17025 standards.

MICROSTRUCTURE STUDY

Microscopy of the cast specimen using Carl Zeiss metallurgical microscope showed the following results.

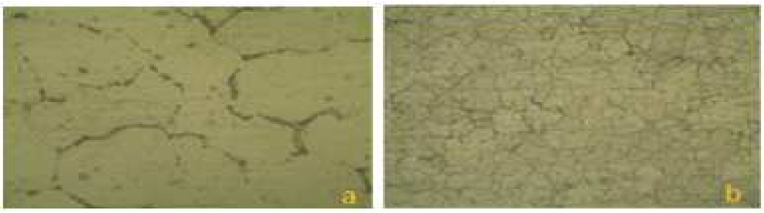


Figure 4: Optical Micrograph of as-Cast Sic Reinforced AMC (A) 500X (B) 100X

Micro examination reveals homogenous dispersion of silicon carbide particles in the aluminium matrix and ensures that the material possess desired mechanical properties. The SiC reinforced Al-SiC matrix composite have rarely pore, compact structure, and good interfacial bonding. Presence of equiaxed grains with fine intermetallic precipitates is seen in the matrix of aluminium. During heat treatment thermally-induced dislodgments (formed upon quenching from the solution treatment) aid as heterogeneous nucleation spots for precipitate formation during the aging treatment. SiC in aluminum leads to an accelerated age hardening, compared to the unreinforced alloy.

TENSILE TEST RESULTS

Tensile test is conducted on WDW-50/100 series computer control electronic universal testing machine. Four specimens were prepared for tensile test of which two are T6 heat treated specimens.

Table 3: Tensile Test Results

Test Parameters	Observed Values			
	As Cast Specimen		Heat Treated Specimen	
	1	2	1	2
Yield strength (MPa)	91.49	88.66	267.48	294.70
Ultimate tensile strength(MPa)	174.11	168.49	278.67	298.55
Percentage elongation	5.5	4.5	1.53	1.50

The presence of SiC filler material enhances the tensile properties of the cast aluminium matrix significantly. The tensile strength of the composite is further augmented by T6 heat treatment. The reduction in percentage elongation as observed from the results indicate a transition from ductile to brittle nature.

SCANNING ELECTRON MICROSCOPE (SEM) STUDY OF TENSILE FRACTURED SPECIMEN

The tensile fracture surface is studied and results are described below.

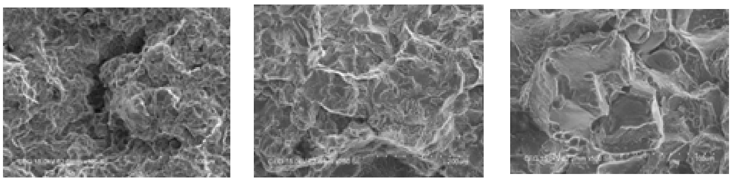


Figure 5: SEM Image of Tensile Fractured Specimen

The tensile fracture surface of the specimen shows quite a contrast between the dimpled nature of fracture in the matrix coupled with brittle fracture of the SiC particle. From primary observation, SiC addition decreases the ductility of the matrix and the failure mode is predominantly brittle in nature though there are cup and cone type of fracture relating to ductile nature. There are more cleavage facets, voids with inclusions and micro cracks which are characteristic features of brittle nature of failure. The deep voids with inclusions may be possible cause of fracture in this case. Even though the images indicate brittle fracture at macro level, some ductile features in the form of depressions are obvious due to the localized deformation at the fracture surface. In short, brittle fracture is predominantly observed.

IMPACT TEST

Four specimens were prepared for impact test keeping two as heat treated specimens and the results obtained are provided below.

Table 4: Impact Test Results

Test Parameters	Observed Values			
	As Cast		Heat Treated	
	1	2	1	2
Absorbed energy in joules	16	14	24	22

SiC reinforcement in the aluminium alloy 6061 increases the impact strength of the material. T6 heat treatment upgraded the impact strength of the composite material drastically.

HARDNESS TEST

Two specimens are prepared for Brinell hardness test out of which one is heat treated. Three indentations were made on each specimen using the 5mm ball indenter

Table 5: Hardness Test Results

Test Parameters	Observed Values	
	As Cast	Heat Treated
Observed Values in BHN (5mm Ball/250Kg Load)	56.8, 57.1, 60.3	80.4, 79.9, 80.8

Al-SiC composites exhibit relatively higher hardness than the matrix material upto 25% weight fraction. Past this weight fraction the hardness trend may start declining as SiC particles interact with each other leading to clustering of particles and consequently settling down.

COMPARISON OF SIC CONTENT AS REINFORCEMENT

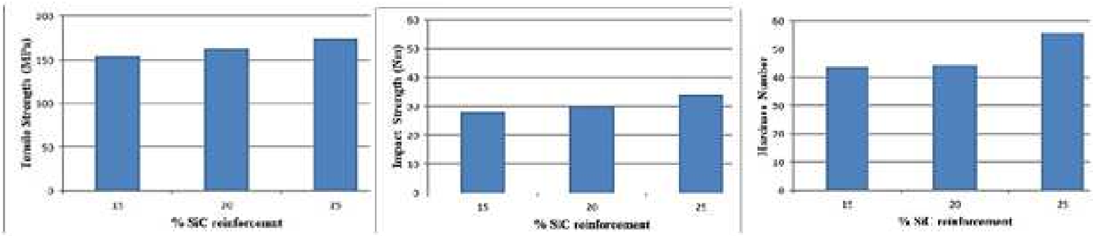


Figure 6: Comparison of SiC Reinforcement

The comparison of 25% SiC content with that of 15 and 20% of SiC content illustrates that in general, mechanical properties like tensile strength, hardness and impact strength increase with SiC content.

TRANSIENT STRUCTURAL ANALYSIS

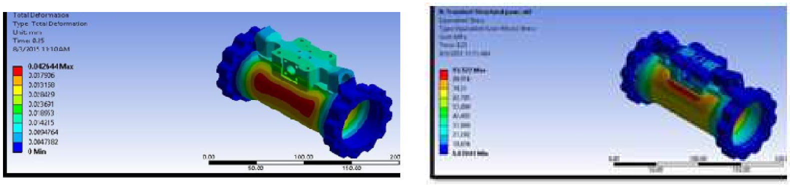


Figure 7: Total Deformation and Stress Developed

When the cylinder material is replaced with Al-SiC composite maximum stress developed equals 95.522 MPa. The total stress developed inside the cylinder is below the yield point of composite and the design can be accepted but the cylinder has to be redesigned to obtain a factor of safety comparable to that of 15-5 PH Stainless steel.

Table 6: Comparison of Actuator Cylinders

Properties	15-5 PH Stainless Steel	Al-Sic Composite
Density	7.85 g/cc	2.69 g/cc
Mass	2.1435 kg	0.73452 kg
Volume	2.7305×10^5 mm^3	2.7305×10^5 mm^3
Total Fabrication Cost	**Rs. 204284.35**	**Rs. 91806.67**

From the density analysis results, Al-SiC composite possess a density of 2.69g/cc compared to 7.85 g/cc of stainless steel. That implies there will be a huge reduction in overall weight as observed from the results. Multiple hydraulic actuators are generally used in Thrust Vector Control (TVC) system depending upon the type of space vehicle and thus the substitute material can be made use of for substantial weight reduction. Besides actuator cylinder, the end caps, reservoir, accumulator and the fixturing tools can be substituted with the proposed material and it unquestionably saves considerable amount of weight that can be used for added devices in the vehicle.

CONCLUSIONS

Al-SiC matrix composite is fabricated using stir casting method by employing two step mixing technique. T6 heat treatment is also conducted to improve the mechanical properties of the composite. The weight of the existing design of actuator cylinder can be reduced substantially by replacing the cylinder material with the proposed Al-SiC matrix composite. Al-SiC composite possess a density of 2.69g/cc compared to 7.85 g/cc of stainless steel and when replaced, reduces the weight of actuator cylinder by 65.73 %. Mass of the actuator cylinder came down from 2.1435 kg to 0.73452 kg. From the cost analysis, total fabrication cost and time consumed can also be reduced by replacing the existing design with Al-SiC composite in addition to weight saving attributes. Total fabrication cost after considering all machining aspects can be reduced to 44.95 %. It can be concluded from transient structural analysis of the cylinder that the dilation of the cylinder is within permissible limits and the maximum stress developed is less than the yield strength of the material. Redesigning the cylinder with added stiffeners and other members can further reduce the total stress developed inside the cylinder. Microstructure studies confirm homogenous dispersion of reinforcement particles in the aluminium matrix and SEM images of the tensile specimen gives the idea that the failure is predominantly brittle in nature.

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