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Master's degree thesis

TOPIC

"ALUMINIUM FOAMS AS CORES IN CASTING"

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Contents

Introduction and Aim

It is very beneficial if the performance of an engine is unchanged even after its weight reduction as it results in many positive effects such as improved efficiency, increase in speed. However, to reduce weight of the component with an unaltered performance is an important challenge for engineers. Same scenarios can be expected in various fields of engineering, automotive, aerospace, transport, structural engineering and many more. A large number of material researchers have taken up this challenge to produce lightweight components with reliable properties. This challenge led researchers towards an excellent idea called composite materials. Composite materials are nothing but combination of two materials with different chemical and physical properties. As far as the lightweight components are concerned, focus of the interest lean towards Metallic foams which indeed inspired by naturally existing materials with porosity (wood, bone etc.). Even though the metallic foam is not exactly a composite material however, the idea is similar. Metallic foam would be the important subject of interest when it is combined with one of the important and most used metals in almost all the industries - aluminum. To design and produce a lightweight engineering component with good mechanical properties (considerably high strength, good bending stiffness etc.,), it is essential to consider several engineering aspects starting from chemical composition of the metal/alloy to casting techniques and various factors (surface treatment, cooling rate etc.,). Advantageous properties that make foam the center of interest is low density, Energy absorbing ability, damping behavior and others. A foam is a cellular structure which consists of gas filled pores in a solid metal. Defining characteristic of the foam would be the high porosity. Typically, 5-25% of the volume is the base metal [4].

Purpose of this experimental thesis is to apply innovative strategies for the use of aluminum foams as cores in aluminum castings. Several important aspects such as chemical composition, surface treatment and cooling rate have been considered at this purpose. This helps us to understand the correlation between the above stated aspects (e.g., surface treatment, cooling rate) and the final properties of the produced light weight component (e.g., core shell bonding, core porosity maintenance, shell hardness). We compare the results obtained from this research work to one which is already done but with different aspects, this way outcome of the current research work will be helpful for the researchers to improve the final properties of the cast object. A major issue which plays a vital role in producing these lightweight materials is the reaction/bonding between the foam and the solid metal/alloy [3]. Several factors affect this reaction, but possible major factors are chemicals that are present on the foam surface after the surface treatment and the cooling rate. On the other hand, these factors should be very carefully analyzed and exploited because mechanical property is the final and more important goal of this research work. This research involves many operations such as sample preparation, morphological (microstructural), Energy Dispersive x-ray spectroscopy (EDS) analysis and micro hardness tests.

The aim is to identify, characterize and investigate possibility of improving the final properties of the lightweight component (aluminum alloy casted with an aluminum foam as the permanent core) in doing so it is mandatory to improve the bonding between the foam and the aluminum alloy and also to keep SDAS (secondary arm dendrite spacing) as low as possible (this can be achieved by appropriate cooling rate) [1]. Chemical composition, surface condition of the aluminum foam, cooling rate and molten metal infiltrations are the important factors which affects the bonding between the porous metal and the solid metal. It is possible to make the best use of temperature evolution over time recorded using the thermocouples attached to different parts during the casting process. CT scan (micro x-ray Computed Tomography which is a non-destructive testing for visualizing the object interiors) must be done in order to locate the bonding zones because techniques are yet to be improved to produce a lightweight component (foams as cores in aluminium alloy) which attributes complete bonding of core (foam) and the shell (aluminium alloy) [2]. Few procedures must be carried out in order to prepare the sample to be analysed (cutting of casted block based on the position suggested by CT scan, Resin mounting and polishing). Microstructural analysis must be done very carefully which in return obtain us material properties such as SDAS (secondary dendrite arm spacing), amount of bonding between the core and the shell followed by analysing the chemical composition of the foam and the microstructure by means of a chemical analysis tool called Scanning Electron Microscopy equipped with Energy Dispersive Spectroscopy (SEM-EDS) [3]. Vickers micro hardness should be performed to measure the hardness of the casted component. This analysis should be performed on a casted object (aluminum foam as the permanent core) which is produced from a Gravity die casting technique. Provided the fact that surface treatment had carried out on the foam before casting. Outcome of this research work should allow us to observe the characteristics of the casted component which undergone with no surface treatment followed by careful observation of results in improving the properties of the casted component (aluminum component having foam as permanent core).

A potential correlation should be observed between the *casting conditions* - chemical composition of the foam surface, surface treatment methods, cooling rate, level of infiltration, and the *material properties* - porosity, chemical composition of the final casted object (main focus is on the interface), microstructural properties (SDAS) and the micro hardness. Conclusion should be stated upon the observed results.

Chapter 1

1. Cast aluminum alloys

Aluminum alloys are incredibly versatile, strong, and reliable. For this reason, they are very sought-after in engineering, construction, and automotive applications, making for one of the most widespread metal materials, alongside steel. The qualities, applications, and unique characteristics of aluminum alloys are explained. While aluminum presents some amazing properties as a pure element, it might not be strong enough for the high-durability purpose. For this reason, it can be combined with other elements (silicon, copper, magnesium, manganese, and zinc) to form alloys, which are exponentially more durable and suitable for industrial applications. In comparison with wrought alloys, casting alloys contain larger proportions of alloying elements such as silicon and copper. The elongation and strength, especially in fatigue, of most cast products are relatively lower than those of wrought products. This is because current casting practice is yet unable to reliably prevent casting defects[6].

Properties that make aluminum alloy very distinctive and most preferable are, melting temperature is 660°C and young's modulus of 70 Giga Pascals (young's modulus is inversely proportional to strain). It has comparatively less density (2,700 kg/m^3), exhibits a good stiffness and strength to weight ratio. It has good electrical and thermal conductivity which makes it possible to extend its application to electrical and thermal engineering. Some alloys can be hardened with solution heat treatment (it is a technique to change certain characteristics of the alloy to make it more suitable according to respective application areas). Al alloys can be utilized in high operating temperatures. Aluminum shows a good corrosion resistance. Good finishing characteristics (surface finish) and Full recyclability are the other properties of aluminum which makes it very suitable for many engineering domains [4].

Based on the type and amount of alloying elements, cast aluminum alloys are subdivided into following alloys with different composition and identified by the designation system - three digit plus a decimal - **xxx.x**. The first digit indicates the principal alloying element, second and third digits are the arbitrary numbers used to identify the specific alloy in the series and decimal digit indicates whether the alloy is casting (.0) and the ingot (.1 or .2). A capital letter represents if there is a modification to a specific alloy (e.g., **A356.0** is the modified aluminum alloy of Al-Si-Cu-Mg combination which is a casting not an ingot.

Pure Aluminum (**1xxx**)	Al-Cu (**2xx.x**)
Al-Si-Cu-Mg (**3xx.x**)	Al-Si (**4xx.x**)
Al-Mg (**5xx.x**)	Al-Zn (**7xx.x**)
Al-Sn (**8xx.x**)	Al-Other elements (**9xx.x**)

Each type of casted aluminum alloy shows different properties hence can be used in specific application fields. **2xx.x** Aluminum alloys are widely used in aircraft industries in wing structure (fig.1.1) because it is heat treatable, can be produced from sand and permanent mould castings also shows high strength at room and elevated temperatures. It has found its usage in civil engineering as structural and construction components, light poles, and drill pipe (fig.1.2). **3xx.x** series of castings is one of the most widely used because of the flexibility provided by the high silicon content and its contribution to fluidity, plus their response to heat treatment, which provides a variety of high-strength options for example complex shapes (fig.1.5).

4xx.x - these aluminum alloys are non-heat treatable and made from sand, permanent mould, and die castings which provides an excellent fluidity and very suitable for intricate castings. Its good thermal conductivity property can be better exploited, electric module packaging & electronic technology (printed circuit boards, computer chips, hard drive, CPU heat sinks), and it can be used in heat exchangers (fig.1.6). **5xx.x** aluminum alloys exhibits non-heat treatable property and can be casted by sand, permanent mould, and die casting techniques and provides good finishing characteristics and shows Excellent corrosion resistance. Machinability, and surface appearance. Hence, they can be used in automotive industry especially in body structure, wheels, engine, gear boxes (fig.1.3), cooling system, and axle housing (fig.1.4). Space crafts and satellites (rocket tankage, rivets, propellers). Also, in marine industries (propellers of the ship, boats, offshore stations), containers and cylinders (containers for hydrogen peroxide), beverage industry (cooldrink cans), wind and solar energy equipment (blades and solar panels), petrol and chemical industry components (chemical piping, pressure vessels, pipelines), rail transportation (beam, exterior panels, tank cars, coal cars, cars for hot cargo). While **6xx.x** and **9xx.x** alloys have not been found many practical applications [6].

fig.1.1

fig.1.2

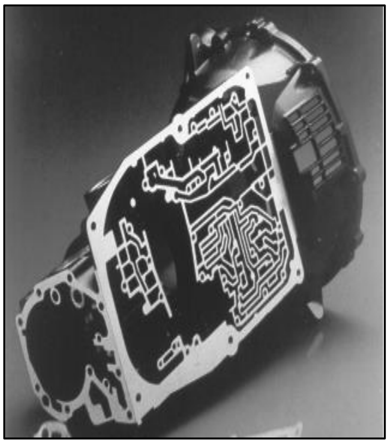


fig.1.3

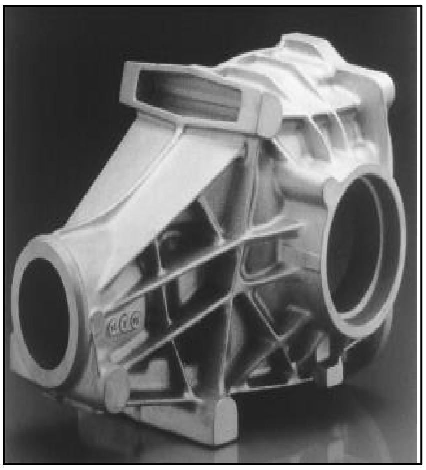


fig.1.4

fig.1.5

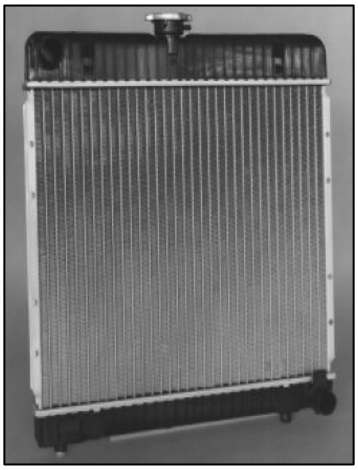


fig.1.6

Different casting techniques can be used considering various number of Quality factors (cracking, surface imperfections, risk of porosity, cooling rate, feasibility, and cost factors). Desired properties can be achieved according to the Specific usage field and casting techniques should be chosen accordingly. It is impossible to eliminate the porosity completely but possibly can be reduced to a minimum level, also cooling rate should be closely monitored.

Sand casting, in the conventional sand casting the mold is formed around a pattern by ramming sand, mixed with the proper bonding agent, onto the pattern. Then the pattern is removed, leaving a cavity in the shape of the casting to be made. If the casting is to have internal cavities or undercuts, sand cores are used to make them. Molten metal is poured into the mold, and after it has solidified, the mold is broken to remove the casting. In making molds and cores, various agents can be used for bonding the sand. The agent most often used is a mixture of clay and water. (Sand bonded with clay and water is called green sand.) Sand bonded with oils or resins, which is very strong after baking, is used mostly for cores. Water glass (sodium silicate) hardened with CO_2 (Carbon dioxide) is used extensively as a bonding agent for both molds and cores. The main advantages of sand casting are versatility (a wide variety of alloys, shapes, and sizes can be sand cast) and low cost of minimum equipment when a small number of castings is to be made. Among its disadvantages are low dimensional accuracy and poor surface finish; basic linear tolerances of ±30 mm/m and good surface finish as well as low strength because of slow cooling, are typical for aluminum sand castings. Use of dry sands bonded with resins or water glass results in better surface finishes and dimensional accuracy, but with a corresponding decrease in cooling rate [6].

Investment casting of aluminum most commonly employs plaster molds and expendable patterns of wax or other fusible materials. A plaster slurry is "invested" around patterns for several castings, and the patterns are melted out as the plaster is baked. Investment casting produces precision parts; aluminum castings can have walls as thin as 0.40 to 0.75 mm, basic linear tolerances as narrow as ±5 mm/m. Some internal porosity usually is present, and it is recommended that machining be limited to avoid exposing it. However, investment molding is often used to produce large quantities of intricately shaped parts requiring no further machining so internal porosity seldom is a problem [6]. Because of porosity and slow solidification, mechanical properties are low. Investment castings usually are small, and thus gating techniques are limited. Christmas-tree gating systems often are employed to produce many parts per mold. Investment casting is especially suited to production of jewelry and parts for precision instruments. Recent strong interest by the aerospace industry in the investment casting process has resulted in limited use of improved technology to produce premium quality castings. The "near-net-shape" requirements of aerospace parts are often attainable using the investment casting techniques

Permanent mold (gravity die) casting, just like die casting, is suited to high-volume production. Permanent mold castings typically are larger than die castings. Maximum weight of permanent mold castings usually is about 10 kg [6], but much larger castings sometimes are made when costs of tooling and casting equipment are justified by the quality required for the casting. Surface finish of permanent mold castings depends on whether a mold wash is used. Basic linear tolerances of about ±10 mm/m, and minimum wall thicknesses of about 3.6 mm, are typical. Tooling costs are high, but lower than those for die casting. Because sand cores can be used, internal cavities can be complex. (When sand cores are used, the process usually is referred to as semipermanent mold casting.) Permanent mold castings are gravity-fed and pouring rate is relatively low, but the metal mold produces rapid solidification. Permanent mold castings exhibit excellent mechanical properties. Castings are generally sound, provided that the alloys used exhibit good fluidity and resistance to hot tearing. Mechanical properties of permanent mold castings can be further improved by heat treatment. If maximum properties are required, the heat treatment consists of a solution treatment at high temperature followed by a quench (usually in hot water) and then natural or artificial aging. For small castings in which the cooling rate in the mold is very rapid or for less critical parts, the solution treatment and quench may be eliminated and the fast cooling in the mold relied on to retain in solution the compounds that will produce age hardening.

Continuous Casting, here casting is continuously withdrawn from the bottom of the mold; because the mold is water cooled, cooling rate is very high. As a result of continuous feeding, castings generally are free of porosity long shapes of simple cross section (such as round, square, and hexagonal rods) can be produced by continuous casting, which is done in a short, bottomless, water-cooled metal mold [6]. In most instances, however, the same product can be made by extrusion at approximately the same cost and with better properties, and thus use of continuous casting is limited. The largest application of continuous casting is production.

Squeeze casting is also known as liquid metal forging, is a process by which molten metal solidifies under pressure within closed dies positioned between the plates of a hydraulic press. The applied pressure and the instant contact of the molten metal with the die surface produces a rapid heat transfer condition that yields a pore-free fine grain casting with excellent mechanical properties [6]. The squeeze casting process is easily automated to produce near-net to net-shape high-quality components. Applications of squeeze-cast aluminum alloys include pistons for engines, disk brakes, automotive wheels, truck hubs, barrel heads, and hubbed flanges. Squeeze casting is simple and economical, efficient in its use of raw material, and has excellent potential for automated operation at high rates of production. The process generates the highest mechanical properties attainable in a cast product [6].

Shell Mold Casting, in shell mold casting, the molten metal is poured into a shell of resin-bonded sand only 10 to 20 mm thick, much thinner than the massive molds commonly used in sand foundries. Shell mold castings surpass ordinary sand castings in surface finish and dimensional accuracy and cool at slightly higher rates; however, equipment and production costs are higher, and size and complexity of castings that can be produced are limited.

Casting processes	Cooling rate, °C/s	Dendrite-arm spacing, mm
Plaster, dry sand	0.05–0.2	0.1–1
Green sand, shell	0.1–0.5	0.05–0.5
Permanent mold	0.3–1	0.03–0.07
Die	50–500	0.005–0.015
Continuous	0.5–2	0.03–0.07

Fig.1.7 Comparison of casting condition and SDAS [6]

Quality factors are also important in the selection of a casting process. It is evident that high cooling rate is of paramount importance in obtaining good casting quality. The fig.1.7 presents characteristic ranges of cooling rate for the various casting processes and the grain property (SDAS).

Chapter 2

Aluminum foams

Concept of porosity (macropores) are developed from the bone and wood which later on better explored through metallic foams that are the best solution to reduce the weight of any component. Metal foams have a unique property such as light weight in combination with higher compression strength, lower specific weight, high stiffness and better energy absorption quality. The idea is adapted to aluminum alloy which is being used in different application areas. A foam is a cellular structure which consists of gas filled pores in a solid metal. Foam exhibits the properties of its parent metal but at a fraction of the weight. They can be classified as closed cell and open cell foams which can be produced by methods such as powder metallurgy technique, addition of gas in melt injection, sintering technique, using agent in melt foaming, and investing casting [3], specific methods are explained. Foams with closed cells are quite strong and less flexible comparing to open cell foams.

Foams can also be distinguished based on the thickness of the outer surface. Foams would be with thick or thin outer skin. Each type of foam exhibits different characteristics for example we can observe different levels of infiltration of the molten metal after casting. Foams can be produced by powder metallurgy has a thick outer layer that prevents the molten metal from entering the foam. Secondly foam with a thin outer skin that is nonhomogeneous and only two faces are facilitated by a fine layer hence cannot be subjected to any kind of surface treatments and high infiltration can be observed after casting. Production of metal foams is a very difficult task because of the simultaneous occurrence of solid, liquid, and gaseous phases at different temperatures. There are number of technologies and methods of manufacturing foamed metals are available but still the foamed metal suffers from deficiencies and non-uniformities. To improve the foam quality, it is necessary to study and understand the foam stability of liquid metals, which will help production techniques of foam metals more reliable and producible. In this review finds the best suitable method for production of aluminum metal foam for mechanical application. It has been experimentally confirmed that aluminum metal foams produced by the Powder Metallurgy method present high pore connectivity hence there is a chance to get good result when we will do the analysis over application.

Production of closed-cell Al-based foams [2] through direct gas injection in the molten metal (fig.2.1): The involved materials generally an aluminium alloy added with 10–30% of ceramic particles (SiC or $Al2O_3$, MgO) with average dimension 5-20 µm, and a gas (air, nitrogen, or argon) injected into the melt through a rotating impeller or a vibrating nozzle to develop a homogeneous dispersion of gas bubbles. The process parameters (gas flow, rotor type, and rotation speed) allow the tailoring of gas bubbles dimensions, while the ceramic particles stabilize cell walls by increasing liquid viscosity and avoiding bubble collapse.

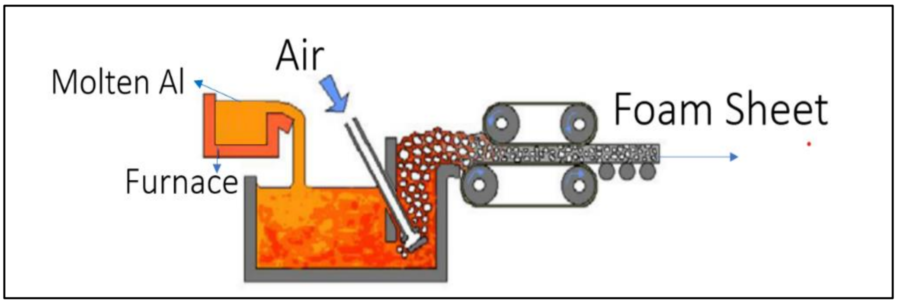


Fig. 2.1 Direct gas injection [13]

Production of closed-cell Al-based foams through in situ gas generation [2], According to this method, gas bubbles are generated by the decomposition of a solid precursor. The Shinko-Wire process foresees the optimization of the viscosity of the molten metal through the addition of about 1.5% wt. calcium metal at 680°C (its affinity for oxygen makes it works a deoxidizer, thus inducing the formation of compounds, e.g., CaO and $CaAl_2O_4$, which increase the melt viscosity).

Production of closed-cell Al-based foams through powder compaction method [2]: The process foresees at first by mixing the metallic powders with foaming agent ones and then by compacting the powders (e.g., uniaxial or isostatic pressing, rod extrusion, or rolling) in order to obtain a compact object with negligible or reduced porosity. Finally, the "green compact" is heated to melt the metallic matrix and decompose the foaming agent. Roll cladding of the foamable precursor with Al dense sheets allows the production of Al-Al foam sandwich panels Among the above-described processes, only the last one produces foams with a continuous and homogeneous external skin with a thickness comparable to the thickness of the pore walls (about 200 μm).

Foam has a melting temperature 660°C and serves up to a maximum temperature 450°C. Most important and very beneficial properties of the aluminum foam are large surface area to volume ratio and high strength to weight ratio thus they can be effectively used in aircrafts and space crafts. It exhibits Isotropic load response which means the foam responds the same way in all dimensions. Good resistance against Corrosion enables them to be used in marine industries. Foams are also well known for their Good electrical and thermal conductivity (less than the dense aluminum alloy because of the presence of air in the pores). Nowadays, manufacturers of aluminum foams can produce metals with similar properties relatively easily. The range of applications of aluminum foams is now much wider. Foams are being used as weight reducing components in aircraft and automotive applications, also Core structures for high strength panels.

Lightweight construction*:* Foams can be used to optimize the weight-specific bending stiffness of engineering components. The bending stiffness of flat foam panels of a given weight, width, and length is approximately proportional to their thickness and therefore inversely related to density [4].

Damping and insulation: Foams can damp vibrations and absorb sound under certain conditions. Moreover, their thermal conductivity is low. These properties are not outstanding polymer foams are much better sound absorbers, but they could be useful in combination with other features of the foam [4].

Foams can be used in crash absorption system due to its Impact absorption ability. Due to its good thermal conductivity, can be used in Heat sinks and exchangers. Matrix for chemical beds and scrubbers and because of good electrical conducting ability foams have found use in Battery plates and spacers. One more interesting application is Filters and mist elimination in water and oil. Sound absorption (sound insulation in cinema and concert halls), Substrates for catalytic converters.

Energy absorption: Owing to their high porosity, foams can absorb a large quantity of mechanical energy when they are deformed, while stresses are limited to the compression strength of the material. Foams can therefore act as impact-energy absorbers used, for example, to limit acceleration in vehicle crash situations. Foams are very useful in Marine industry (ship building) also are being used for military equipment (armor and explosion protection devices).

architecture (interior and exterior designs). These wide range of applications can still be extended but requires further refinement in the quality and manufacturing techniques.

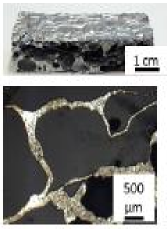
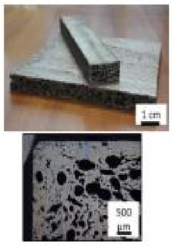
	Foams Produced by Direct Gas Injection (e.g., Cymat Type)	Foams Produced by Powder Compaction Route (e.g., Alulight Type)	Foams Produced by in Situ Gas Generation (e.g., Alporas Type)	Dense Al/Al Alloys	Scaling Factors
Visual appearance and optical microscopy observation of the cross section (example,					-
Material	Al/Al-alloy-SiC	Al/Al-alloy	Al/Al-alloy	Al/Al-alloy	-
External skin	Not continuous	Yes	No	-	-
Density ρ (g/cm^3)	0.054–0.540	0.270–0.945	0.216–0.270	2.7 (Pure Al)	-
Relative density ρ/ρ_s	0.02–0.2	0.1–0.35	0.08–0.1	1 (Pure Al)	-
Elastic Modulus E (GPa)	0.02–2.0	1.7–12	0.4–1.0	70	$E_f = (0.1–1.0)E_s [0.5(\rho/\rho_s)^{2/3} + 0.3(\rho/\rho_s)]$
Compressive Elastic limit σ_c (Mpa)	0.04–7.0	1.9–14.0	1.3–1.7	-	-
Densification strain	0.6–0.9	0.4–0.8	0.7–0.8	-	-
Tensile Elastic Limit σ_y (MPa)	0.04–7.0	2.0–20	1.6–1.8	40–325 (Range for most used Al alloys)	-
Tensile strength σ_T (MPa)	0.05–8.5	2.2–30	1.6–1.9	45–400 (Range for most used Al alloys)	(1–1.4)σ_c
Melting Point (K)	830–910	840–850	910–920	933.15 (Pure Al)	As dense Al
Thermal expansion coefficient α (10^{-6}/K)	19–20	19–23	21–23	21.8–25.5 (Range for most used Al alloys)	As dense Al
Thermal conductivity λ ** (W/mK)	0.3–10	3.0–35	3.5–4.5	218–243 (Range for most used Al alloys)	$\lambda_f = (\rho/\rho_s)^{1.8} < \lambda/\lambda_s < (\rho/\rho_s)^{1.65}$

fig.2.2 Comparison of aluminum-based foams with dense aluminum alloy [2]

fig2.2 summarize the important properties of both aluminum foam and the dense aluminum alloy. the main parameters of foams that affect their final properties are the properties of the material that constitute the foam, the relative density (foam density/bulk material density), foam type (close/open cells), irregularities/defects, dimension, shape, distribution of cells, and their connection. Among them, the highest influence is determined by the relative density.

Furthermore, in the case of closed-cell aluminium foams, the absence of an external continuous skin showed a better sound absorption behaviour when compared to their counterpart with dense skin and some surface mechanical processing (such as drilling, rolling, or compression) have been successfully used to improve sound absorption ability of closed cells aluminium foams, with a continuous skin, by means of the creation of discontinuities in the surface skin or the pores walls [2].

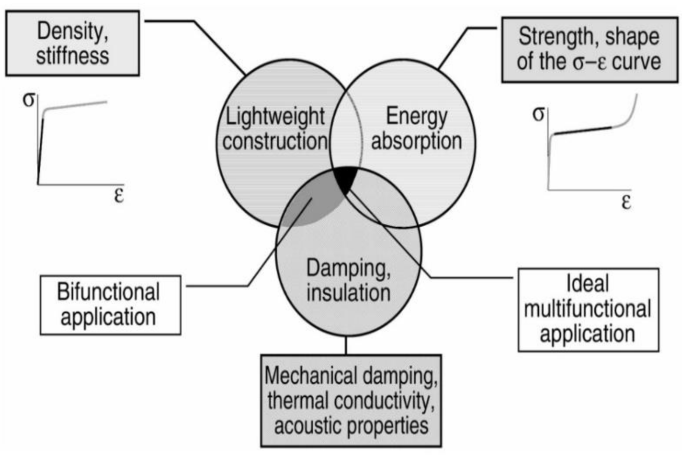
Chapter 3

ALUMINIUM FOAMS AS PERMANENT CORES IN CASTING

POTENTIALITES:

Originally, the inventors of such materials were inspired by natural porous materials such as wood, bone, pumice (a type of stone) and some other porous minerals. Number of new metal foaming technologies have been developed in the past decade which now offer a wide range of different forms of this exciting material. Compared to early developments in the 1950s to 1970s the quality of metal foam has been improved and the possibilities for making composites widened. With some first applications already on the road it seems quite realistic that aluminum foams will find an even wider use very soon in cars, ships, aircrafts or even spacecrafts. Few properties of foam can be related to its applications in fig.3.1.

Recently, LKR (light metals competence center, Austria) and the German car maker BMW have jointly designed an engine mounting bracket based on such composites. It can be loaded with the high weight of a car engine and absorbs mechanical vibrations by internal dissipation into thermal energy. Stiffness is enhanced and, as fracture toughness of such composites is high, these parts also increase safety in crash situations. A new concept developed (gas injection) that leads to foams with excellent cell size uniformity also involves the relatively gentle generation of a multitude of uniform bubbles in the melt. The melt is foamed by injecting gases (air, nitrogen, argon) into the melt using specially designed rotating impellers or vibrating nozzles that generate gas bubbles in the melt and distribute them uniformly. The resultant viscous mixture of bubbles and metal floats to the surface, where it turns into a dry liquid foam as the liquid metal drains out. The foam is relatively stable, owing to the presence of the ceramic particles in the melt. It can be pulled off the liquid surface (e.g., with a conveyor belt) and is then allowed to cool and solidify. Moreover, by casting the foam into moulds, complex-shaped foamed parts with a closed outer skin can be produced [4].



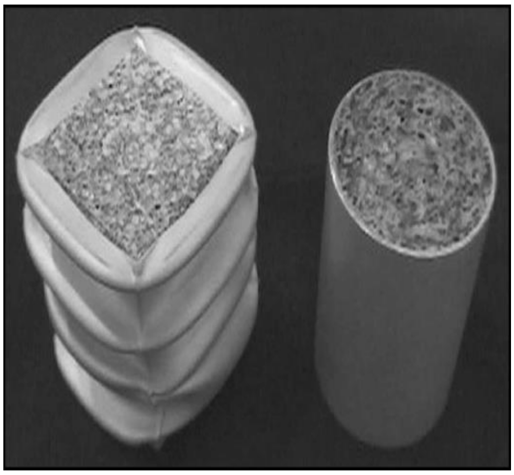


fig.3.1 Mechanical attributes & applications [4]   fig.3.2 prototypes of crash absorber [4]

Thanks to the high flexibility and adaptability of recent developed technologies, porous aluminum(foam) can successfully compete with many porous materials in many applications. In most cases, porous aluminum replaces sintered metals, porous ceramics, porous plastics, nets and wire materials [8]. Fig3.2 shows a deformed foam-filled tube. Studies done by Fiat and the Norwegian University of Science and Technology deform to absorb all the energy of a

15 km/h (9.3 mph) crash, protecting expensive front-end components and the car frame as well as the passengers within. That along with the improved axial energy absorption, there is also great improvement in energy absorption in off-axis collisions because isotropic foams can absorb energy from all directions [4].
Aluminum foam (the porous metal based on aluminum and its alloys) has been known for more than half a century, but still has a relatively small distribution and application. The main reason for this was the low reproducibility of structure and material properties. Thanks to the development of aluminum foam technology has made it possible to overcome some of these difficulties.

CHALLENGES/CRISTICISM

Practically, components produced from this idea is not yet extended to all application levels in a huge amount because there is still a lot to understand and poorly investigated so far. Following are the challenges/criticisms the researchers trying hard to come over:

- **Lack of understanding of the basic mechanisms of metal foaming:** knowledge is still speculative, some points remain unclear, example what is the reason for the existence of a critical cell wall thickness?
- **Insufficient ability to make foams of a constant quality:** with predefined parameters that is, lack of control of structure and morphology. Limited stability of emerging metal foams is one reason for these problems.
- **Need of Rigorous analysis:** the interrelationship between morphology and structure on the one hand, and mechanical properties on the other is not sufficiently understood.
- **Physical properties of the foams are not good enough:** these seems to be still some potential for an improvement of properties by optimizing foaming processes and material selection.
- **Knowledge of foam properties is insufficient:** further characterization of properties is necessary.
- **Transfer of research results to construction engineers not sufficient:** databases and design guidelines for metallic foams must be created or shared.
- **Foams are still too expensive:** mass production will lead to lower prices, but metal foam will never be a cheap material. Therefore, the selection of applications where the specific properties of foams are fully exploited is indispensable. Because this search cannot be done without a detailed knowledge of the properties of foams and of the limits of foaming design engineers will not start such a search: a classical viscous circle [8].

Though, these components have been found to be useful, a lot to be focused on implementing innovative surface modifications for this external skin as promising strategies for the optimization of cast components with a foam core. Bonding between the foam and the aluminium and infiltration of molten metal into the foam must be investigated rigorously, on the other hand porosity of foam, chemical composition of both the aluminium foam and the aluminium alloy must be taken into consideration along with the casting conditions (cooling rate). The few published works related to the use of Al-based foams as cores in casting include some details and characterizations, but almost no solutions have been proposed and discussed to overcome the criticisms.

Chapter 4
Materials and Methods

Casted components (from which samples are taken out) with foam cores were prepared by gravity casting of Al-Si-Cu-Mg alloy (ENAB.46400) by TEKSID ALUMINUM SRL. Aluminum metal foams with thick outer skin (AlMgSi1 alloy with limited amount of TiH_2 as foaming agent, Havel metal foams) were used as cores. A surface treatment with surface grinding followed by Nitric acid etching (HNO_3-12%) was performed on the foams before inserting as cores. Samples 15 & 19 have been investigated through CT scan, underwent metallographic preparation (which consists of cutting, resin mounting and polishing), optical observation, measurements of hardness, scanning electron microscope (EDS). CT scan and EDS analysis can be carried out in any stage to understand and identify the further possible interaction regions.

Fig.4.1 CT scan set up with acquisition system

Computed tomography (CT-Scan) is a nondestructive technique, based on absorbing X-rays, that helps in visualization of the internal microstructure of material. X-rays can travel through matter, losing energy on the way, in accordance with the law of Beer that equates intensity (I) with a monochromatic X-ray travelling through an object in terms of the following expression.

$$I=I_0 * e^{\{-\int \mu(s)ds\}}$$

where I_0 is the initial intensity of the ray and μ(s) the linear attenuation coefficient along its trajectory. The above-mentioned linear attenuation coefficient (μ) fundamentally depends on the density (ρ), of the material at each point through which the ray travels. The quotient μ/ρ is approximately proportional to Z3 in the standard range used in the computed tomography (CT) scan. An acquisition system attached to it helps us in identifying zones of bonding where our focus of attention concentrates on. This was done in a closed environment to avoid the effect of radiation.

Fig.4.2 Cutting Machine

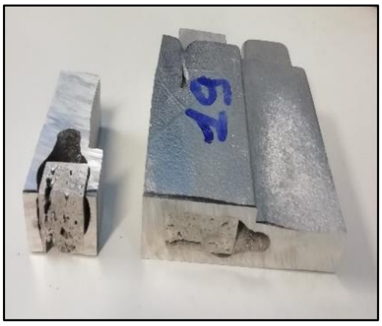


fig.4.3 After cut-sample 19

Cutting: Component is cut in such a way (into cubes-fig.4.3) that it can be gone through the further preparational processes using cutting equipment depicted in the fig.4.2. Safety measures were respected to keep the operation safe. It is recommended to be precise while cutting the casted components because it is very essential to cut the component in the position suggested after performing the CT scan.

Resin mounting: the cut samples should be mounted in the resin to make the samples convenient to handle. Any resin is basically a polymer which will be in powder form, after which becomes a permanent solid reacting with chemicals. Resin powder is used twice the quantity that of the liquid (2:1). Which is later positioned in a mould in which our test specimens are placed in inverted position. Then it must spend some time in Hood Integrated control to avoid inhalation of the reaction products which might affect one's health. This process took place in a laboratory (closed environment) then following polishing is carried out. All these works are carried out in the room temperature.

Fig.4.4 Polishing machine

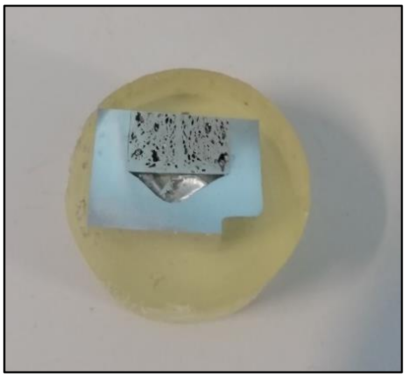


fig.4.5 Sample 15

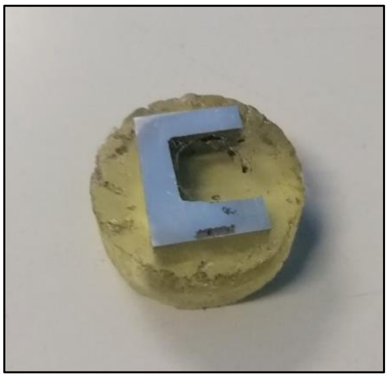


fig.4.6 SAB

Polishing: Generally, to observe at an optical microscope, its surface should be clearly polished up to a mirror finish is observed. If not, there would not be chance of proper recognition of the microstructure due to a bad reflection caused by the imperfect surface. Sandpaper with different grit number is used in an ascending order (60,80 up to 4000 grit no.) because higher the grit number (represents the silicon carbide particle sizes in µm) finer the sand particles are. The surface of the sample is polished mainly because of the friction between the fixed sample and the rotating sandpaper which is mounted on the rotating table (fig.4.4). Water is used to control the temperature under safe limit and to flush out the residuals come out after the abrasive action between the sample(which is mounted in the resin-fig.4.4). In the final round of polishing diamond paste (1µm) which is shown in the fig.4.7 is used to achieve mirror finish. Getting the mirror finish is the essential output of the metallographic preparation. It was a big challenge to obtain the mirrored area because aluminum is comparatively soft metal which is vulnerable for damages. Well prepared Samples are depicted in the fig.4.5 & fig.4.6.

Fig.4.7 Diamond pastes (different size)

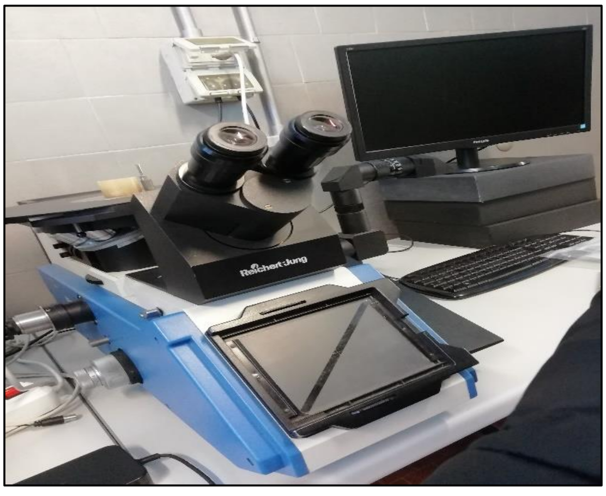


fig.4.8 Optical Microscope

After, these well-prepared samples are analysed with optical microscope (fig.4.8) to which an acquisition system is attached that helps in storing the real time images. These images will be

taken with different magnifications (20x,50x,100x and 200x). It is possible to achieve magnifications up to 500x & 1000x, but it is very difficult to focus since the operator should be very experienced to operate the microscope in the microscale.
Clear microstructural images of the cast objects at a good magnification are used for calculating the secondary arm dendrite spacing (measured using the software ImageJ) considering the scale of the image. SDAS is nothing but the distance between the secondary arms and is calculated by deviding the entire length of the primary arm with total number of secondary arms minus one. The same is formulated below:

$$SDAS = \frac{total\ length\ of\ the\ primary\ arm\ segment}{total\ no.\ of\ secondary\ arms - 1} \quad (\mu m)$$

SDAS is directly linked to properties of the materials[1], it is very essential to have the SDAS value as low as possiple which yields better properties of the materil. It is also an important aspect to be considered and it can also be affected by cooling rate. Hence these two factors have higher significance in improving the material properties.

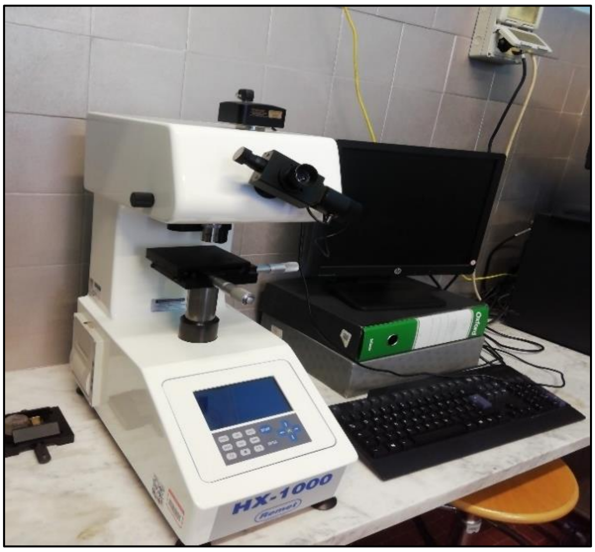


fig.4.9 Vickers Microhardness test setup

Hardness Measurements: Sample prepared from the casted object (dense steps) is subjected to hardness test. There are various number hardness tests available such Rockwell, Brinell, Vickers and so on. Vickers hardness is the preferred as it allows us to measure the microhardness of the sample. This is done by using vickers hardness test setup (fig.4.9) along with data acquisition system through which results can be stored in a computer. 10 gram force was applied on the sample for 10 seconds. Multiple number of trails have been performed to reduce the errors thus increasing the reliability of the results.

To be more rigorous about the chemical composition of the casted component, EDS can be performed to analyse and distinguish the chemical composition of the sample in the different region along with the interface (in some regions it is necessary to confirm that bonding zone is metal not resin). It is necessary to understand the chemical composition in the interface which helpd us tp characterize the material properties. The chemical analysis (microanalysis) in the scanning electron microscope (SEM) is accomplished by measuring the energy and intensity distribution of the X-rays generated by the electron beam on the sample using an energy dispersion detector EDS (energy dispersion spectrometry). Increased magnifications allowed us to quantify the elements both in terms of mass and atomic percentages. The energy emissions are translated into spectral peaks of varying intensity, resulting in a spectrum profile. We had to wait for a period of 1 minute for the acquisition system to acquire a spectrum under stabilized signals which results in more reliable attribution. EDS privileged us to a magnification of 1000x where in SEM allowed furthermore magnifications. This chemical analysis was done very carefully because signals were affected by the surrounding objects.

Chapter 5

Results and Discussion

Results obtained are investigated considering the properties of the foam along with potentially affecting factors such as surface treatments, chemical composition. We have to situate the findings of each steps performed which will help us correlate the affecting factors with material properties. It was clearly visible that casted component without surface treatment on the foam (fig.5.1) showed high level of separation between the foam and the aluminium. The main reason was the aluminum and magnesium oxides which prevents the bonding after the molten metal enters the mold. Below images helps us to distinguish the catsed camponents in a explicit manner. Fig.5.2 shows the final casted component, we can notice the bonding between the foam and the aluminum is very poor, the same can be expected in interiors.

Fig.5.1

fig.5.2

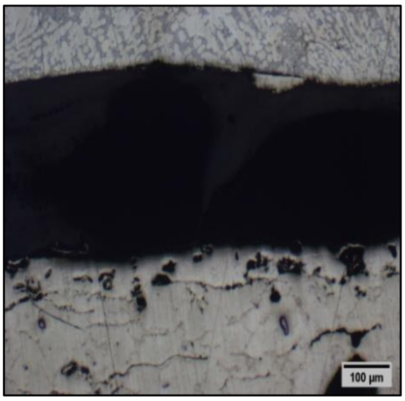


fig.5.3

In fig.5.3 (microscopic view), it is clearly noticable that there is a big gap between the core and the shell. This is because, the Mg & Al oxide layers preventing the interaction.

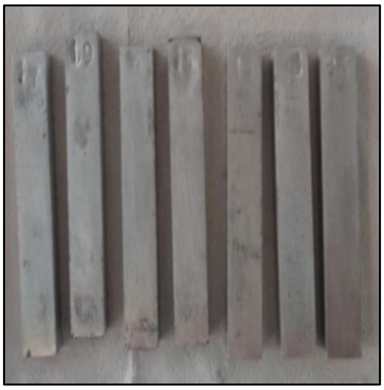


Fig.5.4

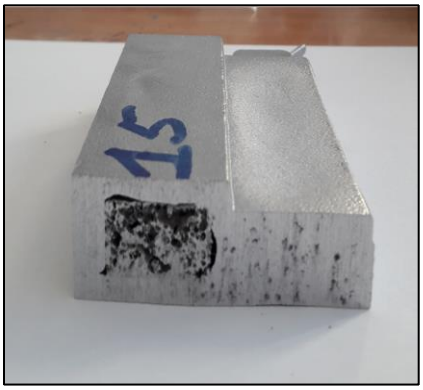


fig.5.5

fig.5.6

Wherein the surface treatment (grinding with grit no.320 and 13% nitric acid etching) resulted in a quite good bonding as depicted in the fig.5.5. Effect of the surface treatment on the foam is depicted in the fig.5.4. In the microscopic view of the component (surface treated foam) is easily noticable (fig.5.6) that there is quite good bonding. We should observe that thick outer skin of the foam prevented the molten metal from infiltration while casting in both the treated and untreated cases. However, surface treatment has played a vital role in the interaction between the foam and the aluminum.

CT scan images also helps us to understand the difference between the treated and untreated foams in the aspect of bonding.

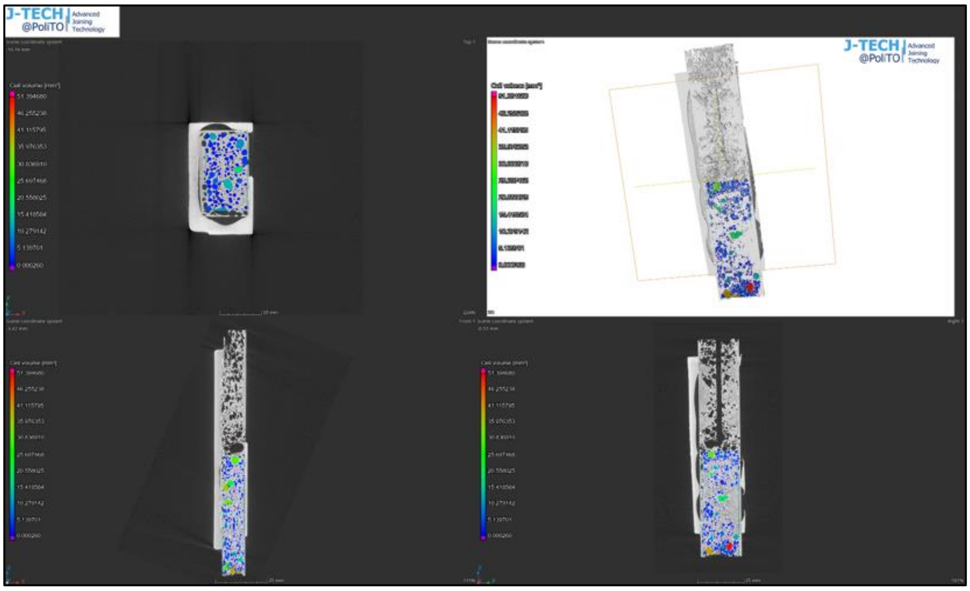


Fig.5.7 CT scan images of the cated component (untreated foam)

Recently developed softawares can be used in the acquistion system not only to visualize the interior but also the objects can be coupled with thermal analysis.

We can clearly observe a big gap between the foam and aluminum in the fig.5.7 throughout the casting which was caused due to presence of the Mg and Al oxides. This suggested us the removal of these oxides will improve the bonding between the foam and aluminum. Grinding with sand paper (grit no.320) and 13% nitro acid etching were carried out to eliminate these oxides and casting is performed.

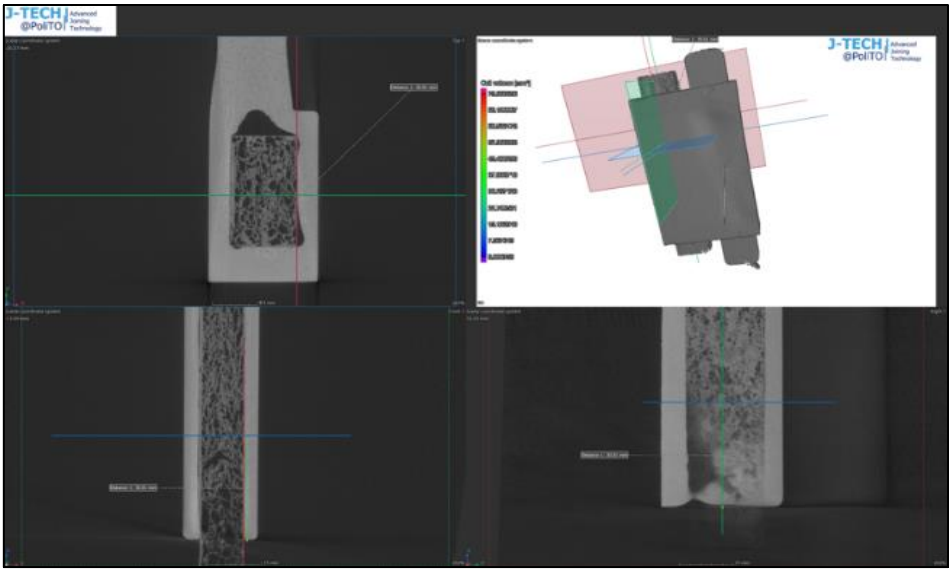


Fig.5.8 CT scan images of sample 15 (surface treated foam)

Improvement of level of bonding can be observed in the fig.5.8 as we are succeeded in eleminating the gap which was observed in fig.5.7. There is a presence of the macro pore that is created due to the shrinkage of the casted object which can be avoided with the better control of temperature.

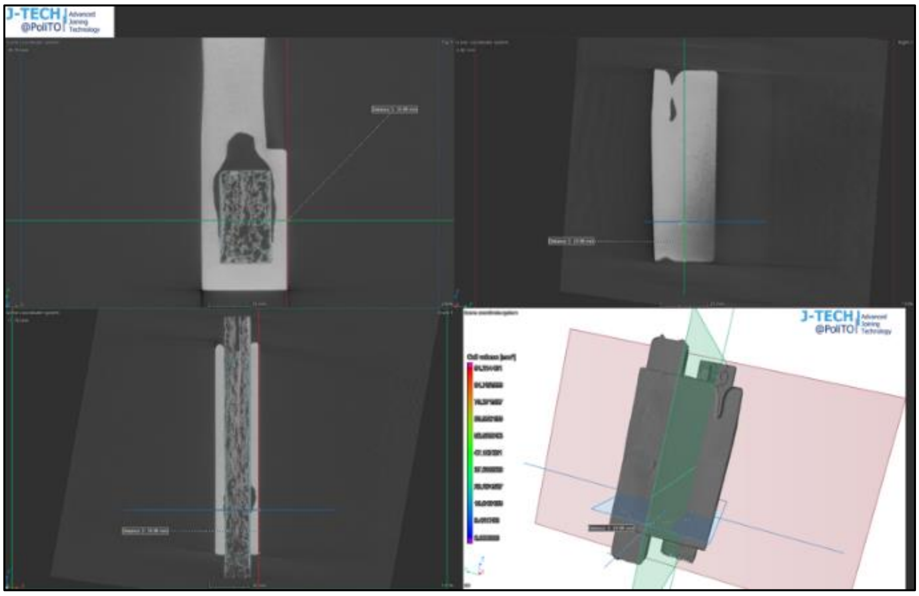


Fig.5.9 CT scan images of sample 19 (surface treated foam)

Fig.5.9 is the CT scan image of sample 19 demostrates the same result as the sample 15. We do not get to observe a big separation between the foam and aluminum instead we obtained a considerably better bonding. The marco pores that are present outside the foam is due to shrinkage of the aluminum and there is no infiltration due to the presence of thick outer skin. It can be noticed that there is a presence of the marco pore around the foam is mainly occured to the shrinkage of the aluminum during the solidification process. This technique can also be used after the preparation of the samples to investigate furthermore points where foam and the aluminum are reacted and bonded.

Observing the well-polished surfaces of the prepared samples in the optical microscope helped us to understand the microstructure of the respective samples. Focus of attenstion is concentrated on the interface between the core and the shell. Fig.5.10, 5.11 & 5.12 depicts the optical microscopic views of sample 15 in different bonding regions, It is observed that there is a significant bonding (which can be seen in fig.5.13, 5.14 & 5.15 of sample 19 also). These images represents the microstructural view of a perticular location hence these can be furthermore subjected to metallographic preparation and optical observations.

Further magnifications can be achieved inorder to anlyse but very difficult to focus.

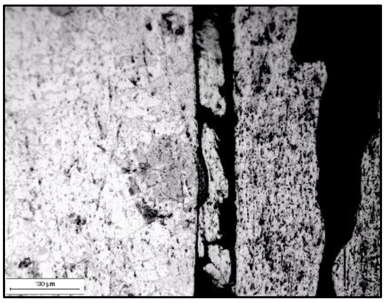


Fig.5.10 sample 15 (100x)

Fig.5.11 sample 15 (200x)

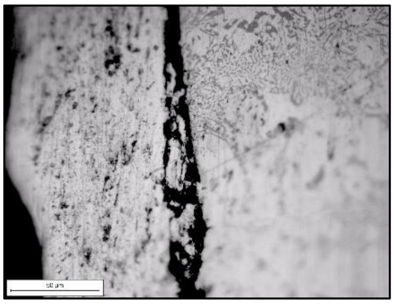


Fig.5.12 sample 15 (50x)

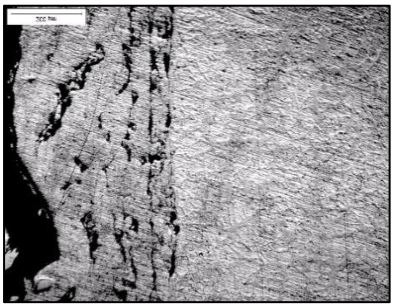


Fig.5.13 sample 19 (100x)

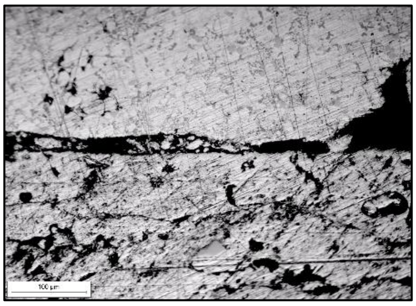


Fig.5.14 sample 19 (200x)

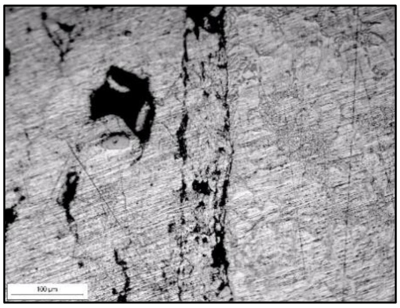


Fig.5.15 sample 19 (200x)

Focusing in the aluminum, properties of which is more essential that will affect the properties of the whole casted component. Observations used for SDAS calculations are:

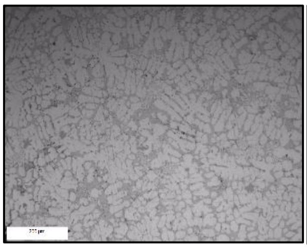


Fig. 5.16 sample 15

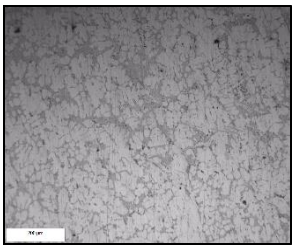


fig.5.17 17 shell

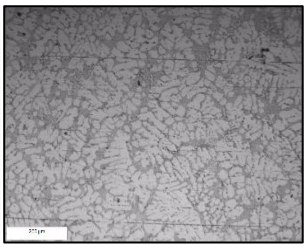


fig.5.18 sample 19

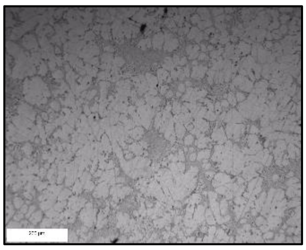


fig.5.19 No insert

We know the fact that more refined grain structure results in better material properties such as strength, fatigue life, yield strength and toughness. So it is important to keep the secondary dendrite arm spacing as low as possible.

Along with the sample 15-fig.5.16 & sample 19-fig.5.18 which are prepared so far, other samples (e.g,. sample 17-fig.5.17 & sample No insert-fig.5.19) are also subjected for SDAS calculations and micrso hardness test which help us to better understand, compare and investigate the material properties. SDAS values obtained are represented in the fig.5.20.

multiple trials were considered for the calculation which resulted with deviation in values. Higher deviation values indicates the deviation the test results form the mean value.

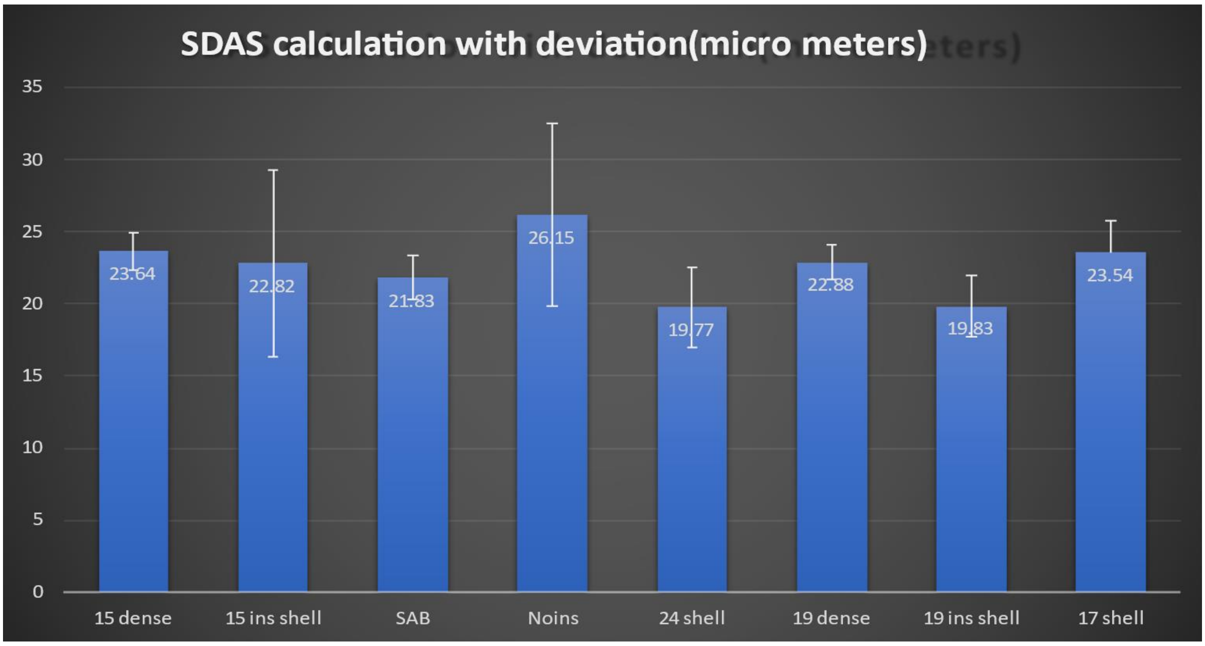


Fig.5.20 Secondary dendrite arm space values of respective samples

SAB in the fig.5.20 represents the sample that was casted with sand core as the temporary core. Further processes of removing of the sand from the core and cleaning are necessary. Foam is used as the substitute in the place of care to to act as a permanent core to overcome these issues. We can observe that Noins (dense aluminum) shows the highest SDAS value which is supposed to be refined under controlled cooling rate.

Followed by, the results obtained from the microhardness test (Vickers test) are depicted in the fig.5.21 which underwent with more number of trials to compensate the errors caused by eutectic regions.

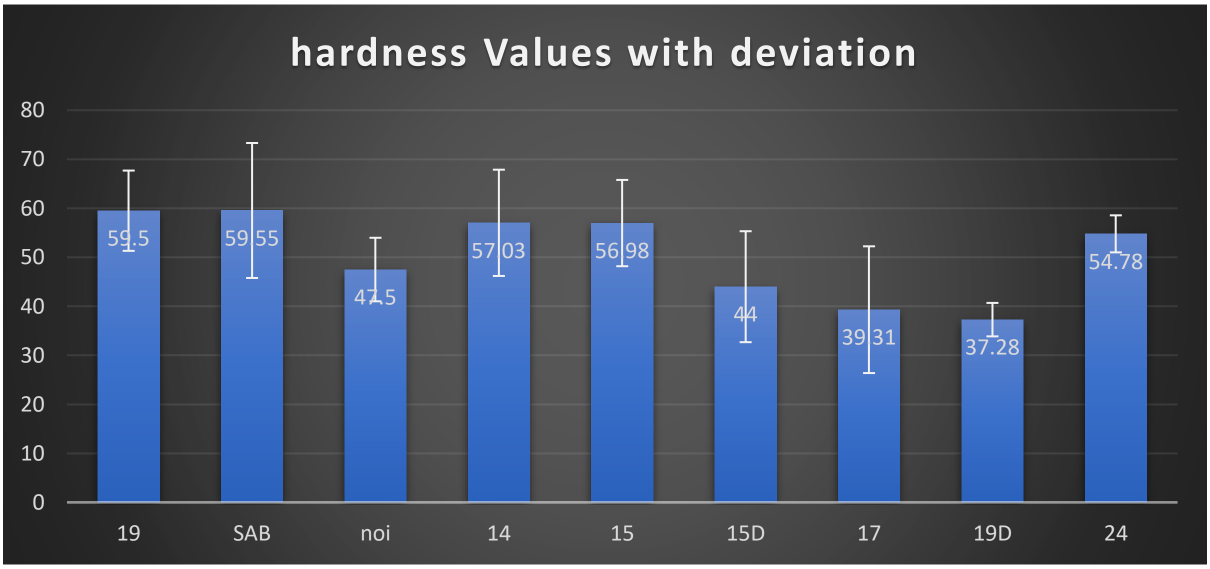
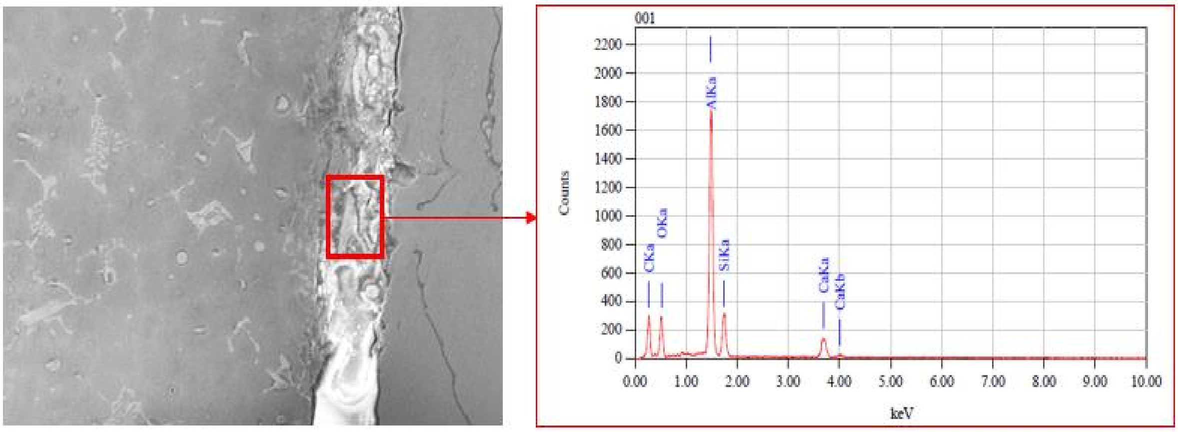


Fig.5.21 Micro hardness test results for different samples

Deviation values are calculated also for these results which indicates how data are dispersed with respect to the mean value (Average value). Hardness of the tested sample (foam as core) is higher than that of dense aluminum which can be seen in the fig.5.21.

EDS analysis is performed to underatand the chemical spetra. We are more focused on the reaction zone/interface because that is where improvemnts have to done. Fig.5.22 quantifies the chemicals in the bonding zone and represented in the chemical spectra.



ZAF Method Standardless Quantitative Analysis
Fitting Coefficient : 0.0786

Element	(keV)	Mass%	Sigma	Atom%	Compound	Mass%	Cation	K
C K*	0.277	38.20	0.58	52.75				14.3376
O K	0.525	24.88	0.66	25.80				23.3302
Al K	1.486	25.29	0.31	15.55				43.8572
Si K	1.739	6.19	0.19	3.65				7.9156
Ca K	3.690	5.44	0.20	2.25				10.5594
Total		100.00		100.00				

Fig.5.22 EDS Analysis at the interface (zone 1)

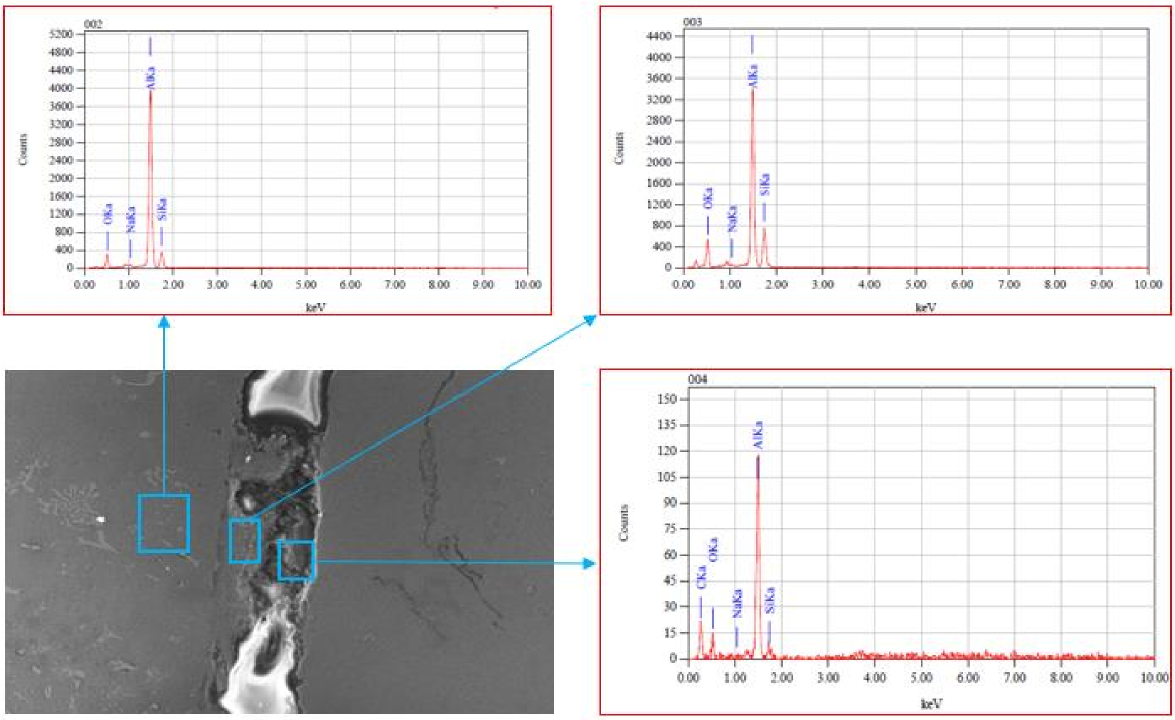


Fig.5.23 EDS Analysis at zone 2

Different positions at the zone 2 are focused, analysed and chemical spectrum is generated as shown in the fig.5.23. This analysis supports an effective bonding at the interface.

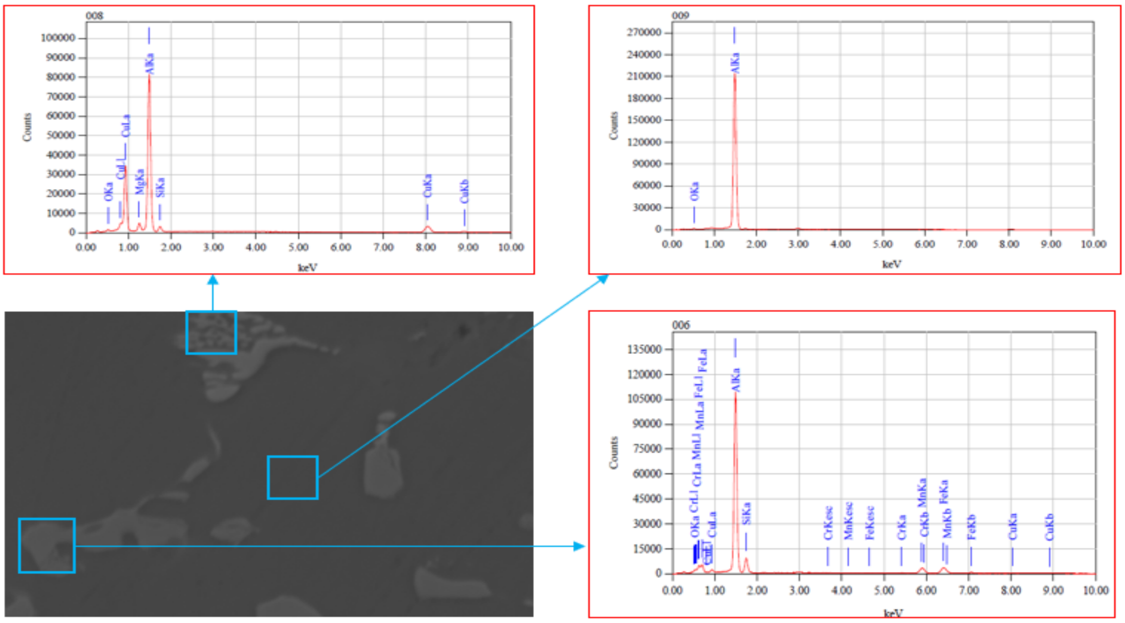


Fig.5.24 EDS Analysis at zone 3

The results obtained for zone 3 (quite far from the interface) are presented in the fig.5.24. This chemical analysis suggests the presence of Cu,Si, as major alloying elements and a small trace of O and C in the interface and are characteristics of second phase highlighted in the picture. The acquisiton system took aprroximately took 1 minute to display the results. The obtained results from the tests so far, should be analysed on scientific and rational basis, they can be correlated with solidification rate which was recorded by implementing the thermocouples to the casting components. The cooling rate (temperature evolution with respect to time) is recorded and depicted in the fig.5.25. Blue graph represents the thermocouple connected to foam insert, green represents the molten metal and red graph is the die. The cooling rate must be determined which is avilable for each samples and should be exploited for the further improvements in the material properties. Cooling rates are clculated for samples 14, 15, 14 and 19. They are 99°C/sec (sample 14), 106°C/sec (sample 15), 162°C/sec (sample 17) and 152°C/sec (sample 19) from the fig.5.22.

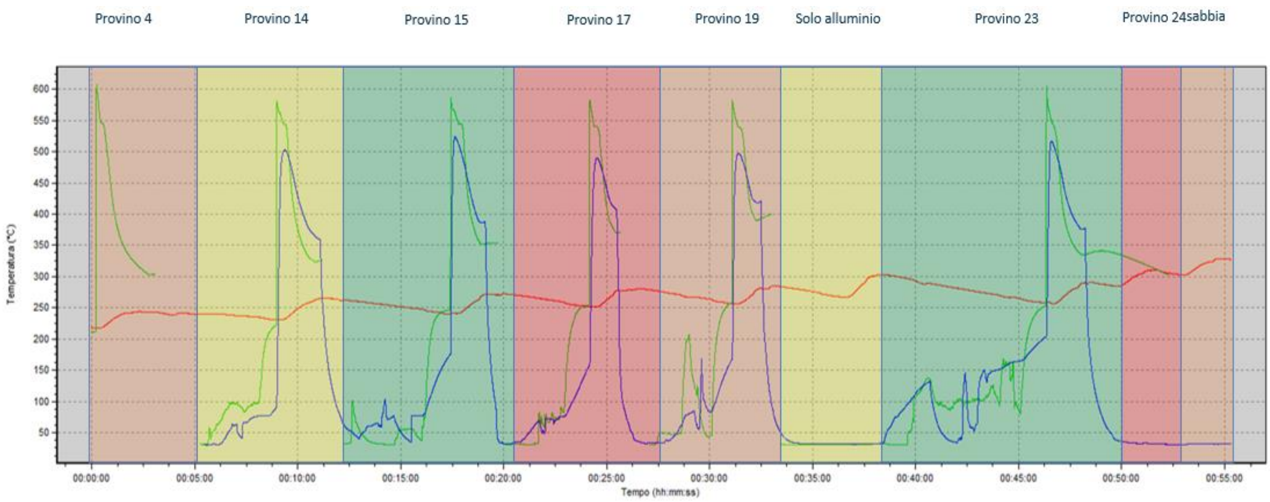


Fig.5.25 Cooling rate of each samples

Conclusion:

Major observation is that surface preparation (grinding with grit no.320 and 13% nitric acid etching) resulted in better bonding between the aluminum foam and the molten aluminum, since the oxides of aluminum and magnesium are eliminated using this surface treatment technique. It can still be improved presumably by heating the foam core to increase the time of contact between the molten metal and the permanent foam core. However, It is still considerably good comparing to the one without any surface treatments before the casting. It should be acknowledged that marco pores around the foam which was occurred mainly due to shrinkage during the solidification process can be reduced by better control of the temperature. CT scan supported the same observation (surface preperation yileded good reaction at the interface) and helped to visualize the same result in the interior part of the casted object. CT scan evidenced thatsurface treatment ended up with notable improvements in better bonding. One more important remark is that the thick outer skin layer of the foam completely prevented the molten metal from penetrating into the foam (infiltration) throughout the foam length.

Using the aluminum foam as the permanent core is very much preferable over sand core which is being used as a temporary core in casting techniques considering the fact that it exhibits almost the similar properties which was observed in the SDAS (secondary arm dendrite spacng) and Microhardness tests. Infact using sand cores requires post casting processes such as removal of the sand from casted object and grinding to get a better surface finish. So it is commodious to use the permanent foam core as the substitute for the sand core. Refined Secondary dendrite arm spacing and microhardness tests concluded the certainty that material displayed better mechanical properties which means that use of foam cores does not increas SDAS compared to the absence of the insert.

Solidification rate is strongly linked with the material properties (mainly SDAS and Hardness values). Rapid cooling (high solidification rate) results in more refined SDAS which means better material properties (hardness). However, there is no significant evidence that correlates SDAS and hardness values. The results from this work would be very useful for the future application of this technology in Mechanical Engineering field.

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