Ultrasonic Treatment to Molten FEM©™ Aluminum Alloy and Effects of Ultrasound Treatment Time Period on Porosity

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***Abstract*—Today, in the industry of aluminum, the D. C. casting of billets and slabs is playing the major role. The producers of these slabs and billets are many. The end users of the product are OEMs. The degassing technology for producing these aluminum slabs and billets is provided by very few.**

There are two types of degassing methods currently in use. One of these, vacuum degassing, is used primarily in the steel industry and thus not generally used in the aluminum industry. The second method, generally employed in the aluminum industry, is rotary degassing, which uses finely dispersed argon, chlorine, fluorine to remove dissolved hydrogen and various salts from melt.

The challenges associated with producing aluminum are reducing porosity due to hydrogen precipitation during casting through degassing processes; which generates detrimental effects on mechanical properties of alloy castings and removing impurities like; the Ca, Mg salts etc. from the molten metal.

Looking at the degassing systems provided by these players, are going to be obsolete as the environment norms will become stricter in the next decade, because of the use of Fluorine and Chlorine for removing the Ca, Mg, etc. impurities from the molten metal as the ozone layer is getting depleted and process becomes more cumbersome and hazardous.

So, the innovation in the technology is needed; which leads research interest on development of the ultrasonic degassing as a better option.

During this research authors would be using ultrasonic technology over existing technology to compare the results of conventional degasser units available in the market such as LARS™, SNIF™, STAS™ - ACD™, Alpur™, MDU™ etc., and would be finding out the better operating parameters of ultrasonic equipment for the process for replacement of Fluorine and Chlorine based old technology with Ultrasonic Technology.

This research paper should underpin improvement in the process and hence improved hardness of material by elimination of the fluorine and chlorine usage by replacing it with ultrasonic technology with suitable mechanical design, metallurgical criteria and thermal analysis consideration.

During the entire research and development authors had carried out various operations like Research on thermal and metallurgical behavior of the molten metal and alloys, Comparison of results achieved using ultrasonic technique over existing technique, Formulation of conclusion; making ultrasonic technique a proven technology, and Identifying the further scope of research and development.

With the experiments carried out, authors found significant reduction in porosity of the material produced by ultrasonic degassing as compared with the porosity of material produced by conventional degassing.

***Index Terms*—Ultrasonic Degassing, Aluminum Purification, Dissolved Hydrogen, Porosity, Hardness, Green Technology for Aluminum Purification.**

I. INTRODUCTION

Ultrasonic degassing uses high-intensity ultrasonic vibrations to generate oscillating pressures in molten aluminum. In the region of minimum pressure, cavitations occur in the melt, and fine bubbles are produced. The bubbles produced during cavitations could provide nuclei for hydrogen bubbles to coalesce and flow out of the melt [5, 10, 12, 16, 19].

However, very little work has been reported on the application of ultrasonic energy to the degassing of aluminum alloy melts. Most of the data is empirical, and only general phenomenological studies have been conducted.

An initial work had been reported by G. I. Eskin et al. who had studied the effect of Ultrasonic Processing of Molten Metal on Structure Formation and Improvement of Properties of High Strength Al-Zn-Mg-Cu-Zr Alloys [12]. They also had reported investigation on Broad Prospects for Commercial Application of the Ultrasonic (Cavitations) Melt treatment of Light Alloys [16].

A. R. Naji Maidani et al. had studied hydrogen bubble growth during ultrasonic degassing of Al–Cu alloy melts [5]. The mathematical model developed by them for bubble dynamics is the driving force behind the ultrasonic degassing technology.

Furthermore, LÜ Shu-Lin et al. had studied the effect of semi-solid processing on microstructure and mechanical properties of 5052 aluminum alloy [10].

Effect of power ultrasound on solidification of aluminum A356 alloy had been demonstrated by X. Jiana at al. [2]

LI Guo-feng et al. had reported their work on effects of retrogression heating rate on microstructures and mechanical properties of aluminum alloy 7050 [1].

A comparative study about evolution of the Eutectic Microstructure in Chemically Modified and Unmodified Aluminum Silicon Alloys had been done by Hema V. Guthy [3].

Thomas T. Meek had developed Ultrasonic Processing of Materials laboratory at University of Tennessee with co-operation of Oak Ridge National Laboratory of USA [9].

Although the increasing popularity of ultrasonic degassing technique and remarkable efforts and significant achievements of all above mentioned researchers, it is not used commercially for degassing because lack of experimental work comparison of results associated with ultrasonically degassed material properties with conventionally degassed material.

Moreover, not a significant work has been reported after the tilting mechanism added to existing degassing technique in recent years. No work has been reported on the Aerospace (6xxx, 7xxx, 8xxx), Marine (5xxx), Automobile (2xxx), and FEM©™ Directionally Chilled Aluminum Alloys using Ultrasonic Degassing Principle. No metallurgical study and experiments carried out for above mentioned alloys produced using Ultrasonic degassing technique. No validation of the properties of above mentioned alloys has been done using ultrasonic degassing technique.

Authors had identified this research gap and had developed ultrasonic degassing equipment which is suitable for industrial application and commercialization of the technology. The author's research work on comparison of results associated with ultrasonically degassed material properties with conventionally degassed material properties would be a step towards breaking the barriers for adopting the technology for industrial use. In the ultrasonic degassing, purification and grain refinement rate can be found maximum which is actually resulting into minimum porosity level in treated solidified samples under reduced atmospheric testing conditions as compared with conventional degassing sample and hence the improvement in material properties after solidification can be observed [1, 2, 4, 8, 9, 10, 12, 16]. In context with this point, authors had performed the experiments during monsoon days when the relative humidity of surrounding atmosphere was observed and recorded 70 % which is a crucial parameter to be considered. More the relative humidity level attracts more hydrogen contamination within the stipulated time period after degassing in a degassed molten metal. Authors had considered this factor and hence the experiment was performed with maximum relative humidity level in surrounding atmosphere of experimental work. However, authors had left the option of studying the effect of relative humidity of atmosphere on degassing process for aluminum alloys for the future work for researchers inclined to develop this technology to further advance level.

Material's porosity plays an important role in its applicability. This research paper should underpin improvement in reduction of porosity level of material which is widely used in Automobile, Marine and Aerospace Industry. Authors had considered Ultrasonic Processing Time as individual parameter as a prominent input factor and effect of it is discussed on the porosity in this research paper.

II. NOMENCLATURE

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D. C. Castings: Directionally Chilled castings

OEM: Original Equipment Manufacturer

Ca: Calcium

Mg: Magnesium

Zn: Zinc

Cu: Copper

Zr: Zirconium

Ti: Titanium

V: Vanadium

Al: Aluminum

USA: United States of America

Kg: Kilo Gram

KHz: Kilo Hertz

Hz: Hertz

KW: Kilo Watt

Ar: Argon

N_2: Nitrogen

F_2: Fluorine

Cl_2: Chlorine

%: Percentage

°C: Degree Centigrade

K: Kelvin

m: Meter

mm: Millimeter

μ: Micron

μm: Micrometer

GPa: Giga Pascal

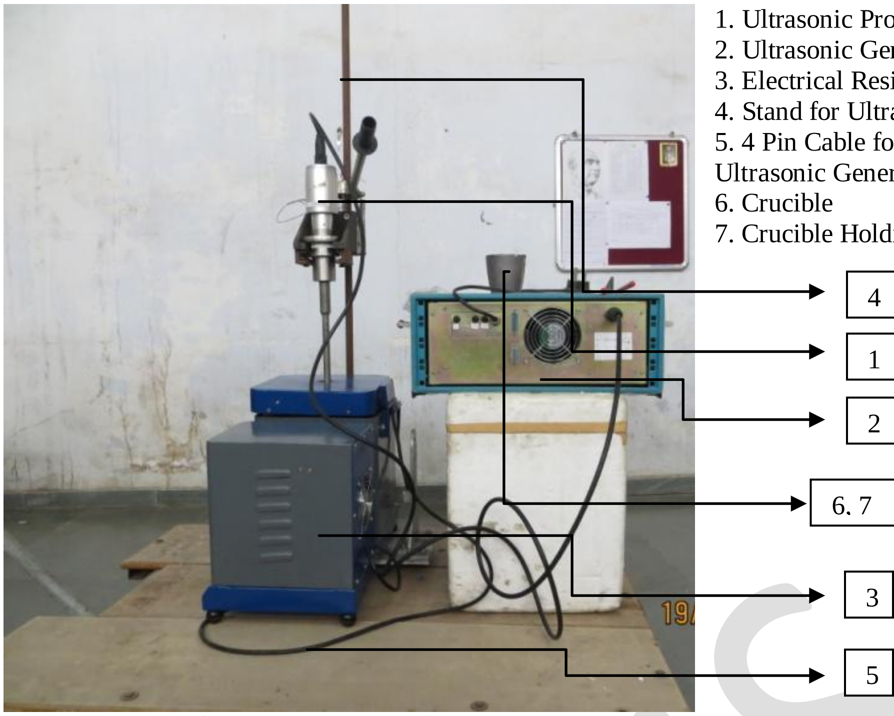
MPa: Mega Pascal

KN: Kilo Newton

LED: Light Emitting Diode

III. EXPERIMENTAL SETUP

Author's equipment is as per Figure-1. It consists of graphite crucible of 3 Kg capacity in which molten metal gets purified by inserting an ultrasonic probe with 20 KHz frequency [10] and 2 KW power, which is surrounded by resistance furnace with temperature control device which can heated up to 1280 °C temperature within the time period of 30 minutes. The furnace has set temperature device which can be used for setting up the temperature as per user's wish. The heating coil gets disconnected when temperature reach + 3 °C than set temperature value. Heating starts again as the temperature falls down -3°C than set temperature. The ultrasonic probe is made up of titanium niobium alloy and can be fitted on a stand with mechanism which provides linear movement to it in vertical direction for insertion and removal purpose. The probe gets connected with the ultrasonic generator by flexible four way cable. Authors had replaced rotating parts of existing technology equipment with ultrasonic probe as per Figure-2. In details of Figure-2 the cross sectional view of ultrasonic probe with internal parts is shown.



1. Ultrasonic Probe Assembly
2. Ultrasonic Generator Assembly
3. Electrical Resistance Furnace
4. Stand for Ultrasonic Probe Fitment
5. 4 Pin Cable for connection of Ultrasonic Probe Assembly to Ultrasonic Generator Assembly
6. Crucible
7. Crucible Holding Device

Photograph 1: Experimental Setup

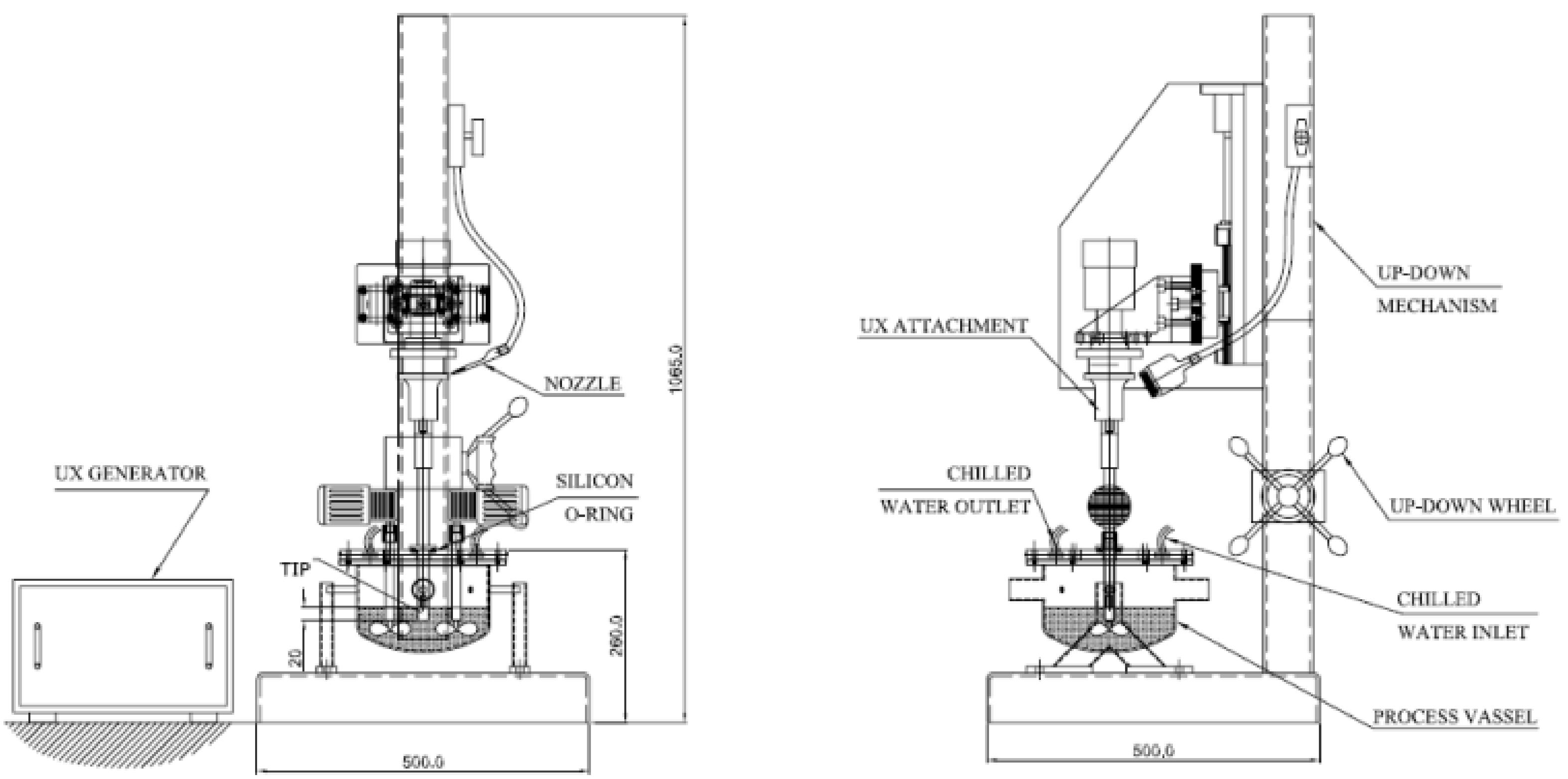


Figure-1 Equipment Front View and Side View

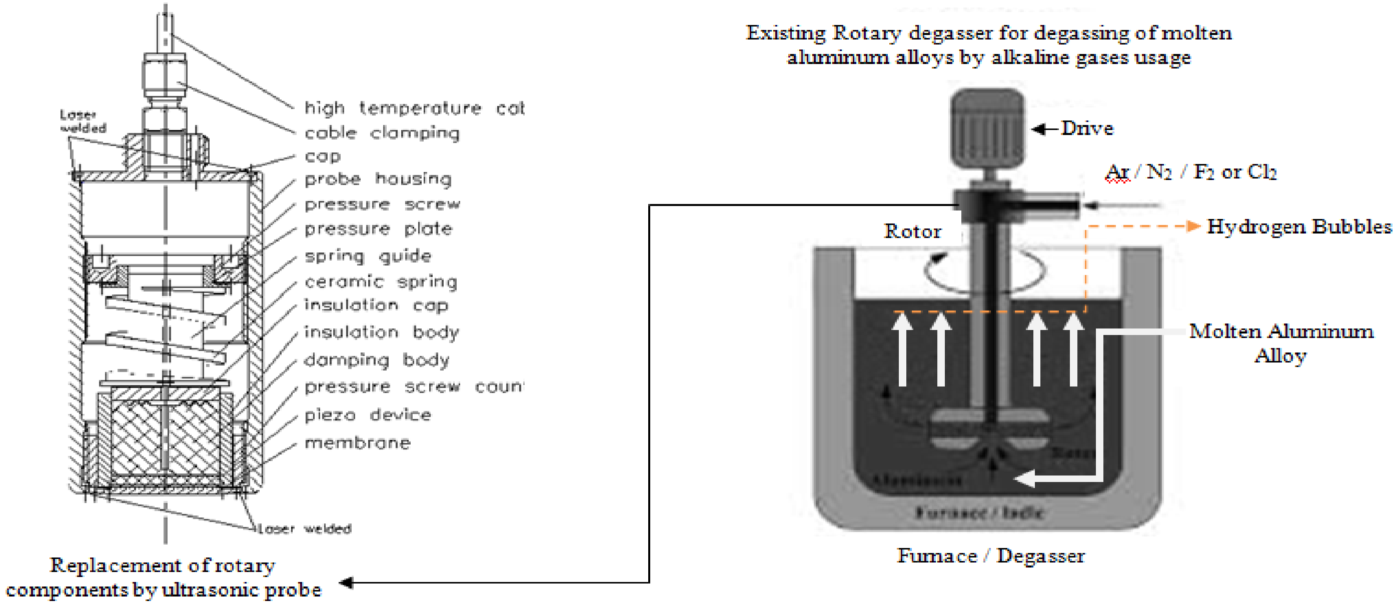


Figure-1 Replacement of Rotary parts by Ultrasonic Probe in Degassing Chamber

IV. PROCEDURE FOR EXPERIMENT

A. Design of Experiment

In author's experimental work there are three variables namely Time of ultrasound treatment, Amplitude of ultrasound and Temperature of melt. Due to design and funding for experimental set up constrains, authors had fixed the total quantity of melt, which is 3 kg. Thus their crucible of cylindrical shape and size was fixed by the dimensions such as 4 inch internal diameter and 3 inch total depth; due to these fixed parameters their immersion depth of ultrasound probe tip was also fixed which was 2 inch from the free surface of melt. This 2 inch facilitates the bubbles to grow enough while travelling from bottom of melt to free surface of melt and hence better absorption of dissolved hydrogen can be achieved. The penetration of ultrasound up to bottom of melt can also be achieved by keeping the depth of immersion of ultrasound probe by 2 inch from the free surface of melt and hence the salts and impurities of Ca, Mg, etc. could be broken down into small particles and could float in form of dross on the free surface of melt, which can be removed with the help of graphite rod by skimming action. 20 KHz frequency was also a fixed parameter due to design and manufacturing constrains of ultrasound generator. However, this parameter can be made variable with the evolution of technology in ultrasound generator system in future [10].

Thus, according to their experimental setup authors had chosen three variables with values as per below:

1. Time of ultrasound treatment: 1 minute, 2 minute, 3 minute [10]
2. Amplitude of ultrasound: 70% , 80% and 90% of 2µm peak to peak
3. Temperature of melt: 690 ºC, 705 ºC and 720 ºC [10]

B. Governing Theory for Bubble Dynamics through Ultrasonic Vibrations:

In author's experimental work bubbles play an important role. More the finer bubble size more they will travel slowly against metallostatic pressure exerted by liquid aluminum and while doing so bubbles will absorb the non dissolved hydrogen through melt height and eventually grow bigger and come up to the free surface of molten metal pool. The bubbles will burst atop of molten metal pool and will liberate contained hydrogen gas to atmosphere. The ultrasonic vibrations help to produce very small bubbles and also break the alkaline impurity particles to very small size as they would float on the molten metal pool as dross. The graphite skimmer helps to remove such dross. The Rayleigh – Plassett theory is governing this phenomenon [5, 12, 16, 19]. As their work is totally on experimental basis authors have accepted the theory and had worked based on the same.

C. Properties of FEM©™ aluminum alloy (Courtesy: Inspiron Engineering Private Limited)

1. Chemical Properties:

Aluminum: 80.67 %
Silicon: 9 %
Iron: 0.15 %
Copper: 0.03 %
Manganese: 0.10 %
Magnesium: 0.4 %
Zinc: 9.5 %
Titanium: 0.15 %

2. Mechanical Properties:

Casting Method: Sand Casting, Die Casting, Permenant Mould Casting, Directionally Chilled Casting

T1: Self Hardened
Yield Strength: 195 MPa
Ultimate Tensile Strength: 205 MPa
% Elongation: 3 %
Rockwell Hardness B: 58
Fatigue Resistance: 95 MPa

3. Metallurgical Properties:

Good Water Resistance, Average Sea Water Resistance, Very Good Weldability, Excellent Machineability, Excellent Brilliance after Polishing
Density: 2850 Kg/m^3
Modulus of Elasticity: 77 KN/mm^2
Co-efficient of Linear Thermal Expansion (20 °C-200 °C): 21 1/K*10^{-6}
Thermal Conductivity (20 °C-200 °C): 125.5 W/mK
Electrical Conductivity: 18.5 m/Kmm^2
Melting and Solidification Interval: 550 – 650 °C

4. Process Properties:

Self hardening alloy
Very good mechanical strength and elongation
Very good for mechanical polishing and machining
Good for welding
Regains hardness after thermal stress
Good castability

5. Applications:

Engine Constructions
Vehicle Constructions
Hydraulic Unit
Household Appliances
Textile machinery
Military equipment
Mould making
Huge castings without heat treatment

D. Ultrasonic Equipment Specifications:

1. *Generator Specifications:*

Fully automatic frequency control
Optional Manual Filter for frequency control
Amplitude regulation to ± 2 %
Electronic amplitude selection from 70 % to 100 % of nominal
Automatic overload and circuit protection
LED displays for indicating working frequency, instantaneous load and overload
Power supply: 220 V / 50 Hz (± 20 %)
Maximum input current: 10 Ampere

2. *Transducer Specifications:*

Material: Titanium alloy front section (Ti 6Al 4V)
Four piezo-ceramic disks
Steel back block
Connection to generator: Four pin plug and socket
Working Frequency: 20000 Hz
Nominal Amplitude: 20 µ peak to peak
Maximum input power: 2000 Watt

3. Ultrasound Properties of Titanium Aluminum Alloys:

Young’s Modulus: 114 GPa
Density: 4400 Kg/m^3
Poisson’s Ratio: 0.33
Sound Velocity Longitudinal: 5090 m/second
Sound Velocity Radial: 5390 m/second
Quality Factor: 24000
Acoustic Impedance: 220000 Kg/m^2second
Thermal expansion co-efficient: 11 X 10^{-06} 1/K

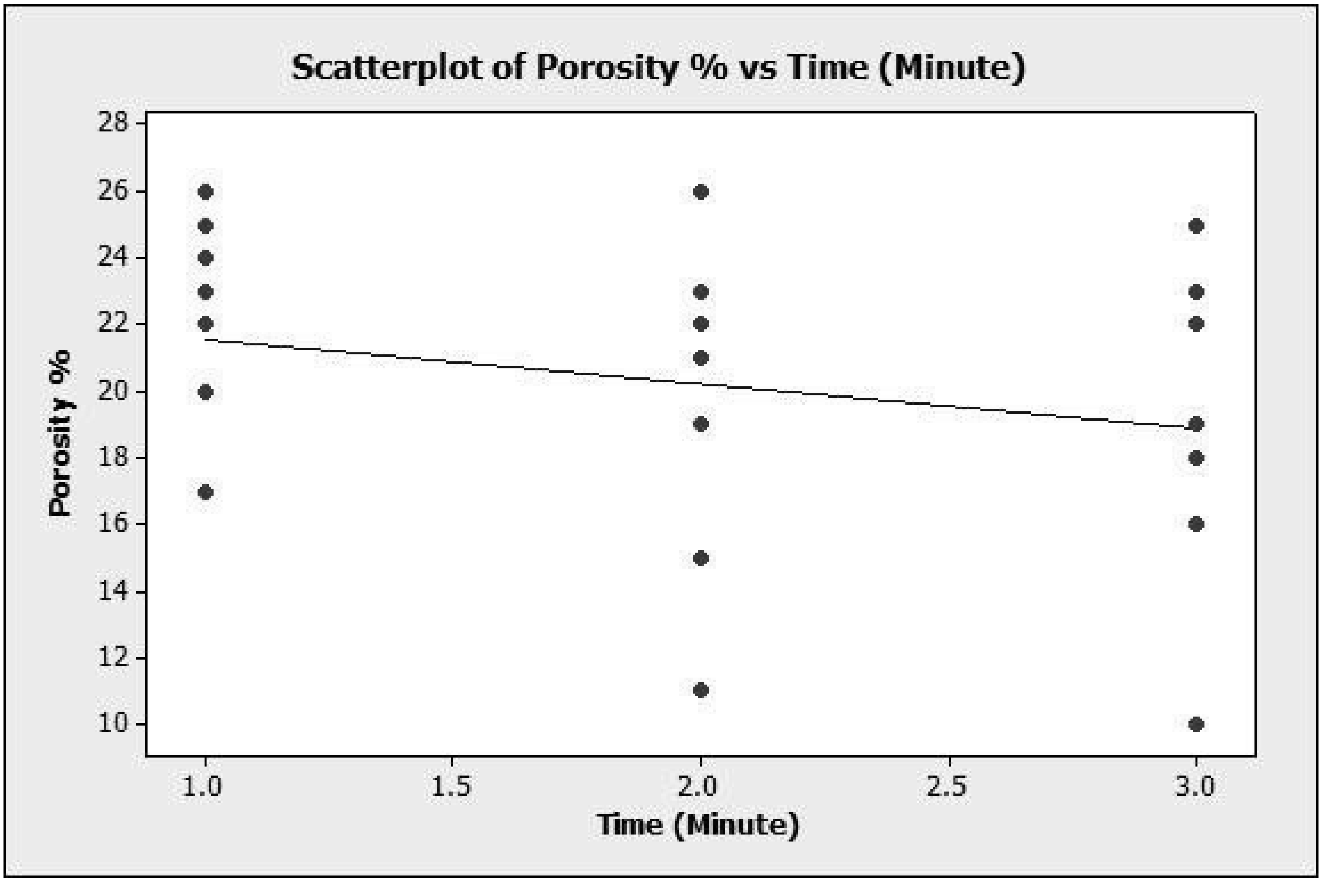
E. Reduced Atmospheric Testing System Equipment Specifications for Solidification of material in Vacuum:

Model No.: RATS™ 401
Range: 0 mm of Hg to 760 mm of Hg with 660 mm of Hg to 711 mm of Hg precise calibration
Size: 230 mm X 255 mm X 355 mm
Weight: 20 Kg
Pump: 2 Cylinder 2 Stage
Power: 248 Watt
Permanent split capacitor motor drive
Non lube piston
High temperature glass vacuum chamber for better view of sample
Main body of SS 304
Valves of Vacuum Pump: all aluminum valves

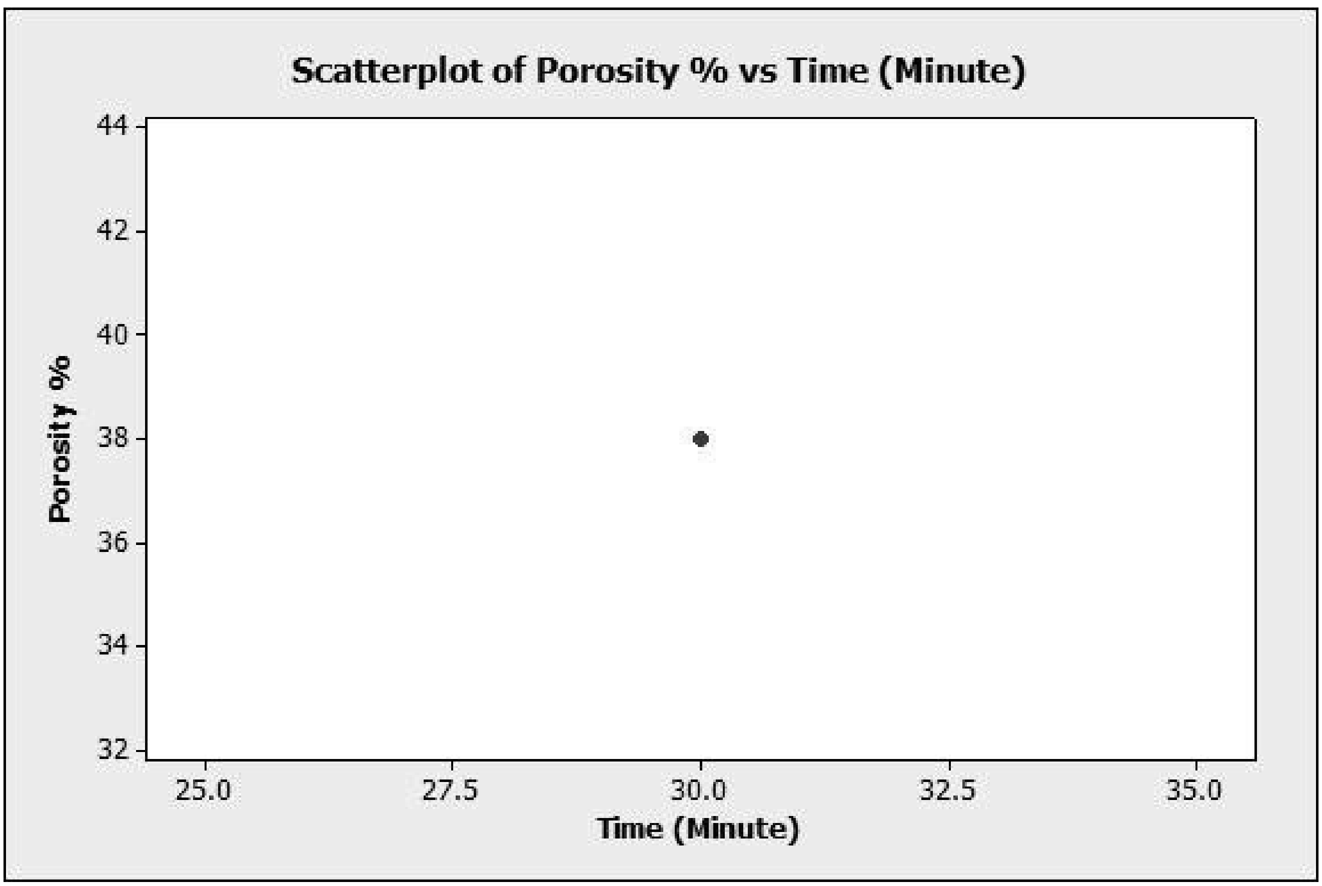
V. RESULTS

A. Graphical Results

As a result of experimental work authors had obtained 27 samples of ultrasonically degassed aluminum alloy as per their design of experiment and tested the porosity. Authors had compared the ultrasonically degassed FEM©™ aluminum alloy samples with the sample of conventionally degassed FEM©™ aluminum alloy. The conventional process of degassing of FEM©™ aluminum alloy takes 30 minutes time and at 710 ºC, which are the optimized parameters for the process as per Inspiron Engineering Private Limited, which gives precise fixed output quality of material with precise mechanical properties. Thus one sample of conventionally degassed material was sufficient for comparison. Authors found 38 % porosity in the conventionally degassed FEM©™ aluminum alloy sample. Authors had measured porosity of all samples including conventionally degassed material sample. The graph 1 shows porosity of ultrasonically degassed material with respect to ultrasonic degassing time periods as per design of experiments, while graph 2 shows porosity of conventionally degassed material. Furthermore, tabular results are also provided in table 1 for better statistical review and ready reference for readers. Some results are overlapping in graph 1 because of same porosity values, which in fact are appearing distinctly in results shown in table 1.



Graph 1: Ultrasonic Degassing Process - Material Porosity (%) Vs. Time (Minute)



Graph 2: Conventional Degassing Process - Material Porosity (%) Vs. Time (Minute)

B. Tabular Results

Table 1: Effect of Ultrasonic Degassing Time on Porosity of FEM©™ aluminum alloy samples

Sample No.	Time Minute	Porosity %
Conv.	30	38
1	1	22
2	1	26
3	1	20
4	2	19
5	2	21
6	2	23
7	3	25
8	3	16
9	3	18
10	1	17
11	1	25
12	1	24
13	2	11
14	2	22
15	2	22
16	3	19
17	3	10
18	3	18
19	1	23
20	1	17
21	1	20
22	2	22
23	2	15
24	2	26
25	3	19
26	3	23
27	3	22

Sample No. Conv. – Conventionally treated FEM©™ aluminum alloy (Highlighted Cells of Table 1)

Sample No. 1 to 27 – Ultrasonically treated FEM©™ aluminum alloy

VI. CONCLUSION

1. The degassing effect of ultrasonic vibration is found evidently significant for molten FEM aluminum alloy. The porosity level of 38 % found in conventionally treated FEM©™ aluminum alloy while the porosity found is 10 % to 26 % in ultrasonically treated FEM©™ aluminum alloy. It clearly indicates 31.57 % to 73.68 % improvement in material's porosity quality. Alternatively, average of porosity improvement can also be observed more than 50 % which is remarkable.
2. It is also observed that the degassing time period is significantly reduced. The conventional degassing gets maximum effect at 30 minutes while ultrasonic degassing gets maximum effect at 2 minutes. Saving of time attracts an attention of industry.
3. It can further be concluded that the acceptable porosity range found with minimum possible values in ultrasonically treated FEM©™ aluminum alloy are from 10 % to 20 % which clearly means that these are the samples with minimum porosity and the input parameters of ultrasonic treatment associated with these samples are the best suitable parameters.
4. It is also evident from the results that the time should be kept 2 minute to 3 minute for ultrasonic treatment to FEM©™ aluminum alloys to achieve minimum porosity in solidified FEM©™ aluminum alloy.
5. The ultrasonic technique of degassing is more environment friendly than conventional degassing because no Halides are employed in this technique and also due to saving of degassing time.

VII. FUTURE SCOPE

There are many parameters besides time period of ultrasonic degassing which play an important role in process. Authors had considered three of them such as time period, amplitude and temperature. Researchers can consider other parameters such as relative humidity of surrounding environment and its effects on degassing, different type of aluminum alloy, various values of frequency, etc. for further development of technology.

VIII. ACKNOWLEDGEMENT

Authors extend their sincere gratitude towards Kadi Sarva Vishwa Vidhyalaya University for provision of huge funds to get the experimental setup designed, manufactured and assembled. Authors had applied for patenting (Application Number Vid. 3176/MUM/2013) of this technology for commercialization purpose, which would be benefited to researchers, the university and hence the society.

Authors also express their gratitude to Roop Telsonic Ultrasonix Limited for providing complete package solution of experimental setup.

Hindalco Limited and Inspiron Engineering Private Limited has provided their plants and resources to carry out experiments. Without their support these experiment and comparison between the ultrasonic degassing technology and existing conventional degassing technology would never have been possible.

Authors are also obliged to the researchers who had reported their initial work towards development of ultrasonic degassing technology which indeed is found very much useful for their research work.

The vote of thanks along with credit of this research work goes to Dr Nilesh M Bhatt, for being a constant & potential source for information, guidance, and inspiration.

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