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A Development of Technology for Making Porous Metal Foams Castings

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Abstract

Metal foams are revolutionary materials that exhibit different attractive characteristics when compared to their solid material counterparts. Cellular structure of these materials provides the tool for the realization of optimal combination of properties. In the past, when a large dense metal contained any kind of pores, it was considered “defect” and therefore unsuitable for engineering purposes. In recent years, a great importance has been attached to a new class of engineering material, known as “Porous metals or metal foams” as a result to their unique mechanical and physical properties. This paper deals with the method of producing porous gray cast iron castings. Experimentation is done and involves the development of a porous gray iron casting, using casting techniques, Box-Behnken Design is applied and density, percentage porosity is found out also radiography, microstructure, SEM analysis, compression and hardness testing is done.

Keywords: Metal foams; Porosity; DOE; Hardness; SEM; Radiography.

1. Introduction

Metal foams are a subgroup of cellular metals, usually having polyhedral cells, but shapes may vary in cases where directional solidification creates different morphologies. Metal foams are either open cell, closed cell, or a combination of the two. Owing to their pores, metal foams are classified into open cell, closed cell metal foams. Open cell foam forms a network of interconnected solid struts. Open cell foam allows fluid media to pass through it. Closed cell foam is made up of a network of adjacent sealed pores, all sharing walls with each other. The difference between the closed and open cell configuration is clearly seen in pores. Open cell allows the passage of fluids and gasses for different applications ranging from filtering to heat exchange and gives the foam its increased surface area while the closed cell configuration is optimal for energy absorption and structural applications like in car bumpers, bridges and buildings. A fluid media can not pass through closed cell foam. Closed cell foams are being used in light-weight constructions due to their high stiffness and low density. The development of metal foams improves the properties when compared to non-metal foams and solid metals. Compared to non-metal foams, metal foams offer higher stiffness, better strength to weight ratios, increased impact energy absorption, a greater tolerance to high temperatures, and adverse environmental conditions. In comparison to solid metals, metal foams offer higher specific stiffness (stiffness to weight ratio) and by altering the size, shape, and volume fraction of cells, mechanical properties can be engineered to meet the demands of a wide range of applications. In this paper, Design of Experiments (DoE) is implemented as it is widely used in research and development, where a large proportion of the resources go towards solving optimization problems. The key to minimizing optimization costs is to conduct as few experiments as possible. DoE requires only a small set of experiments, and thus helps to reduce costs.

2. Literature Survey

The first metal foam was invented in 1943, by Benjamin Sosnick of San Francisco California. A pore is the open volume within the metal matrix or network with uniform distribution and length of passages. By manipulation of the process parameters, the pore structure can assume continuous or discontinuous geometries, a range of pore sizes, pore fractions, and a controllable shape of the final product. The continuous pores are connected together and to the surfaces of the component to allow fluid flow from one side to the other. Banhart has summarized the potential applications of metallic foams as a function of their porosity. High porosity metallic and nonmetallic media are engineered materials designed for special properties which can be used in many industrial applications including transportation. Metallic foams possess unique combinations of properties such as unusual

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acoustic properties, altitudinous damping energy capacity, and in automotive industry, the most important driving forces are cost reductions. The development of new porous structures can be a relevant challenge for materials scientists.

The ways by which cellular metallic materials can be produced are Liquid Metallurgy Route & Powder Metallurgy. Liquid Metallurgy Route method involves foaming of metallic melt either by using reactant and foaming agent, or by inert gas injection in the melt. The foaming agent and the reactant are mixed after pretreatment into the melt through mechanical stirrer; and is allowed to dissociate the foaming agent to release gases so that the metallic foam is formed. Powder Metallurgy powder route involves metal and foaming agent which are mixed and compacted. Then the compacted mass is heated just above the solidus temperature under pressure. The powder compaction of metal and foaming agent can be subsequently hot rolled to obtain sheet of porous metallic foam.

2.1. Foams Made from Metallurgy Route Using Filler Materials

A first group of foam making processes starts from the molten metal that is processed to a porous material by either foaming it directly, by using an indirect method as by casting the liquid metal around solid filler materials which reserve space for the pores or which remain in the foam. Light-weight porous metals can be produced by casting around inorganic granules or hollow spheres of low density or by infiltrating such materials with a liquid melting. The granules are then introduced into the melt, or the melt is poured over the bulk of filler material. The heat capacity and conductivity of the granules is very low and therefore does not disturb the flow of the metal too much. A wide range of metals can be processed this way including aluminum, magnesium, iron, zinc, lead, tin etc. Parts of a predefined shape can be fabricated by designing a mould of the appropriate geometry. In this paper, sand balls are introduced in molten gray cast iron for the production of porous castings.

2.2. Gray Cast Iron

Gray iron is one of the most easily cast of all metals in the foundry. It has the lowest pouring temperature of the ferrous metals, which is reflected in its high fluidity and its ability to be cast into intricate shapes. The graphite flakes which are rosettes in three dimensions, have a low density, and hence compensate for the freezing contraction, thus giving good castings. The flakes of graphite have good damping characteristics and good machinability because the graphite acts as a chip-breaker and lubricates the cutting tools. In applications involving wear, the graphite is beneficial because it helps to retain lubricants.

In this paper, Design of Experiments is applied, and it is one of the Quality tool. Taguchi has developed a system of tabulated designs (arrays) that allow for the maximum number of main effects to be estimated in an unbiased (orthogonal) manner, with a minimum number of runs in the experiment. Here Box-Behnken design is a response surface methodology design. It is used to further study the effect of factors after identifying the significant factors using screening factorial experiments.

3. Experimentation

3.1. Casting Metal around Granules

It is a manufacturing process by which a liquid material is usually poured into a mold which contains a hollow cavity of the desired shape, and then allowed to solidify. The solidified part is also known as a casting, which is ejected or broken out of the mold to complete the process. The casting of metals and alloys around a filler material has recently attracted a lot of interest. In this process, the following three steps are done as Preparation of space-holder filler, by using either inorganic or organic granules Infiltration of the filler with a metal, Removal of filler granules.

3.2. Preparation of Sand Balls

Sand balls were prepared manually, using core box with the mixture consisting of Silica sand, Bentonite, Dextrin and Sodium silicate as filler materials, Fig. 1 showing the picture sand balls.

Figure 1. Showing the picture of sand balls.

3.3. Melting & pouring of gray cast iron

A wooden pattern 180mm X 170mm X 65mm was used to produce a mould, using green sand mold with 5% clay and 3.5% moisture. The sand balls were filled in to the mould cavity. Sand casting done with molding box of 640mm X 480mm X 150mm made of cast iron was used. Gray cast iron was melted in an induction furnace with the following proportions as listed in table 1 and inoculated with 0.2% Barium based inoculant added at the ladle was poured into the mould cavity at various temperatures as 1380 °C. (2516° F), 1385 °C. (2525° F) and 1390° C. (2534° F)composition shown in table 1,table 2& table 3 The poured mould was knocked off, separated from the gating system and shot blasted for all three different pouring temperatures.

Table 1. Proportion of gray cast iron at 1380 C. (2516 F)

Element	C	Si	Mn	S	P
Wt %	3.34	2.18	0.56	0.14	0.25

Table 2. Proportion of gray cast iron at 1385 C. (2525 F)

Element	C	Si	Mn	S	P
Wt %	3.38	2.20	0.60	0.16	0.28

Table 3. Proportion of gray cast iron at 1390 C. (2534 F)

Element	C	Si	Mn	S	P
Wt %	3.36	2.20	0.58	0.15	0.27

4. Testing of Porous Gray Cast Iron

4.1. Density and Development of porosity

The foams are characterized in terms of their density since the mechanical properties of metallic foams depend largely on the density. Density is a physical characteristic; and is a measure of mass per unit of volume of a material or substance.

Density = weight of the porous casting / volume of the casting produced.

Percentage Porosity is a rough measure of the open volume equal to 100% minus the part density. The total open volumes of interconnected and isolated porosity are normally found out. Here, experiment was done with a non porous model initially to find the density and with porous models from run 1 to trail 15 using Box-Behnken design analysis.

$$\% \text{ Porosity} = \frac{\text{Bulk casting density} - \text{Produced casting density}}{\text{Bulk casting density}} \times 100$$

Table 4. Showing Pattern size, weight, density and % Porosity of nonporous sample

Type of Casting	Sand balls size, mm	Pattern size(l x b xw), mm	Weight, kg	Density,10–6 kgfmm–3	% porosity
Non porous	Nil	180 X 170 X 65	14.32	7.2	Nil

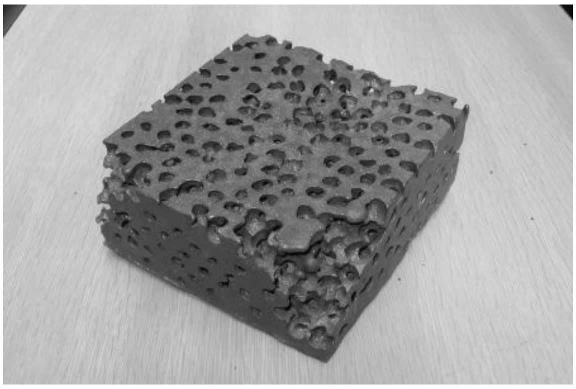

Figure 2.Minimum % porosity 43.61.

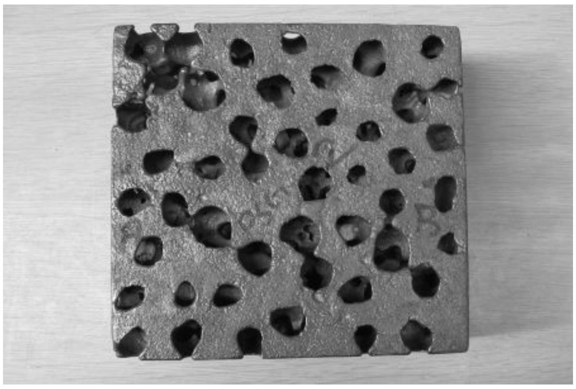

Figure 3.Maximum % porosity 72.08.

4.2. Factors Which Influence The Castings

a). Pouring temperature, (b). Composition, (c). Casting Prcessing techniques in foundry, (d). % Bentonite in sand mixture, (e). Size of sand balls, (f).Solidification & Cooling rates, (g). Inoculation, (h). Mould material.

In this research paper, factors like which influence the porous gray iron casting are temperature, % Bentonite in sand ball mixture and size of sand balls and the response factors are weight, density and percentage porosity.

The percentage porosity is being considered as a main property for structural applications as designed parts have their dimensions, defined according to the known material strength. The changes are seen in percentage porosity levels when weight and density decrease and the understanding the relationship with the processing variables may be accomplished by applying statistical techniques as design of experiments (DOE).

Design of experiments is an advanced statistical tool to efficiently study the effect of a large number of variables with a minimum effort in data collection. The inputs and outputs are described as factors, and responses and the experimental settings of the factors are designed with orthogonal arrays. Statistical means are available for analysis of the response data. This method can give maximum amount of information with a given amount of experimental data, in other words more information can be obtained through a minimum number of experiments. Box-Behnken designs are experimental designs for response surface methodology, devised by George E. P. Box and Donald Behnken in 1960,Table 5 showing the response factors. Table 6 shows BOX-Behnken design matrix. By using Box-Behnken design, Table 7 is formed and weignt,density & % porosity is shown. Using Box-Behnken design response, the results are shown in ANOVA table 8 as Analysis of variance

Table 5. Showing the response factors.

Process parameter	-1	0	1
Temperature °C	1380	1390	1398
% of Bentonite in sand balls mixture	6	8	10
Sand ball size (mm)	15	30	45

Table 6. Box-Behnken design matrix.

RUN	X1	X2	X3
1	-1	-1	0
2	-1	1	0
3	1	-1	0
4	1	1	0
5	-1	0	-1
6	-1	0	1
7	1	0	-1
8	1	0	1
9	0	-1	-1
10	0	-1	1
11	0	1	-1
12	0	1	1
13	0	0	0
14	0	0	0
15	0	0	0

Excel's Solver is a good tool for solving simple problems (continuous and discrete). The model can be incorporated into existing spreadsheets. Objective functions and constraints can reference and be referenced by other aspects of the worksheet, because spreadsheets are excellent tools for viewing data and for building models. Moreover, spreadsheets provide utilities such as graphing capabilities that facilitate analysis. And finally they offer links to other utilities that greatly expand the domain of an application.

Table 7. Box-Behnken design matrix showing weight, density & % porosity.

Run	X1	X2	X3	Weight	Density	% porosity
1	1380	6	30	5.3	2.66	63.05
2	1380	10	30	4.9	2.46	65.83
3	1398	6	30	5.4	2.71	62.36
4	1398	10	30	5.0	2.51	65.13
5	1380	8	15	7.2	3.61	49.86
6	1380	8	45	4.2	2.11	70.69
7	1398	8	15	7.0	3.51	51.25
8	1398	8	45	4.3	2.16	70.00
9	1390	6	15	7.3	3.67	49.02
10	1390	6	45	4.1	2.06	43.61
11	1390	10	15	6.8	3.41	52.63
12	1390	10	45	4.0	2.01	72.08
13	1390	8	30	5.2	2.61	63.75
14	1390	8	30	5.1	2.56	64.44
15	1390	8	30	5.0	2.51	65.13

Table 8.ANOVA table showing analysis of variances.

Factors	WEIGHT		DENSITY		% POROSITY	
Source	Regression	Residual	Regression	Residual	Regression	Residual
Sum of squares	18.33	0.047	4.602	0.012	942.152	171..015
Df	9	5	9	5	9	5
Mean squares	2.037	0.009	0.511	0.002	104.684	34.23
F-ratio	214.38		212.59		3.061	
P-value	0		0		0.175	
R	0.999		0.999		0.920	

ANOVA table evaluated results using SYSTAT-15 software, Multiple value "R" for weight gives 0.999 then Multiple value "R" for Density denotes 0.999 and Multiple value "R" denotes for % porosity as 0.920,hence all are in good agreement at acceptable levels. Using solver it is solved and optimized

DY-Linear model equation for **DENSITY** analysis

DY=2.560+0.006*A-0.089*B-0.732*C+0.043*A^2-0.017*B^2+0.245*C^2+0.038*A*C+0.052*B*C

Ans= 2.0077

Table 9. the coded and uncoded values for optimising temperature

Factors	Coded values	Uncoded values
Temperature	-0.5116	1384.7

Using lagrangian method of interpolation, temperature final values are optimized

Table 10 Showing the levels for optimising temperature .

x	-1	0	1
y	1380	1385	1390

X=0. -0.5116(coded value) from table 9

Y=(x-0)(x-0)/(-1-0)(-1-1)*(1380)+(x+1)(x-1)/(0+1)(0-1)*(1385)+(x+1)(x-0)/(1+1)(1-0)*(1395)

Y=1384.7

Linear model equation for WEIGHT analysis

WT=5.100+0.012*A-0.175*B-1.463*C+0.088*A^2-0.037*B^2+0.487*C^2+0.075*C*A+0.100*B*C

Ans = 3.990

Table 11. the coded and uncoded values for optimizing % of Bentonite in sand ball mixture

Factors	Coded values	Uncoded values
% of Bentonite in sand ball mixture	1	10

Using lagrangian method interpolation, % of Bentonite in sand ball mixture final values are optimized

Table 12 the levels for optimising % of Bentonite in sand ball mixture

x	-1	0	1
y	6	8	10

X=1(coded value) from table 11

Y=(x-0)(x-0)/(-1-0)(-1-1)*(6)+(x+1)(x-1)/(0+1)(0-1)*(8)+(x+1)(x-0)/(1+1)(1-0)*(10)

Y=10

Linear model equation for % POROSITY analysis

PY=64.440-0.086*A+4.704*B+6.702*C+2.884*A^2-3.231*B^2-6.874*C^2-0.003*A*B-0.520*A*C+6.215*B*C

Ans=74.297

Table 13. Showing the coded and uncoded values for optimizing size of sand balls

Factors	Coded values	Uncoded values
Size of sand balls	0.90173	43.5

Using lagrangian method interpolation, size of sand ball, final values are optimized

Table 14 Showing the levels for optimizing size of sand balls

x	-1	0	1
y	15	30	45

X=0.90173 (coded value) from table 13

Y=(x-0)(x-0)/(-1-0)(-1-1)*(15)+(x+1)(x-1)/(0+1)(0-1)*(30)+(x+1)(x-0)/(1+1)(1-0)*(45)

Y=43.5

Results after optimization

Predicted values and obtained values using model equations were in very good agreement with the experimental values.

5. Testing of Porous Gray Cast Iron

5.1. Radiography Test

Radiography is an effective method of nondestructively detecting internal flaws in materials and structures. The radiation source emits energy that travels in straight lines and penetrates the test piece. The major objective of radiographic testing of castings is the disclosure of defects that adversely affect the strength of the product. The castings used to produce the standard radiographs have been destructively analyzed to confirm the size and type of discontinuities present. Castings are a product form that often receive radiographic inspection since many of the defects produced by the casting process are volumetric in nature; and are thus relatively easy to detect with this method. The porous gray iron samples were subjected to radiographic inspection for analyzing the pores formed in the metal. The dark region of the film represents the more penetrable part of the object than the light regions which were more opaque. Fig 4 shows the radiography image of % porosity of minimum porosity of 43.61 and Fig 5 shows the radiography image of % porosity of maximum porosity of 72.03.

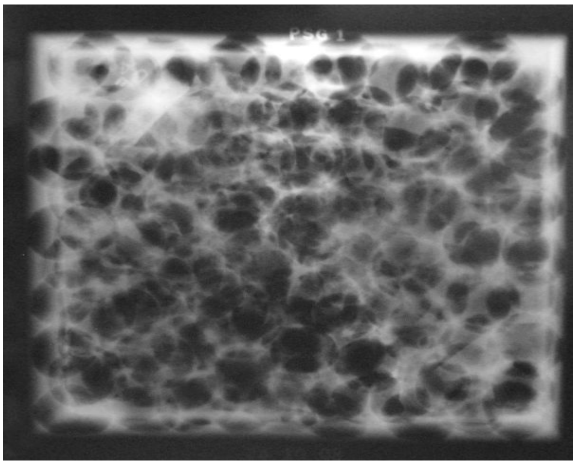

Figure4. Radiography view, % porosity 43.61.

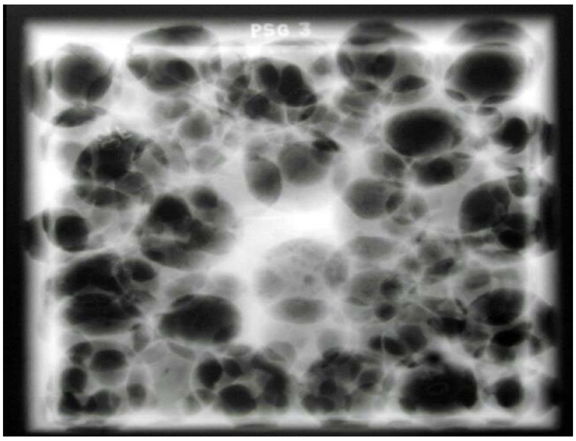

Figure 5. Radiography view, % porosity 72.03

5.2. Hardness Testing -Brinell Hardness Test

The Metals Handbook defines hardness as "Resistance of metal to plastic deformation, usually by indentation. The greater the hardness of the metal is, the greater resistance it has to deformation. Brinell hardness is used as an indication of machinability, resistance to wear, and tensile strength. For light sections, such as piston rings and other light castings have a small graphite size. The Brinell hardness test is a specialized compression test and measures the combined effect of matrix hardness, graphite configuration, and volume of graphite. The full load is normally applied for 10 to 15 seconds in the case of iron and steel and for at least 30 seconds in the case of other metals. Table 9 shows Brinell hardness test for non porous and porous gray cast iron. The diameter of the indentation left in the test material was measured with a low powered microscope. The Brinell harness number is calculated by dividing the load applied by the surface area of the indentation.

$$\mathbf{HB = 2F/ (3.14D*(D-(D^2 - d^2)^{½}))}$$

F- applied load kgf, **D** – indenter diameter mm , d – indentation diameter, mm.

Table 9 showing Brinell hardness test for non porous and porous gray cast iron

Test surfaces	Material	Diameter of indenter “D”(mm)	Load “F”(kgf)	Diameter of indentation “d”(mm)	BHN
Non porous surface	Non Porous gray cast iron	10	3000	3.9	242
Porous sample 1	Porous gray cast iron	10	3000	4	230
Porous sample 2	Porous gray cast iron	10	3000	4.1	218
Porous sample 3	Porous gray cast iron	10	3000	4.2	208

5.3. Compression Test

The compression test of metallic foams is considered as one of the most applicable tests for the characterizations of their mechanical stability. It is the method for determining behavior of materials under crushing loads. Porous Sample was compressed and deformation was recorded.

Table 10. Compression load on non porous and porous samples.

Specimen	Breakable Load, KN	Size(l x b x w) mm
Non-Porous Sample	1400 & above	90x85x65
Porous Sample 1	325	90x85x65
Porous Sample 2	375	90x85x65
Porous sample 3	400	90x85x65

It was seen that during compressive loading of such material are much smoother than those of previously-available melt route materials. Table 10 shows the compression load test which indicates breakable-load capacity for non porous and porous samples.

6. Metallographic Characterisation

The preparation of the samples for the metallographic examination is to preserve the foamed structure, and then the samples containing the pores were sawed carefully to avoid of cast iron specimens usually consists of five stages sampling, cold or hot mounting, grinding, polishing, and etching with a suitable etchant to reveal the microstructure.

Figure 6. Microstructure at unetched condition.

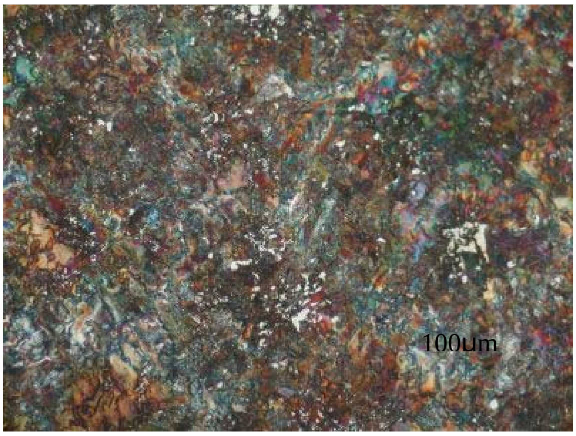

Figure 7. nital etch condition.

Microstructure of gray cast iron etched with 2% nitric acid in ethanol (nital) in fig.7 with 200X nital etched and in Fig.6 with 100X unetched condition.The study of microstructure reveals type A & D graphite with 60-70% pearlite and rest ferrite.

6.1. Scanning Electron Microscope

Scanning electron microscopy is used for inspecting topographies of specimens at very high magnifications, using a piece of equipment called the scanning electron microscope. SEM inspection is often used in the analysis of cracks and fracture surfaces, bond failures, and physical defects on surface. For this research JOEL JSM 6360 was used with an acceleration voltage of 25 kV in order to provide details of the cell wall failure as shown if Fig 8. SEM of porous sample, 500X and Fig 9.SEM of porous sample, 1000X

It is an important tool for materials and failure analysis can provide high magnification, high resolution images of samples at magnifications up to 50,000X.

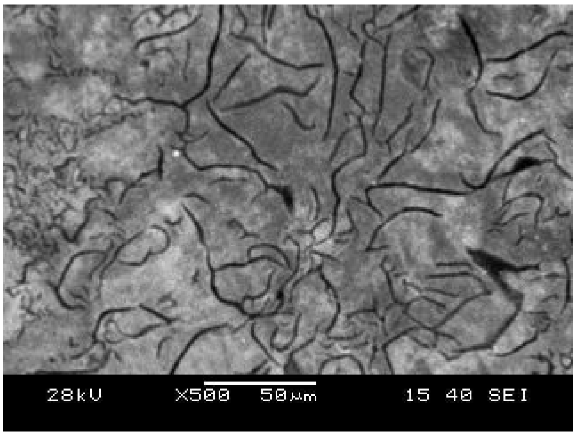

Figure 8. SEM of porous sample, 500X.

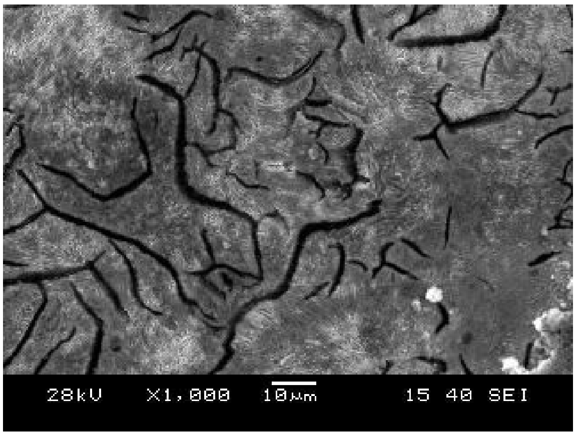

Figure 9.SEM of porous sample, 1000X.

7. Application

- Porous cast iron is used as carrier element for a vechicle body, it relates to a support element, in a cavity is filled with cast iron foam. This metal foam leads to an increase in mechanical strength. Weight saving of over 50% compared to steel.
- Porous cast iron skillet, a Frey pan for faster cooking.
- Porous cast iron bonded diamond grinding wheels used as abrasive grains.
- Porous bearings are very useful in locations with required access when regular lubrication systems are difficult to implement

8. Conclusion

A technique has been developed for preparation of Porous gray cast iron metal foam. The technique is based on casting metal around granules and achieved a maximum percentage porosity in gray cast iron to 72.03%. To determine the dependence of the mechanical properties on varying porosities, the tests are carried out on porous gray cast iron foams of different densities. Design of

Experiment involves designing experiments, in which all relevant factors are varied systematically; the results of these experiments are analyzed using Box-Behnken design. Using these sets of experimental data obtained by mathematical software package (SYSTAT 15), mathematical models were developed to show the effect of each parameter and their interactions. Predicted values and obtained values using model equations were in good agreement with the experimental values. This study proved that Box-Behnken design could efficiently be applied for finding the percentage porosity in porous gray cast iron, they help to identify optimal conditions, the factors that most influence the results. Furthermore, Study of foam cell structures a metallographic examination gives an insight into the pore structure and reveals information on pore size, pore distribution and the interconnections of the open cells. SEM photographs reveal a fractured surface of porous gray cast iron. Radiography test confirms that no mass segregation of the metal at any place in the casting. From Compression test, it is identified that due to porosity, a minimum load of 325 KN was utilized to compress the porous piece whereas maximum load for non-porous model was above 1400 KN and Hardness testing gives 242 BHP to nonporous gray cast iron and 208 to porous gray cast iron.

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