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Investigations for modelling hardness of biomedical implant during replication of FDM-based patterns by vacuum moulding

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Abstract. In the present work, effort has been made for modelling the microhardness of biomedical implant prepared by combining fused deposition modelling, vacuum moulding and stir casting (SC) process. A dynamic condylar screw (DCS) plate was selected as a real '3D' biomedical implant for this case study. The DCS plate, made of acrylonitrile butadiene styrene material, was fabricated as a master pattern by fused deposition modelling. After preparation of the master pattern, the mould cavity was fabricated by the vacuum moulding process. Finally a metal–matrix composite of Al and Al_2O_3 prepared by SC process has been poured in the vacuum mould for fabrication of DCS plate. This study outlines the replication procedure of DCS plate in detail from the master pattern to final product. The contribution of the paper is towards finding out the effect and optimum values of three different process parameters (namely: percentage composition of Al and Al_2O_3, vacuum pressure and grain size of silica) towards microhardness of the DCS plate manufactured by the combined process.

Keywords. Dynamic condylar screw; acrylonitrile butadiene styrene; fused deposition modelling; metal–matrix composite; vacuum moulding; hardness.

1. Introduction

The term 'composite' broadly refers to a material that is composed of a discrete reinforcement distributed in a matrix and it derives its distinguishing characteristics from the properties of its constituents, from the geometry and architecture of the constituents and from the properties of the interfaces between different constituents [1]. Conventional materials have limitations in achieving good combinations of strength, hardness, stiffness, toughness and density. To overcome these shortcomings and to meet the ever-increasing demand of modern day technology, metal–matrix composites (MMCs) are the most promising materials of recent interest [2].

Several investigators have reported that the incorporation of hard particles such as Al_2O_3 or SiC in cast zinc–aluminium alloys improves the sliding and abrasive wear resistance of these alloys for various industrial applications [3, 4]. The bones of the human body and there implants are different in shape and size [5]. The major requirement of biomedical implants to be used in human body is their biocompatibility [6]. It would be useful if bone implants could be custom made economically for the patient using a medical CT scan. Rapid prototyping techniques can be used to fabricate dimensionally accurate prototypes [7].

A set of CT images can be converted into a 3D, digital model using a conversion software such as MIMIC8. The input to this software is usually in the form of 'DICOM' files and output is STL, which can be directly used in a fused deposition modelling (FDM) machine to produce a real pattern. Some researchers have highlighted the mechanical behaviour of biomedical implants fabricated by the vacuum moulding (VM) process [8].

Figures 1 and 2, respectively, show schematics of FDM and VM processes. A pattern made from wood is normally used in the VM process. The VM process is different from conventional sand casting, as this process does not require any binder for sand holding. In this process, a polymer sheet is used to seal the open ends of the mould [9, 10]. Literature review reveals that a lot of work has been reported on the optimization of FDM, SC and VM processes and their various parameters like pouring temperature, film thickness and jolting time for producing sound casting [11–13]. But hitherto no work has been reported on modelling the hardness of biocompatible implants prepared by the replication of FDM-based acrylonitrile butadiene styrene (ABS) patterns and combining with VM and SC processes. In the present research work, investigations have been made for modelling the hardness of biocompatible implant prepared by replication of FDM-based patterns by combining VM and SC processes. The biomedical component selected for this study is a DCS (dynamic condylar screw) plate (see figure 3). It is used for internal fixation of

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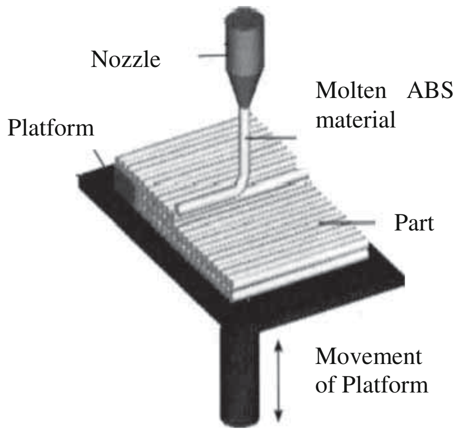
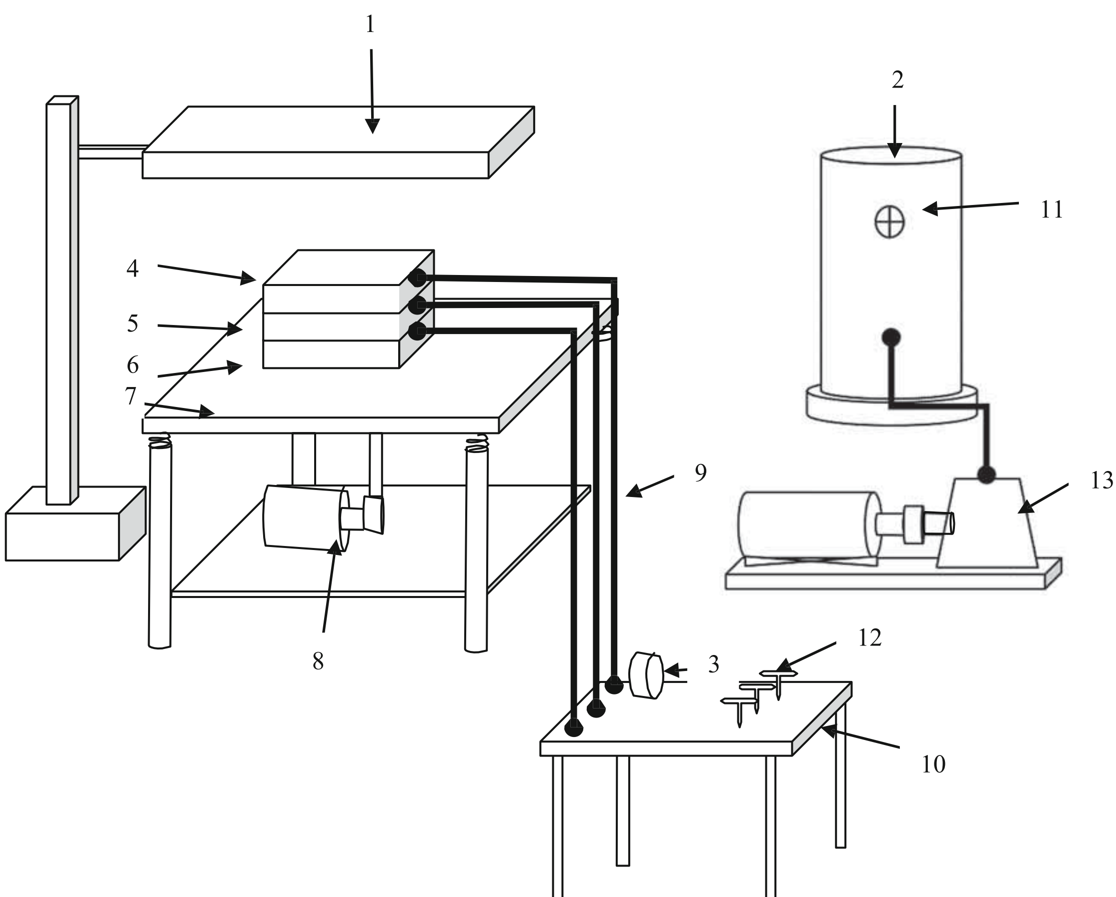


Figure 1. Schematic of FDM [8].

certain distal femoral and sub-trochanteric fractures. DCP holes in the DCS side plate allow angulations of 4.5 mm cortex screws and axial compression across a shaft fracture. Figures 4, 5 and 6, respectively, show the use of DCS plate for the fixation of distal femoral and sub-trochanteric fractures, and a 3D view of DCS [8].

2. Experimentation

For conducting the pilot experimentation, different percentages composition of Al_2O_3 in Al, vacuum pressure (250–450 mm of Hg) and silica sand of grain size 50–70 were used. Commercially pure Al was melted in a silicon–graphite crucible in an electric furnace. The selection of input process parameters was initially based upon previous reported literature [11, 12] followed by counter-verification during trial runs. For example, as regards percentage composition of Al_2O_3 in Al, it was observed that below 5% of Al_2O_3 in Al the change in microhardness values was not evident. Similarly when proportion of Al_2O_3 in Al was raised above 10% again no change in hardness was observed. This may be because of improper mixing. It



1. Heater 2. Surge tank 3. Vacuum gauge 4. Second mould box 5. First mould box
6. Hollow carrier plate 7. Jolting table 8. Vibrating system 9. Vacuum hose pipe 10. Control panel
11. Vacuum gauge 12. Control valve 13. Vacuum pump assembly

Figure 2. Schematic of VM set-up [8].

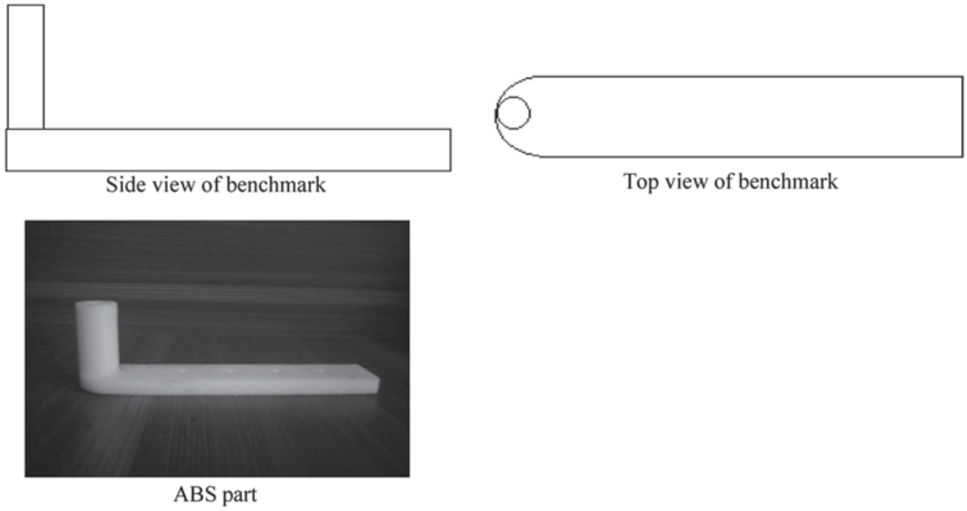


Figure 3. Different views of component manufactured from FDM [1].

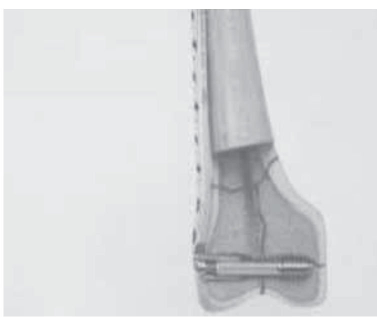


Figure 4. Distal femoral fractures [8].

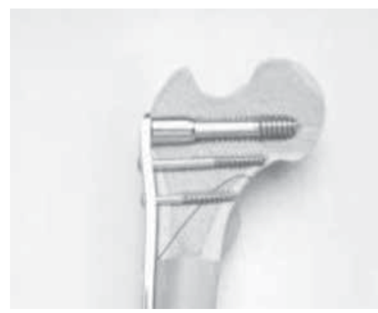


Figure 5. Sub-trochanteric fracture [8].

should be noted that this may be a constraint from stirring set-up point of view. Hence the range of Al_2O_3 particles in Al was selected as 5–10%. A similar trend of hardness was observed for sand grain size of 50–70. As regards vacuum pressure below 250 mm of Hg is concerned no sufficient vacuum was available for tight/sound cavity formation and above 400 mm of Hg the plastic sheet gets torn off.

Therefore for final experimentation the composition of Al with Al_2O_3 (of 150 AFS no.) selected is Al–5% Al_2O_3, Al–7.5% Al_2O_3 and Al–10% Al_2O_3. After sufficient manual mixing was done, the composite (in slurry form) was reheated to a fully liquid state and then automatic mechanical mixing was carried out for about 10 min at a normal stirring rate of 600 rpm as in a commercial SC process. After conducting the pilot experimentation it has been observed that input parameters like vacuum pressure, grain size and Al_2O_3 composition have effect on the microhardness of component prepared. For final experimentation the selected parameters are shown in table 1.

For the optimization process, design of final experimentation was made according to Taguchi's L9 orthogonal array (see table 2). Table 3 shows the observation of final experimentation for microhardness based upon Taguchi L9 orthogonal array. Here H1, H2 and H3 are three repetitions of the experiment conducted. Figures 7 and 8 show casting with a gate, riser attachment and the finished DCS plate, respectively.

3. Results and discussion

The cast component hardness depends upon percentage composition of Al_2O_3, moulding sand AFS no. and vacuum pressure imposed. Signal to noise (*S*/*N*) ratio curves have been drawn to obtain the optimum settings. Table 4 shows the *S*/*N* ratio for microhardness. These results are for maximum the better type case and valid for 95% level of confidence.

Figures 9, 10 and 11 show variation of *S*/*N* ratio and microhardness with respect to percentage composition, grain size and vacuum pressure, respectively. As observed from figures 9–11 the maximum hardness and *S*/*N* ratio was

Figure 6. 3D view of DCS.

Table 1. Process parameters and their levels.

Parameter	Levels 1	2	3
Percentage composition (%Al_2O_3)	5	7.5	10
Vacuum pressure (mm of Hg)	300	350	400
Grain size of silica (AFS no.)	50	60	70

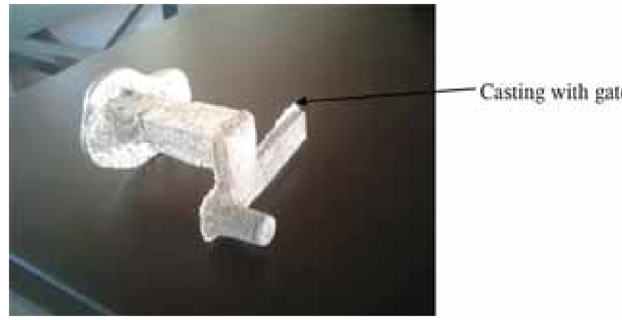


Figure 7. Casting with gate, riser attachment.

attained with 5% SiC, AFS no. 60 and 300 mm of Hg vacuum pressure. The reason for maximum hardness at 5% Al_2O_3 composition may be a constraint from the selection of SC process parameters. As a matter of fact with increase in composition of 'Al_2O_3', hardness must increase, but in the present case this decrease may be because of settlement of these abrasives in castings downward, because of improper mixing or in other words selection of rpm of stirring may be one of the constraint of the SC process used. In actual field environment one cannot increase the rpm of the stirrer beyond a limit while handling the molten metal, because the molten metal may spill out and may cause some accident.

The increase in hardness by using grain size from ASF no. 50 to 60 is but obvious as smaller grains of sand result in better cooling rate and hence more hardness and further

Table 2. The control log of the experimentation.

Sl. no.	Composition (%)	Grain size (AFS no.)	Vacuum pressure (mm of Hg)
1	Al–5%Al_2O_3	50	300
2	Al–5% Al_2O_3	60	350
3	Al–5% Al_2O_3	70	400
4	Al–7.5% Al_2O_3	50	350
5	Al–7.5% Al_2O_3	60	400
6	Al–7.5% Al_2O_3	70	300
7	Al–10% Al_2O_3	50	400
8	Al–10% Al_2O_3	60	300
9	Al–10% Al_2O_3	70	350

Table 3. Observations of final experimentation.

Sl. no.	Composition	Grain size (AFS no.)	Vacuum pressure (mm of Hg)	Microhardness (HV) H1	H2	H3
1	Al–5% Al_2O_3	50	300	54	52	54
2	Al–5% Al_2O_3	60	350	60	62	59
3	Al–5% Al_2O_3	70	400	56	59	60
4	Al–7.5% Al_2O_3	50	350	54	52	50
5	Al–7.5% Al_2O_3	60	400	57	59	58
6	Al–7.5% Al_2O_3	70	300	63	61	62
7	Al–10% Al_2O_3	50	400	50	49	51
8	Al–10% Al_2O_3	60	300	61	60	63
9	Al–10% Al_2O_3	70	350	54	53	56

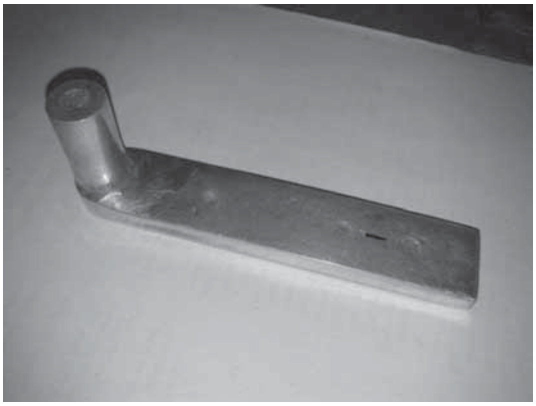


Figure 8. Finished product (DCS plate).

Table 4. *S/N* ratio for microhardness (HV).

Sl. no.	H1	H2	H3	*S/N* ratio	Average
1	54	52	54	34.53583	53.33
2	60	62	59	35.60563	60.33
3	56	59	60	35.30704	58.33
4	54	52	50	34.30721	52.0
5	57	59	58	35.26598	58.0
6	63	61	62	35.84557	62.0
7	50	49	51	33.97592	50.0
8	61	60	63	35.7486	61.33
9	54	53	56	34.69454	54.33

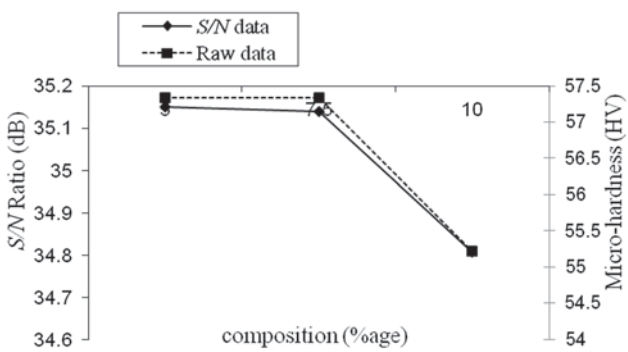


Figure 9. Variation of *S/N* ratio and microhardness with respect to percentage composition.

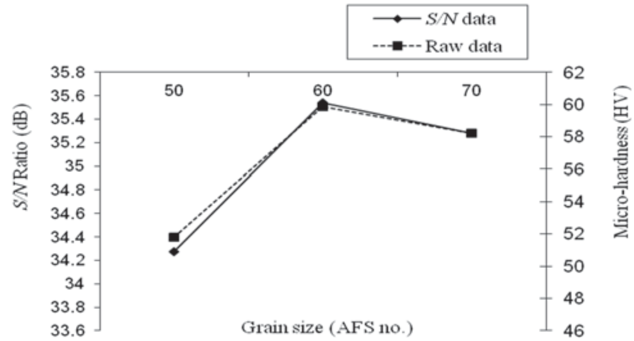


Figure 10. Variation of *S/N* ratio and microhardness with respect to grain size (AFS no.).

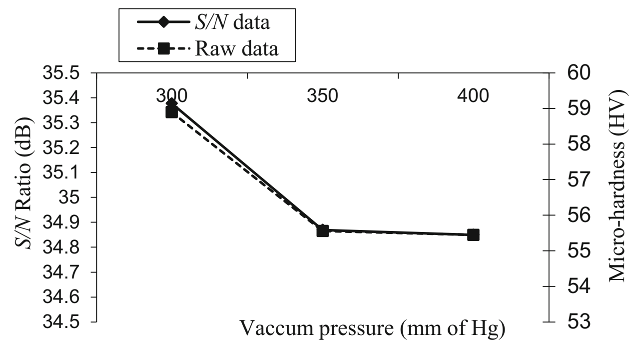


Figure 11. Variation of *S/N* ratio and microhardness with respect to vacuum pressure (mm of Hg).

decrease from 60 to 70 may be again an experimentation constraint. Similarly, as regards vacuum pressure, 300 mm of Hg vacuum pressure gave better results for the following reason: with increase in vacuum pressure above 300 mm of Hg, it has been observed that the effect of vacuum was not limited to providing mould cavity stability but in fact molten metal was being sucked into the vacuum chamber. Confirmatory experiments were conducted at these settings and results of the study show that percentage improvement in microhardness is 3.4%. In order to ascertain these results, cooling rate and microstructure analysis (see figure 12) have been performed for all nine sets of experiments as per table 2.

As observed from figure 12 for microstructure of experiment no. 1, the peaks are sharp and connected while the pits are of different depths and sizes. Also pits remain isolated and unconnected. However, in experiment no. 6 the sample has a fine microstructure, irregular in size and shape. The surface is dotted with fine peaks and pits of different sizes. Pits are relatively round and their size changes along the depth. Since the solidification rate is dependent on the dropping of temperature in a given interval of time, the rate of solidification of nine sets of castings was determined from the cooling curves generated during the experimentation by an IR thermometer. Table 5 shows the rate of solidification and hardness values for the castings prepared.

As observed from table 5 for experiment no. 6, maximum hardness and high solidification/cooling rate are observed. It should be noted that for experiment no. 6, less pitting is observed (see figure 12). Hence it can be ascertained that the input parameters (namely, percentage composition of Al–Al_2O_3, grain fineness no. of silica sand used in VM process and vacuum pressure) influence the microhardness of the MMC prepared. For better understanding of this fact, percentage contribution of various input parameters that affect the microhardness of the MMC has been

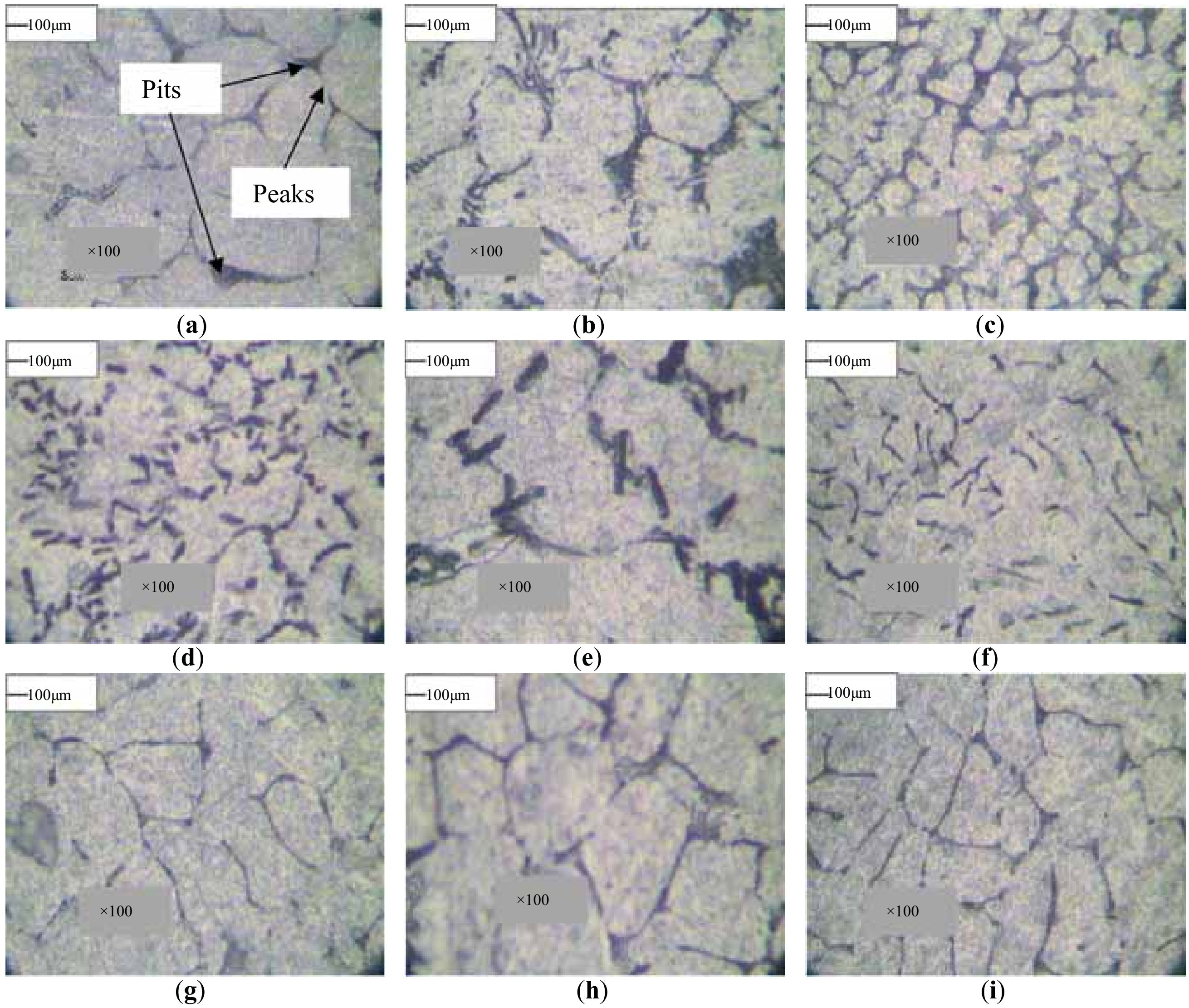


Figure 12. Microstructure for nine sets of experiments (as per table 2). (**a**) Microstructure for experiment 1, (**b**) microstructure for experiment 2, (**c**) microstructure for experiment 3, (**d**) microstructure for experiment 4, (**e**) microstructure for experiment 5, (**f**) microstructure for experiment 6, (**g**) microstructure for experiment 7, (**h**) microstructure for experiment 8, (**i**) microstructure for experiment 9.

Table 5. Effect of solidification rate on microhardness.

Sl. no.	Percentage composition	Grain size (AFS no.)	Vacuum pressure	Microhardness	Solidification rate (dT/dt)
1	5	50	300	54	1.1667
2	5	60	350	60	2.0
3	5	70	400	56	1.867
4	7.5	50	350	54	1.25
5	7.5	60	400	57	1.96
6	7.5	70	300	63	2.3
7	10	50	400	50	0.78
8	10	60	300	61	2.13
9	10	70	350	54	1.2

Table 6. Percentage contribution of various inputs for microhardness.

Parameters	Percentage contribution (%)
Composition	6.29
Grain size	74.01
Vacuum pressure	14.73
Error	4.95

calculated (see table 6). The error contribution below 5% highlights that the process is under controlled conditions and hence a judicious selection of input parameters was made in this experiment design. In other words the effect of any other input parameters for contribution towards microhardness is below 5%.

4. Conclusions

In this case study a DCS plate has been successfully prepared by combining FDM-based patterns and VM, SC processes. The optimum values of three different input parameters and their effect on microhardness of DCS plate manufactured according to the combined process have been highlighted. Results of the study suggest that the best setting for maximum microhardness is the following: composition of Al_2O_3 5%, AFS no. 60 and vacuum pressure 300 mm of Hg. Further, as regards microhardness of MMC prepared by combining FDM-based patterns with VM and SC the percentage contribution of Al_2O_3 composition, AFS no. and vacuum pressure is 6.2%, 74% and 14.73%, respectively. Hence for controlling the hardness with the combined process of VM, SC using FDM-based patterns the maximum focus should be on selection of AFS no. of silica grain used. Finally the current study suggests that it might be possible to manufacture DCS in the proposed fashion to obtain the best microhardness.

Acknowledgements

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