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Effect of forging on micro-hardness of Al7075 based Al_2O_3 reinforced composites produced by stir-casting

Indumati B Deshmanya[1] and Dr GK Purohit[2*]
[1]Research Scholar and Asst Professor, Department of Mechanical Engineering,
PDA College Engineering, Gulbarga-585 102
[2*]Professor & Corresponding Author, Department of Mechanical Engineering, PDA College Engineering,
Gulbarga-585 102

Abstract

Metal matrix composites with aluminium matrix and non-metallic reinforcements are popular candidates in automotive, aerospace and defense fields because of their high strength-to-weight ratio, stiffness, wear resistance, high-temperature resistance, etc. often they are subjected to secondary manufacturing processes like extrusion, rolling, forging, etc. to suit the service requirements. As such, there are no standard methods for selecting the correct proportion of the constituent matrix and reinforcement materials for producing the composites possessing desired properties, particularly in the forged condition. Of late, mathematical modeling is found to be very useful in predicting the influence of process parameters on various mechanical/tribological properties of these composites. This work presents the details of modeling the hardness of forged composites made-up of Al-7075 matrix, reinforced with Al_2O_3 *particles composites produced by stir-casting process. Factorial design of experiments is used to develop model that can predict the influence of four process parameters, viz., size of reinforcement, weight percent, forging temperature and reduction, on micro-hardness of these composites.*

Keywords: *Metal Matrix Composites, Stir-casting, Forging, Hardness, Modeling,*

1. Introduction

Monolithic alloys are slowly being replaced by composites, which combine ductility and toughness of the matrix materials and higher strength, hardness, wear resistance, etc. of the reinforcement materials. Metal Matrix Composites (MMCs) are being extensively used in automotive, aerospace and mining engineering, etc. as they are reported to possess high strength–to-weight ratio at elevated temperatures, improved shock-resistance properties, relatively higher wear resistance, toughness, etc [1-6]. In order to shape these composites, often they are subjected to secondary processing methods such as extrusion, rolling and forging. Consequently, MMCs having Al-7075 alloy as matrix and Al_2O_3 reinforcements in the form of particulates are reported to exhibit improved mechanical properties such as high hardness, wear resistance, tensile strength, etc, not only in the as-cast condition, but also in the forged condition as well [7]. However, a deeper understanding of these alloys in respect of their production; mechanical/metallurgical properties is mandatory to enhance their applicability. Recently, factorial design of experiments has emerged as an important tool to analyze multi-parameter, complex processes [8-11]. A number of researchers have employed this methodology and developed mathematical models for various properties of MMCs [12-21]. For example, D.P. Mondal et al [12] have studied the erosive-corrosive wear of Al-Si alloy based, 10%SiC reinforced, aluminium metal matrix composites. The wear model developed by them indicates that radial distance among other parameters has the maximum effect on the wear resistance. L.J. Yang [13] has developed an equation for transient coefficient of A6061 aluminium reinforced with alumina particulates. He has used the volume loss equation proposed by Zhang et al [18] and concluded that the new equation can be more effective than Archard equation [15]. G. Leisk and A. Saigal [16] have analyzed the tensile strength and Charpy impact values of aluminium/alumina composites. They have used orthogonal experiments and a software package, SADIE (speedy analysis and design of industrial experiments) to evaluate the impact toughness of aluminium based composites. S. Charles & V.P Arunachalam [17] have modeled the metal removal rate (MRR) and tool wear rate (TWR) during electric discharge machining (EDM) of a composite made of Al6061/SiC/flyash. A 3-level full factorial technique has been used to assess the impact of %SiC, current and pulse duration in terms of a second degree response function. Abrasive wear behavior of Al-Cu based alloy (Al 2011) matrix dispersed with SiC and manufactured by liquid metallurgy route has been investigated by Y. Sahin [18] using a 2- level factorial design. He has developed a polynomial equation for wear rate of the composite in terms abrasive size, sliding distance and applied load. S. Charles and V.P. Arunachalam [17] have developed an equation for predicting machining properties of Al-alloy/SiC/fly ash composites produced by liquid metallurgy and powder metallurgy. They have reported that the stir-cast specimens exhibited higher hardness, wear resistance and tensile strength. Huda et al [19] have developed a mathematical model for an Al/Al_2O_3 composite, using response surface methodology and observed that the effect of volume fraction of reinforcement was very dominant. Indumati B.D. and G.K. Purohit [20] have used four factors, five level factorial design to develop the micro-hardness model for Al7075 matrix, Al_2O_3 reinforced metal matrix composite fabricated by stir-casting. Reinforcement size and weight fraction of reinforcement, among other factors, are observed to affect the hardness more severely.

In our view, the properties of aluminium composites such as strength, tensile properties, wear resistance, hardness etc. are not well documented. Of particular importance is a knowledge of hardness of composites is paramount from the stand point of wear resistance, crack initiation and growth, scratch resistance, etc. However, it is noticed from the literature that no systematic approach to model the hardness of aluminium based, alumina reinforced composites, particularly in their forged condition. This paper reports the effect of forging on the hardness of Al7075/Al_2O_3 composites fabricated by stir-casting. Influence of reinforcement size, weight percent, forging temperature and reduction in size on the hardness of Al7075/Al_2O_3 composites was studied and reported Analysis of Variance (ANOVA) was performed to determine the influence of these parameters on the hardness. Fisher's F-test was carried out to arrive at the adequate model that can be used to produce the composites of desired hardness within the range of parameters selected for this study. Sizes of Al_2O_3 particulates (D) ware in the range of 36 to 72µm size, weight per cent of Al_2O_3 (W) ranged from 5 to15%, forging temperature (T_f) was in the range 385-425°C and reduction in area (R_f) was varied from 10 to 50%. The model developed is believed to provide very useful information on the combination of input-parameters that give composites of desired hardness within the framework of the experimental values studied.

2. Experimental work

Table 1a and 1b present the chemical composition and other important properties of the Al7075 matrix material, respectively. Fig. 1 shows the close-up view of the stir-casting process. The details of stir-casting process are presented elsewhere [21,22]. Castings were prepared in the form of 25mm diameter × 280mm long rods using C.I. dies. The cast rods were subjected to forging as per the matrix at temperatures ranging from 385˚C and 425˚C to produce samples with reduction in area in the range of 10-50%. For performing hardness survey, test samples of 12mm were extracted from defect-free regions of the forged composites and at least five indentations were made on the samples using Micro-Vickers hardness tester (Fig. 2). Mathematical models to predict hardness were developed by regression analysis.

3. Plan of investigation

The research work was planned to be carried out in the following steps:

1. Identifying the important controllable process parameters.
2. Finding the range of the identified parameters viz. size of reinforcement (D), % weight of reinforcement (W), forging temperature (T_f) and % reduction of forging area R_f in mm
3. Developing the central composite design matrix.
4. Producing the stir cast and forged specimens as per design matrix and extracting the hardness specimens from defect-free regions of the specimens.
5. Conducting hardness survey and recording the hardness values.
6. Developing the hardness model and checking the adequacy
7. Results and discussion.

3.1 Identifying the important controllable process parameters

Based on the previous work it was observed that reinforcement size and % weight are the two most influential parameters [20]. In order to understand the effect of forging on hardness, forging temperature and reduction in size (area) after forging were included. Hence, the identified parameters are: reinforcement size (D), % of reinforcement (%W), forging temperature (T_f) and % reduction in area (%R_f). It was imperative that these parameters were controllable and reproducible.

3.2 Finding the range of the identified parameters

A number of trial runs were conducted to arrive at the upper and lower limits of the four selected parameters. The criterion for fixing the ranges was based on a visually defect-free fabricated cast specimen. As it was decided to employ central composite design, the extreme values of each parameter were further subdivided into 3 more equal divisions. The five levels were coded as +2, +1, 0, -1, 2. Table 2 shows these along with units.

3.3 Developing the central composite design matrix

The design matrix for the present work was developed as per [23]. Table 3 gives the details. It may be observed that, in all, 31 experimental combinations comprising 2^4 =16 factorial points, 7 center points and 8 star points.

3.4 Producing the stir casting and forged specimens as per design matrix

Following the design matrix, 31 composite rods measuring 25 mm diameter and 280mm long were stir-cast and forged; in a random order, to ensure that no systematic errors crept into the experimentation. The details of stir-casting process are available elsewhere [21, 22].

3.5 Conducting hardness survey and recording the hardness values

The cast and forged specimens were cut and sized to 12mm diameters and length 25mm using standard metal cutting procedure and were subjected to indentation. In each case, 3 specimens were subjected to hardness measurement. A minimum of 5 hardness values were recorded on each specimen and the average values are presented in Table 3.

3.6 Developing the hardness model and checking the adequacy

Micro-hardness (y) of the forged composites was expressed as a function of reinforcement size(D), % weight of reinforcement (W), forging temperature (T_f) and reduction in reduction in area (R_f),
The response is a function of all the process variables and is given,

$$y = f(D, W, T_f, R_f) \tag{1}$$

The resulting 2nd order equation could be expressed as in equation,

$$Y= b_0 + b_1X_1 + b_2X_2 + b_3X_3 + b_4X_4 + b_1X_1^2 + b_2X_2^2 + b_3X_3^2 + b_4X_4^2 + b_{12}X_{12} + b_{13}X_{13} + b_{14}X_{14} + b_{23}X_{23} + b_{24}X_{24} + b_{34}X_{34} \tag{2}$$

Where, b_0 is the coefficient corresponding to the first column with all the values, b_1, b_2, b_3 and b_4 are the coefficients corresponding to the 4 selected process parameters, b_{11}, b_{22}, b_{33} & b_{44} refer to quadratic terms, and b_{12}, b_{13}, b_{14}, b_{23}, b_{24} ,b_{34} indicate coefficients corresponding to 2-factor interaction - b_{12} meaning coefficient of factors 1 and 2, b_{13} meaning coefficient of factors 1 and 3, etc. The values of these coefficients, determined as per ref [24] were used to write the hardness model. The model is presented in Eqn (3).

$$\mathbf{Hv = 131.574 + 0.5416D_1 + 1.792W_2 + 2.791T_3 + 2.625t_4 - 1.925D_1^2 - 0.925W_2^2 + 0.199T_3^2 - 1.050t_4^2 - 0.313D*W - 0.438D*T + 0.063D*t - 0.813W*T + 0.188W*t + 0.063T*t} \tag{3}$$

The adequacy of hardness model developed was tested by employing ANOVA and the results are presented in Table 4. It is noticed that F_{model} (10.764) is more than $F_{tabulated}$ (4.07) and hence, the model was declared to be adequate.

3.7 Results and discussions

Figs. (3) to (12) present the graphical relationships obtained based on the developed models. Figs. (3) to (6) show the effect of main parameters on VHN and Figs. (7) to (12) show the effect of interaction of parameters on VHN.

3.7.1 Effect of main factors on micro-hardness

It is observed (Figs. 3-6) that all the process parameters affect the hardness positively. However, a small increase in micro-hardness is noticeable in case of forged composites compared with as-cast products. Similar observations are made by Ceschini et al [25]. In their study on forged aluminium alloy based composites with Al_2O_3 reinforcement. This could be attributed to the slight grain refinement after forging.
The effect of reinforcement size is more pronounced up to 60µm and after that it has a tendency to reduce the hardness. Maximum hardness is obtained at 50µm. Similarly, at 15% weight proportion, the hardness is maximum (140VHN). From Figs. 5 & 6 it is noticed that at 425°C and corresponding to 15% reduction in area due to forging, the micro-hardness is around 135-140VHN.

3.7.2 Effect of interaction of parameters on micro-hardness

From Figs. 7-12 it is observed that the various 2-factor interactions have a tendency to increase micro-hardness. In fact, it is noticed that there is a point of convergence at which maximum hardness is obtainable (at around 140VHN).

4 Conclusions

The following conclusions can be drawn from the present work.

1. Factorial techniques can be used to model the hardness behavior of forged composites.
2. Al7075/Al_2O_3 composites can be successfully forged to produce items without impairing micro-hardness attained due combining the matrix and the relatively harder reinforcement particulates.
3. Maximum micro-hardness (140VHN) is obtained with reinforcement size of 60µm, 15% weight percentage, forging temperature of 425°C and for a reduction in area of 55% after forging.
4. It is essential to consider interaction effect of process variables along with main factors to arrive at the model.

5 References

1. Basavarjappa, S., Chandramohan, G., Narasimha Rao, K.V., Radhakrishanan R., and Krishnaraj,V., (2006) 'Turning of particulate metal matrix composites-review and discussion', *Proc. IMechE Part B: J. Eng Man* Vol. 220, pp.1189-1204.
2. Srivatsan, T.S., Ibrahim, I.A., Mohamed, E.J., and Lavernia E.J., (1991) 'Processing techniques for particulate-reinforced metal aluminium matrix composites', *J. Mater. Sci.* 26, pp.5965-5978.
3. Pradeep Rohatgi, K., ((1993) 'Metal Matrix Composites', *Def. Sci. J.*, 43**,** pp.323-349.
4. ASM International, (1993) Advanced Material Processing. **143(6),** p.21-23.
5. M.J. Kokazac, S.C.Khatri, J.E.Allison, and M.G.Bader, (1993) MMCs for ground vehicle aerospace and industrial applications, in Suresh et al Edited Fundamentals of Metal Matrix Composites, *Butterworth's, Guildford, (UK)* pp.297.
6. N. Chawla and K.K Chawla, (2006) Metal Matrix Composites, *Springer, New York.*
7. I.A. Ibrahim, F.A. Mohamed, E.J Lavernia, (1991) 'Particulate reinforced metal matrix composites- a review. *J. Mater. Sci.* **26,** pp.1137.
8. Baki Karamis, M., Fehmi Nair., (2008) 'Effects of reinforcement particle size in MMCs on extrusion die wear', *Wear* 265, pp.1741-1750.
9. Palanivel, R., Koshy Mathews P., and Murugan N., (2011) 'Development of mathematical model to predict the mechanical properties of friction stir welded AA6351 aluminium alloy', *J of Eng Sci and Technol Review*, 4 (1) pp.25-31.
10. Raviraj Shetty, Raghuvir Pai, Srikanth S. Rao, and Vasanth Kamath, (2008), 'Machinability study on discontinuously reinforced aluminium composites (DRACs) using response surface methodology and Taguchi's design of experiments under dry cutting condition', *Maejo Int J Sci and Technol*, 2(01), pp.227-239.
11. Mohan Kumar Pradhan and Chandan Kumar Biswas., (2008) 'Modeling of machining parameters for MRR in EDM using response surface methodology', *Proc. of NCMSTA'08*, Nov 13-14 pp.534-542.
12. Kumar S. and Balasubramanian V., (2008) 'Developing a mathematical model to evaluate wear rate of AA7075/SiC_p powder metallurgy composites', *Wear*, 264**,** 1026-1034.
13. Mondal, D.P., Das, S., Prasad, B.K., (1998) 'Study of erosive-corrosive wear characteristic of an aluminium alloy composite through factorial design of experiments', *Wear*, 217, pp.1-6.
14. Yang, L.J., (2003) 'The transient and steady wear coefficients of A6061 aluminium alloy reinforced with alumina particles', *Compo Sci and Technol*, 63, pp.575-583.
15. Gunaraj, V., Murugan, N., (1998) 'Application of response surface methodology for predicting weld bead quality in submerged arc welding of pipes', *J Mater Proc Technol*, 88 pp.266-275.
16. Zhang, W.L., Wang, J.X., Wang, D.Z.,.Gu, M.Y., (2005) 'Compressive stress-strain response of directionally aligned SiCw/Al composite', *J Mater Sci* 40 pp.6091-6097.
17. Leisk, G., Saigal, A., (1995) 'Taguchi analysis of heat treatment variables on the mechanical behavior of alumina/aluminium metal matrix composites', *Com Eng*, Vol.5, No.2, pp.129-142.
18. Charles, S and Arunachalam, V.P., (2004) 'Property analysis and mathematical modeling of machining properties of aluminium alloy hybrid (Al-alloy/SiC/flyash) composites produced by liquid metallurgy and powder metallurgy techniques', *Ind J Eng and Mater Sci* Vol.11, pp.473-480.
19. Sahin,Y., (2003) 'Wear behavior of aluminium alloy and its composites reinforced by SiC particles using statistical analysis', *Mater and Des*, 24, pp.95-100.

20. Huda, D., El Baradie, M.A., Hasmi, M.S.J., (1994) 'Development of hardness model for MMCs (Al/A_2O_3)', *J Mater Proc Technol*, 44, pp.81- 90.
21. Indumati, Deshmanya. B., Purohit, G.K., (2011) 'Studies on modeling of aluminium matrix composites (AMCs) – A review paper', *ICAM-2011*.
22. Surappa, M.K., (2003) 'Aluminium matrix composites: Challenges and opportunities', *Sadhana*, Vol. 28, Parts 1&2, pp. 319-334.
23. Indumati, Deshmanya. B., Purohit, G.K., (2011) 'Developing a mathematical model to evaluate micro-hardness of $Al7075/Al_2O_3$ composites produced by stir-casting', (Communicated).
24. Cochran W.G. and Cox G.M., (1992) 'Experimental Designs', *John Wiley, New York.*
25. Ceschini L., Minak, G., Morri, A., (2009) 'Forging of the AA2618/20 vol.% Al_2O_3 composite: Effect on microstructure and tensile properties', *Comp Sci Technol*, 69, 1783-1789.

Table 1a Chemical Composition of Al7075

Cr	Cu	Mg	Zn	Al	Density g/cc at 20°C
0.22	1.60	2.80	5.50	Balance	2.89

Table 1b Details of other important properties of Al7075

Tensile Strength MPa	Yield Strength MPa	Elongation %	Hardness VHN	Thermal Conductivity $Cal/Cm^2/Cm/°C$ at 25°C	Elect. Resistivity µΩ-Cm at 20°C
228	103	17	79	0.29	5.74

Table 2 Coded values of input variables at different levels

Coded values	Input parameters	Notation	Units	Lower level		Middle	Upper level	
				-2	-1	0	+1	+2
X_1	Size of reinforcement	*D*	µm	36	45	54	63	72
X_2	% Wt of Al_2O_3	*W*	---	5	7.5	10	12.5	15
X_3	Forging temperature	T_f	°C	385	395	405	415	425
X_4	%Reduction in forging area	R_f	---	10	20	30	40	50

Table 3 Design Matrix for Preparation of Stir cast & Forged Samples along with Responses

Trial No.	**Input Parameters**				**Response**
	X_1 Reinforcement size, *D* (µm)	X_2 %Weight of Reinforcement, *W* (gm)	X_3 Forging temperature, T_f (°C)	X_4 Reduction in forging area, R_f %	Vickers hardness, *Hv* (VHN)
1	-1	-1	-1	-1	110
2	+1	-1	-1	-1	115
3	-1	+1	-1	-1	120
4	+1	+1	-1	-1	122
5	-1	-1	+1	-1	124
6	+1	-1	+1	-1	125
7	-1	+1	+1	-1	127
8	+1	+1	+1	-1	123
9	-1	-1	-1	+1	120
10	+1	-1	-1	+1	123
11	-1	+1	-1	+1	127
12	+1	+1	-1	+1	125
13	-1	-1	+1	+1	130
14	+1	-1	+1	+1	128
15	-1	+1	+1	+1	132
16	+1	+1	+1	+1	138
17	-2	0	0	0	130
18	+2	0	0	0	132
19	0	-2	0	0	134
20	0	+2	0	0	136
21	0	0	-2	0	139
22	0	0	+2	0	140
23	0	0	0	-2	133
24	0	0	0	+2	136
25	0	0	0	0	135
26	0	0	0	0	131
27	0	0	0	0	132
28	0	0	0	0	133
29	0	0	0	0	130
30	0	0	0	0	131
31	0	0	0	0	129

Table 4 Analysis of variance

S.No.	Source	DF	SS	MS	F_{model}	R^2	$Radj^2$
Hardness Hv in VHN	I&II order terms	14	595.5686	42.5406			
	Lack of fit	10	815.1045		10.764	98.35	98.09
	Residual error	6	23.714	3.952			
	Total	30	1434.3871	46.4926	10.764	98.35	98.09

As per Table (14, 6, 0.05) $F_{tabulated} = 4.07$. Hence, the model is adequate.

Figure1: A close-up view of the stir-casting process [21,22]

Figure 2: Micro-Vickers hardness tester MVH-I

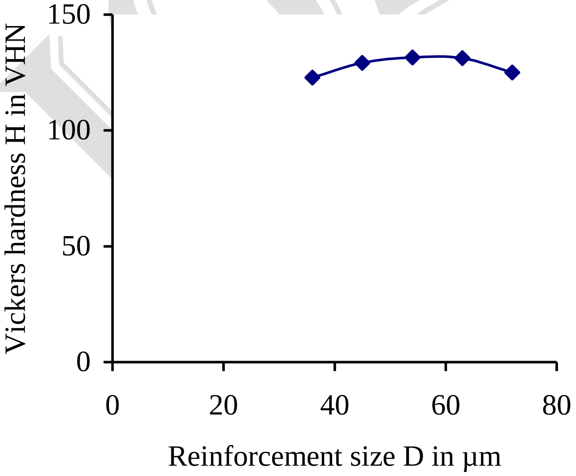

Fig.3 Vickers hardness H in VHN vs reinforcement size D in µm

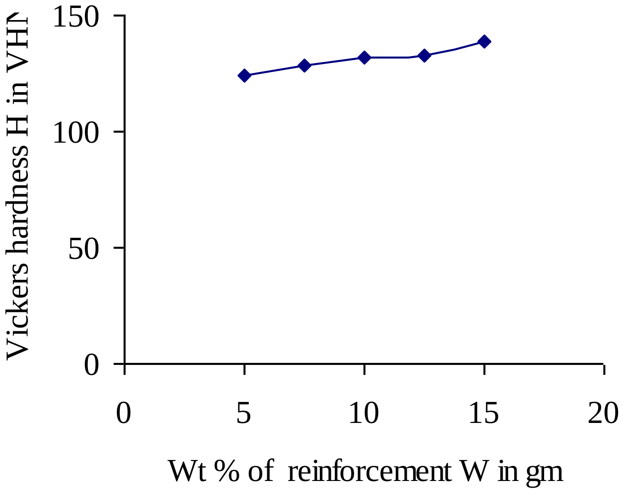

Fig. 4 Vickers hardness Hv in VHN vs weight percent of reinforcement W in gm

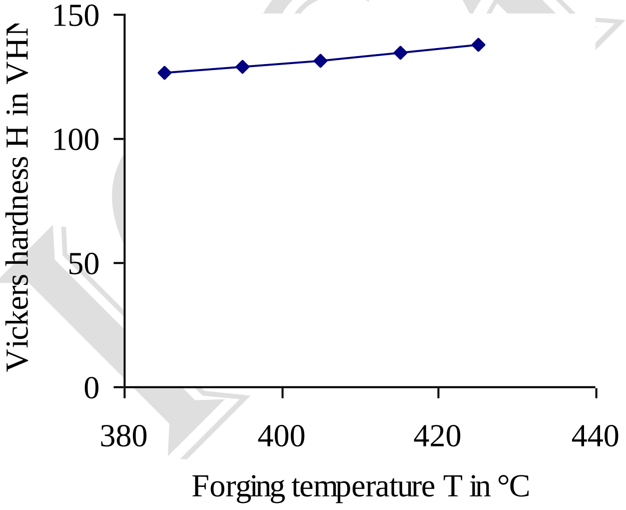

Fig.5Vickers hardness Hv in VHN vs forging temperature T in °C

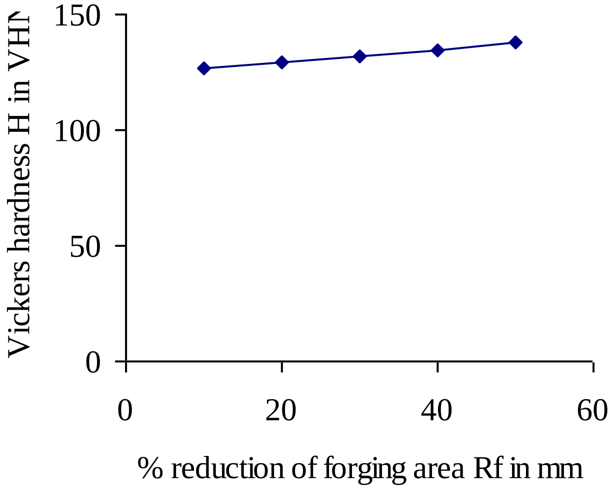

Fig. 6 Vickers hardness Hv vs % reduction of forging area R_f in mm

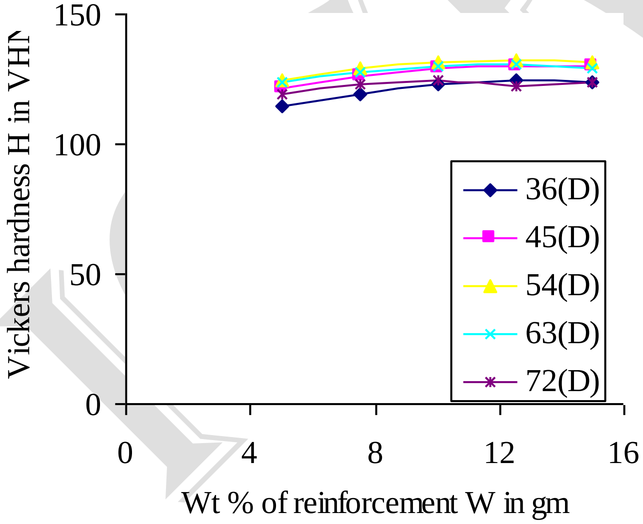

Fig. 7 Effect of interaction between weight percent of alumina and reinforcement size D on Vickers hardness Hv

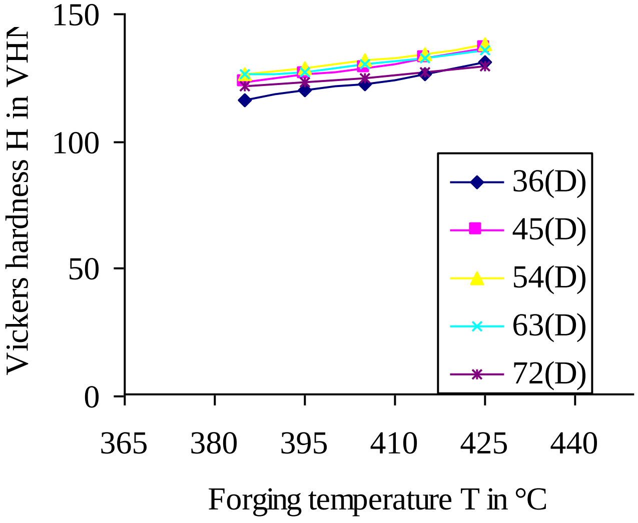

Fig. 8 Effect of interaction between forging temperature T and reinforcement size D on Vickers hardness Hv

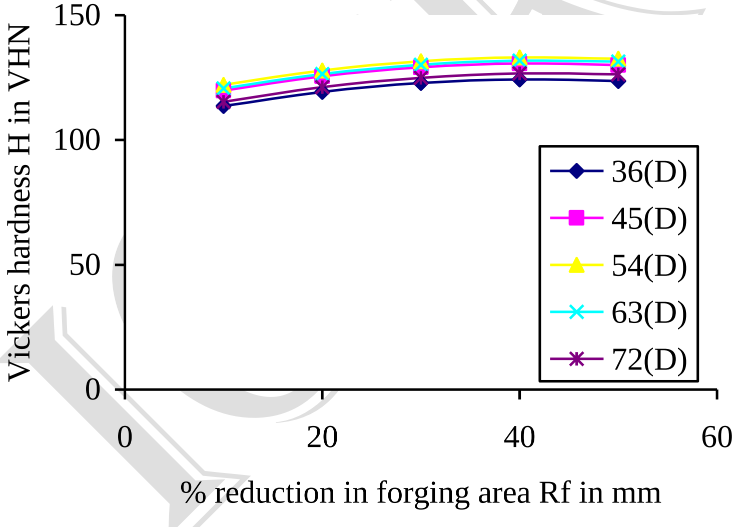

Fig. 9 Effect of interaction between % reduction of forging area R_f and reinforcement size D on Vickers hardness Hv

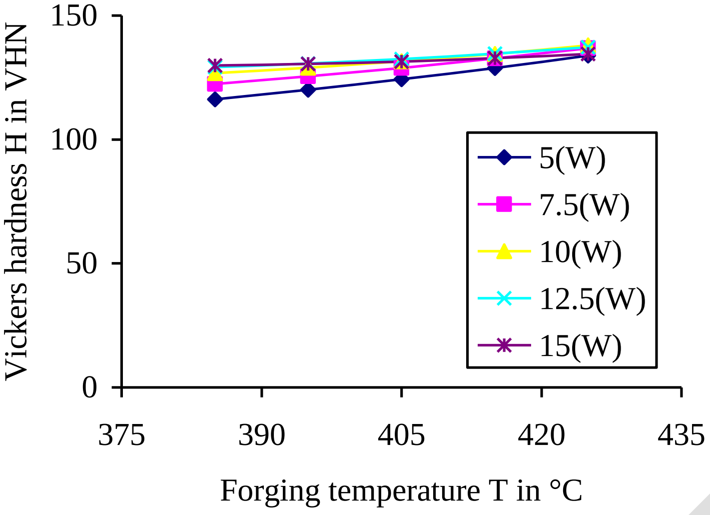

Fig. 10 Effect of interaction between forging temperature T_f and % weight of reinforcement W on Vickers hardness Hv

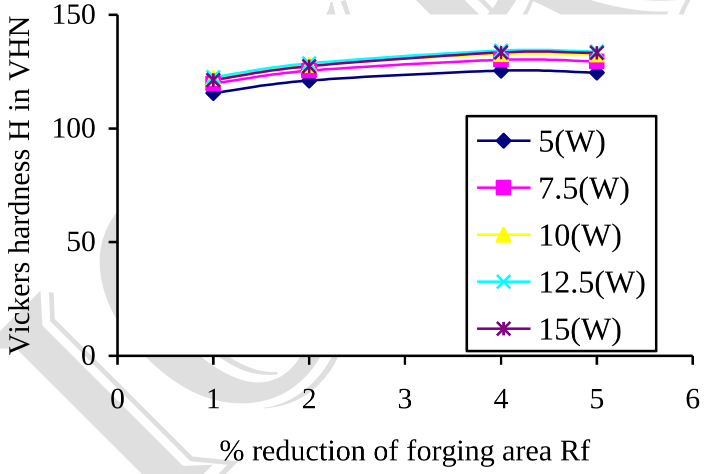

Fig. 11 Effect of interaction between % reduction of forging area R_f and weight % of alumina W on Vickers hardness Hv

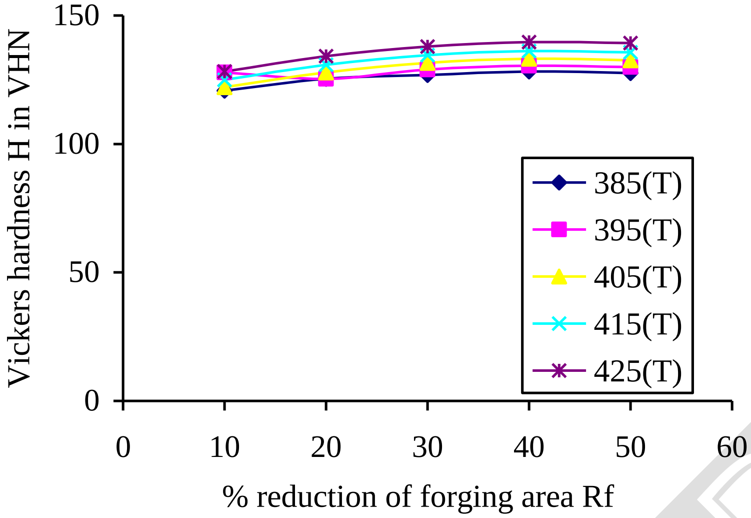

Fig. 12 Effect of interaction between % reduction of forging R_f and forging temperature T_f on Vickers hardness Hv