INFLUENCE OF FORGING PROCESS ON THE MECHANICAL BEHAVIOR OF (AL/SIC) AND (AL/SIC/CU) - MMC'S PRODUCED BY P/M COMPACTS [+]

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Abstract :

In this paper the effects of hot forging used as a secondary process after powder metallurgy in fabrication of Metal Matrix Composites (MMC's) was examined. A comprehensive study was made on the mechanical properties of MMCs after hot forging process, when maximum load of hot forging was estimated by FEM simulation (DEFORM-3D software). It was found that most properties are superior as compared to without forging process. Properties including compression strength, flextural strength and hardness were found to be better for most of the MMC's. The hybrid MMc's has the best properties compared with respective MMC's before and after hot forging.

تأثير عملية الطرق على السلوك الميكانيكية لـ المواد المتراكبة المعدنية (ألمنيوم/ سليكون) و (ألمنيوم/سليكون/نحاس) المصنعة بطريقة كبس المساحيق المعدنية

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المستخلص :

في هذا البحث تم اختبار تأثيرات استخدام الطرق الحار كعملية إضافية بعد عملية مساحيق المعادن في تصنيع المواد المتراكبة المعدنية. تم إجراء دراسة كاملة على الخواص الميكانيكية للمواد المتراكبة المعدنية MMC's بعد عملية الطرق الحار، بعد تخمين أقصى حمل للطرق الحار باستخدام المحاكاة لطريقة العناصر المحددة FEM لبرنامج الديفورم ثلاثي الأبعاد (DEFORM-3D Software). معظم الخواص التي تم التوصل إليها بعد الطرق الحار كانت أفضل عند مقارنتها بدون طرق. تضمنت الخواص إجهاد الانضغاط، إجهاد الانحناء و الصلادة والتي كانت أفضل لمعظم المواد المتراكبة المعدنية. لقد كانت خواص المواد المتراكبة المعدنية الهجينة hybrids أفضل من المواد المتراكبة المعدنية في كل الأحوال قبل وبعد الطرق.

1. Introduction :

Powder metallurgy(P/M), as a technology of production of high-quality composites, is presently recognized as competitive in relation to conventional methods, mainly foundry practice. Additionally, this technology involves low level of waste products, but main

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disadvantage of a classical powder metallurgy, based on compaction and sintering processes, is a porosity of obtained products. Apart from the group of products for which specified porosity is required, the occurrence of pores within the material affects its properties unfavorably. This problem can be eliminated by means of combination of powder metallurgy and plastic working processes [1].

As it was mentioned earlier, one the major drawbacks of PM is porosity. The powder forging (PF) technique has helped the PM industry to mitigate this problem. After PF process there is only residual porosity. However, this porosity problem still does not allow asserting that the PF products have the same properties as the metals [2].

Park et al., describes the process conditions for the powder forging of aluminum alloy piston for vehicles including the determination of composition of aluminum alloy by experiment, preform design by FEM simulation, cold compaction of aluminum alloy powder, sintering of preform, and the experiment of powder forging. The mechanical properties such as hardness, tensile strength, and elongation of the formed piston were invested and compared with casted piston and forged piston. The tensile strength and hardness of the piston formed by powder forging technology were much more excellent than other pistons [3].

While **Leshchynsky, et al**. reviewed current developments in fabrication, microstructure, physical and mechanical properties of nanocrystalline and submicron materials made by Powder Metallurgy and Forging techniques (deformation) of nanostructured materials for a variety of potential tribology and structural applications.. Particular attention is paid to the properties characterization of submicron composites. [4]

Wang, et al., have been proposed and studied experimentally a new method of hot forging PM and compared with the traditional fabrication method of motorcycle connecting rod. The punch divided into three parts to consolidate the loose powder. The effect of forging temperature and initial compact density on densification were evaluated through hot forging experiments. The physical and mechanical properties of the connecting rod produced by the PM hot forging were found to be superior to those manufactured by the traditional method. [5]

CHAWLA et al., showed that in behavior of sinter-forged 2080/SiC/20p composite exhibited higher Young's modulus and ultimate tensile strength than the sinter- extruded material, but lower strain-to- failure. The higher modulus and strength were attributed to the absence of any significant processing-induced particle fracture; while the lower strain- to-failure was caused by poorer matrix inter particle bonding compared to the extruded material. [6]

In this study the effect of hot forging process was studied the mechanical properties for cold compacted sintered composite (Al-SiC) and their hybrid (Al-SiC-Cu) materials was studied and compared. In sinter-forging the powder mixture of (Al-SiC) and (Al-SiC-Cu) are cold compacted, sintered, and hot forged to density almost full. Thus, the main advantage of this technique is that forging is conducted to produce a near-net shape material with minimized machining operations and material wastes.

2. Experimental Procedure :

2.1. Material preparation :

Powder has been inspected at ministry of sciences and technology, SiC powder has been inspected at Iraqi geological survey and Cu powder has been inspected at IbnSina state company, the following results has been found as shown in Table (1) :

Table (1): Results of Powders Inspection.

Materials	Average particle size (μm)	Density (gm/cm^3)	Purity %	Company
Al	38.88	2.57	99.73	Sigma, Aldrich /Germany.
SiC	9.99	3.08	98.79	Ernakulam/ India.
Cu	32.42	9.89	99.82	E.Merck-Dramstadt/ Germany.

2.2. Specimens Preparation :

Silicon carbide is added as the first reinforcement particle of content ranging from (5, 10, 15 and 20) % volume fraction. The second reinforcement is copper (1, 2, 3 and 4) % vol. which is added to the best mechanical composite, know as hybrid composites that can be followed by secondary or finishing operations (in this study is hot forging) to improved mechanical properties.

Powders were mixed by using horizontal mill at 95rpm for 30 min each sample to ensure proper mixing and uniform distribution .To prevent the problem of static-charge induced agglomeration wet mixing was afforded by using the polar solvent n-butanol about of 2%- 3% from weight of composite. [7]

The mixtures were then placed in a type compaction die, the mixtures were then cold compressed at room temperature under pressure 275 MPa and the pressing time was about 15 minute [8]. Pressing process is done in material laboratory at Technical College – Baghdad by the hydraulic press 80 ton capacity.

Samples were dried at 150^{o}C temperature for soaking time 30 min and sintered at 565°C temperature for soaking time 60 min [6], when used a vacuum furnace at heating rate 5°C/min under pure argon at flow rate 2 liters/min in the department of production engineering and minerals in the University of Technology.

2.3. Simulation for Present Work :

DEFORM™-3D software version 10.0 is used to estimate the suitable load value for hot forging process without making crack and failure in samples. The general procedure of the simulation as shown in Figure (1), and is used to calculate the theoretical load value of hot forging process for (Al/SiC) composite and their hybrid (Al/SiC/Cu) samples with various concentrations.

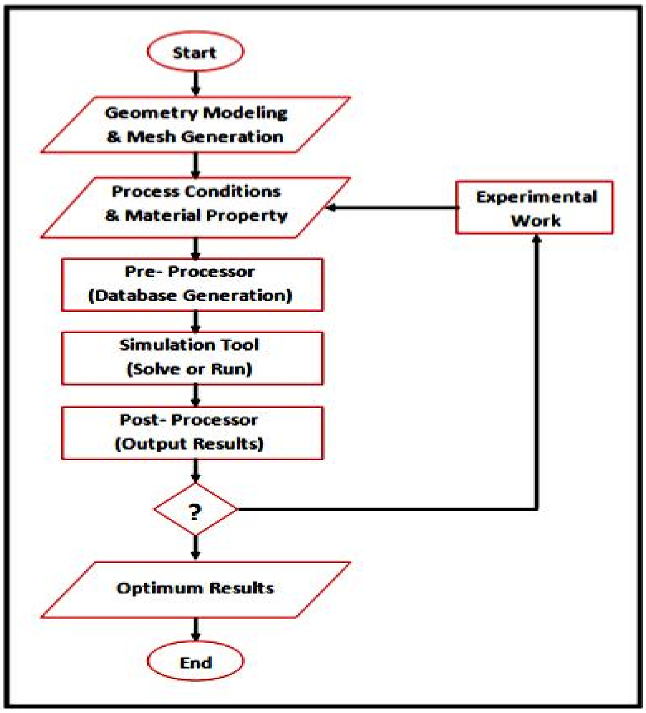


Figure (1): Flow Chart Shows the Steps of Simulation by DEFORM-3D.

Generating mesh for billet with 3000 surface of polygon elements with 580 nodes. After finish all steps above, making verification with experiment work, Figures (2) shows the generation mesh for billet and maximum load vs. stroke for pure Aluminum, Al-SiC composites and their hybrids (Al-SiC-Cu) with weight fractions listed in table (2).

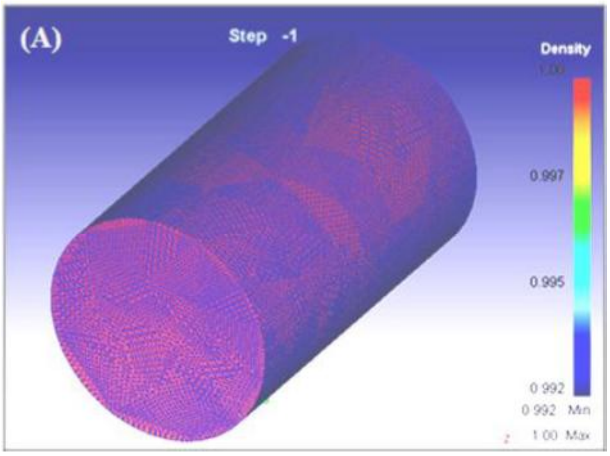
Table (2) : Billet Weight Fractions for Materials Used

Mat.	Al (wt. %)	SiC (wt. %)	Cu (wt. %)
Pure	100	0	0
Composites	95	5	0
	90	10	0
	85	15	0
	80	20	0
Hybrids	(99%) 80	(99%) 20	1
	(98%) 80	(98%) 20	2
	(97%) 80	(97%) 20	3
	(96%) 80	(96%) 20	4

2.4. Forging experiment :

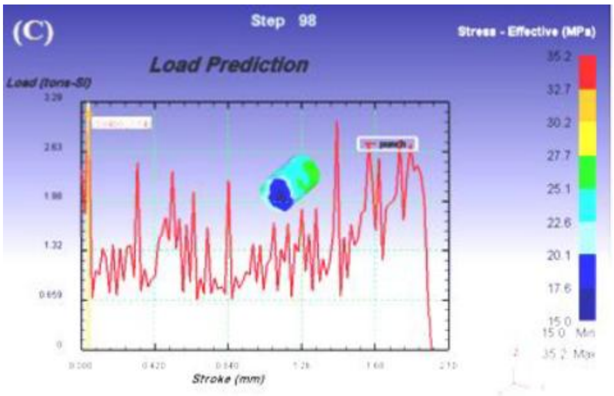
The samples manufactured by powder metallurgy are forged in order to remove pores contained in them to change mechanical properties, all these parameters is constantly used for every specimen.

The forging experiment was carried out with closed forging die, the die temperatures were 250°C, and the material temperatures were 482°C [6]. The compacts destined for forging were heated in furnace at 482°C during 30 minutes, hot forging process is done in material laboratory at Technical College – Baghdad then transported to the heated die cavity and forged.

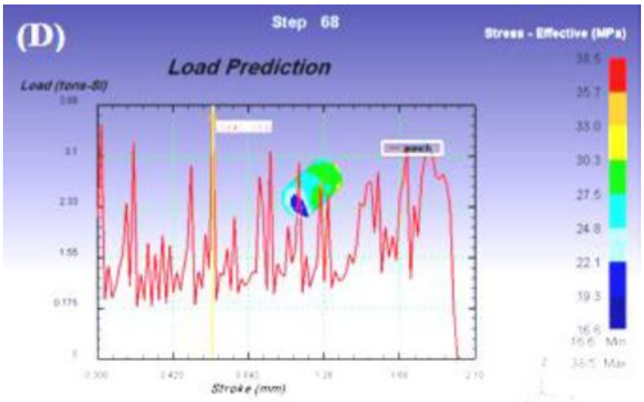


(A) - General Element and Nods Distribution

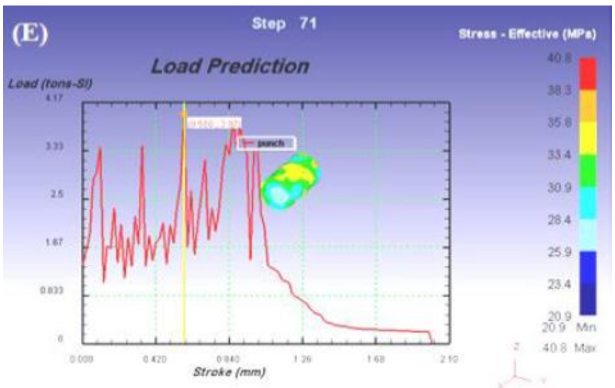
(B) - 100% Al (matrix)



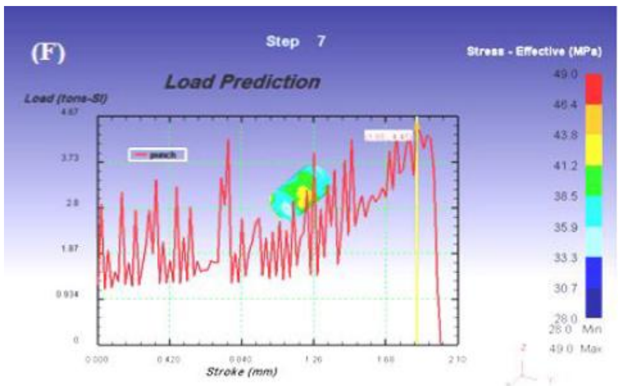
(C) - (95% Al + 5% SiC) Composites



(D) - (90% + 10% SiC) Composites

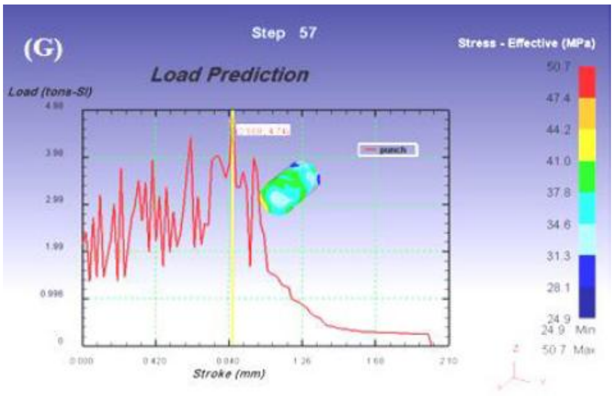


(E) - (85% Al + 15% SiC) Composites

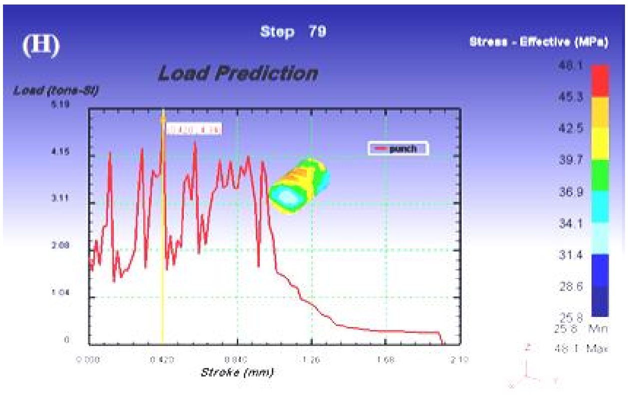


(F) - (80% Al + 20 SiC) Composites

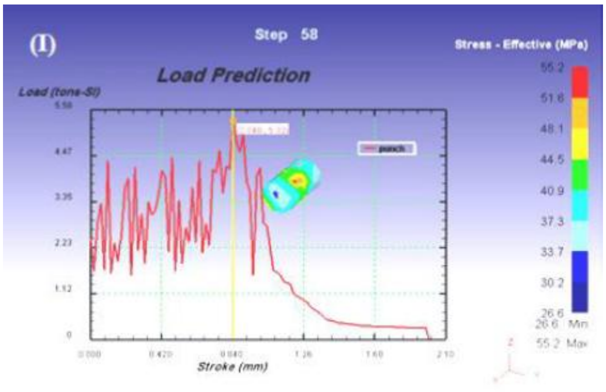
Figure (2): Maximum Forging Load vs. Stroke for Composition Billets. (… to be followed)



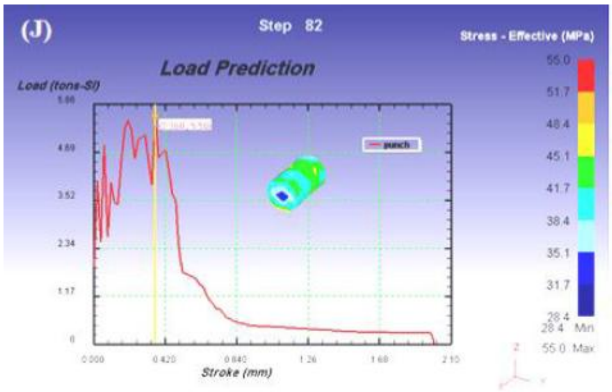
(G) – [99% of (80% Al + 20 SiC)) + 1% Cu Hybrid Composites



(H) – [98% of (80% Al + 20 SiC)) + 2% Cu Hybrid Composites



(I) – [97% of (80% Al + 20 SiC)) + 3% Cu Hybrid Composites



(J) – [96% of (80% Al + 20 SiC)) + 4% Cu Hybrid Composites

Figure (2): Maximum Forging Load vs. Stroke for hybrid Composition Billets. (… continuied)

3. Mechanical Properties Test :

3.1. Compression strength measurement :

Because of the difficulty of a tensile test has been compensated for the compression test. According to ASTM E 9 – 09 standardization compression test of standard specimens (Ø10mm×20mm) was made (Figure 3-a). This test were carried out at ministry of sciences and technology, Three specimens were tested for aluminum, composite and their hybrid materials for each percentage of addition compression properties were measured, This test was performed on universal machines(Mechanical testing machine) in the name of the device (Tinius Olsen), model H50 KT, made England, Max power 50 KN, voltage 220V/50 Hz ,Conditions of compression test are: speed 0.5mm/min, load rang 500N, displacement rang 25mm.

3.2. Flexural Strength Measurement :

The test specimens are based on three points bending condition and the samples dimension(200mm×10mm×3mm), according to ASTM E290 standardization (Figure 3-b).

Flexural test were carried out at ministry of sciences and Technology on the same universal machines above (Mechanical testing machine), when system of testing contain of; Cross head, Control panel, Force measurement (load cell), Speed control and Flexural grips.

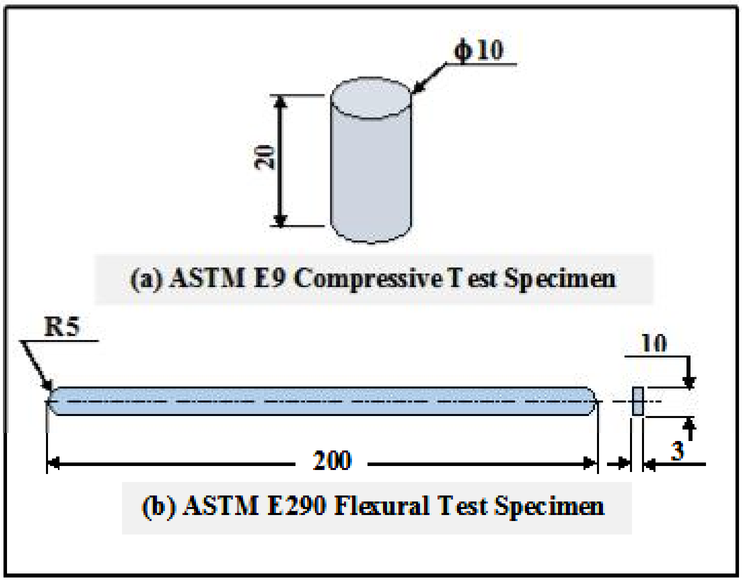


Figure (3): Schematic of standard tests specimen

3.3. Hardness Measurement :

Rockwell hardness was examined according ASTM E18-00 standardization; the first step grinding was carried out with emery paper varying in grit size (from 320,400,600 and 800) and processing of inspection and access to all the hardness of the specimens by taking five readings for each specimen from the wall to the center to illustrate homogeneity of property across section area and then averaged was obtained for the mean value for each section.
In this work hardness was determined using the Rockwell hardness test machine. The indenter used was a 1⁄16 in. (1.588 mm) diameter of steel ball, Preliminary Test Force = 10 kgf (98 N), Additional force = 90 kgf (883 N) and Total Test Force = 10 + 90 = 100 kgf (981 N). Rockwell B scale and Hardness of 101.2 HRB standard block were used.

4. Results and Discussion :

4.1. DEFORM -3D Software Results :

The relationship between the maximum load of hot forging process and the percent volume fraction of reinforcements particles are presented in Figure (4) as predicted by the Finite Element Analysis (FEA) and experimental work. It can be seen that the maximum load of forging is found in the [96% of (80% Al+20%SiC)+4%Cu] reaching (5.58tons) for simulation value and (5.5 tons) for experimental value that mean if increased percent of SiC and Cu % lead to increased require load. This can be seen approximate match of the experimental and the simulation results at high ratios of SiC (20%) and all hybrid composite results which is when this ratio which indicates the accuracy of the boundary conditions for the simulation and the accuracy of the process, especially for hybrid composites.

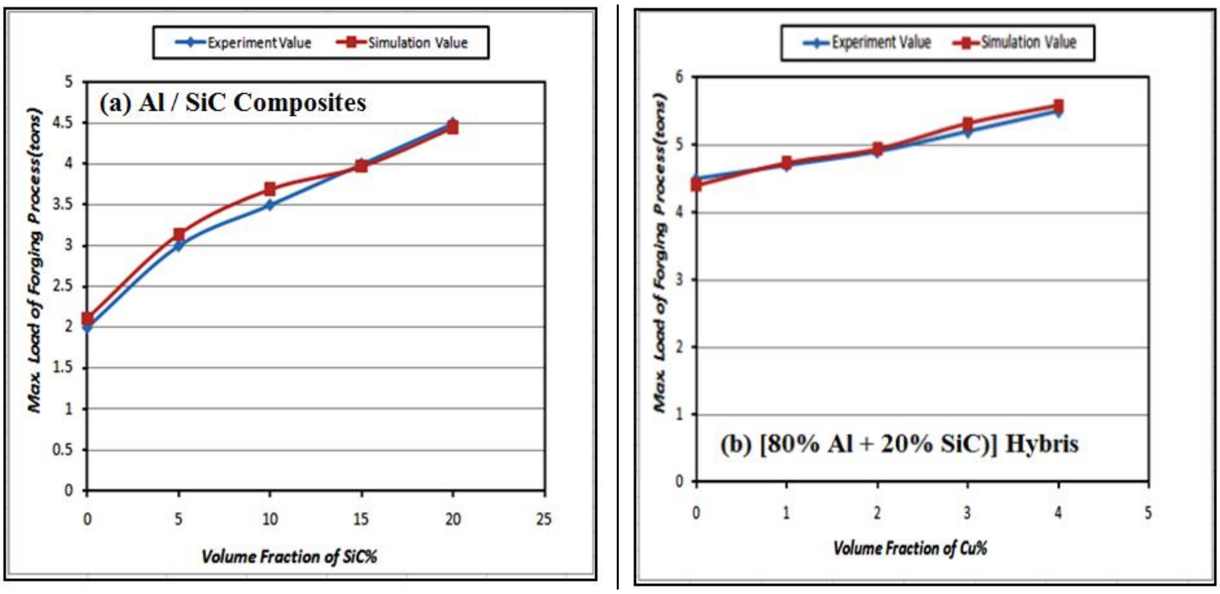


Figure (4): Effect the Percent Volume Fraction vs. Maximum Forging Load for :
(a) SiC% on composites and (b) Cu % on hybrid composites of (80% Al + 20% SiC).

4.2. Compression Test Results :

After forged all group of matrix and composites samples, Figure (5) shows the compression stress-strain curves increasing with forging process 10%, 15% , 28%, and 38% for matrix, 5% SiC, 10% SiC, and for both 15% SiC and 20% SiC composites respectively. When copper powder of (1%, 2%, 3% and 4%) are added to (99%, 98%, 97% and 96%) volume fractions respectively of (80% Al+20% SiC) as reinforcement materials, the aluminum hybrid composite materials for forged process have higher compressive strength than that of un-forged by 47 %, 49%, 50 %, and 47% respectively.

The tendency compression strength increasing is a results of forging process that overcomes all problems after PM process and thereby difficulties in reaching a full density of material. This is attributed to the fact that after forging process for all specimens become strong and has high compression strength that permits it to endure some of the applied compression load [8], therefore all mechanical properties improved after hot forging process such as compressive strength, compressive broken strain, proof yield strength, modulus of elasticity and modulus of toughness.

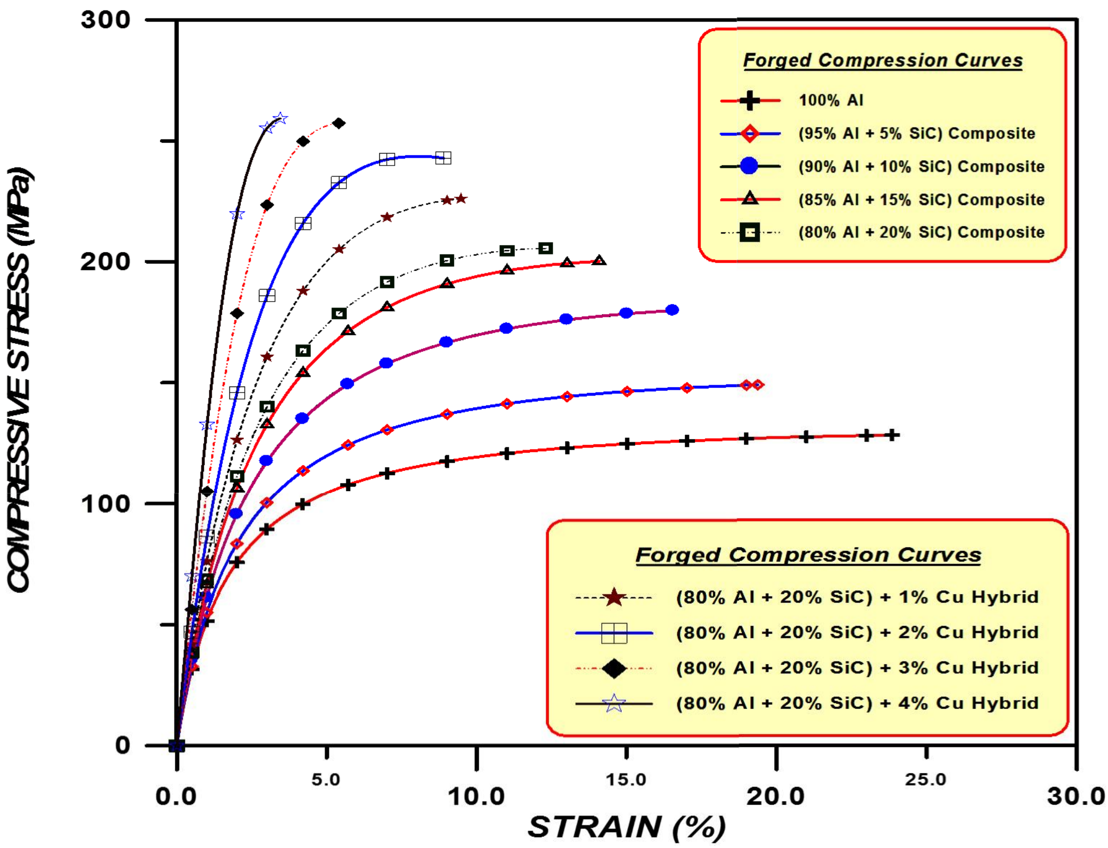


Figure (5): Stress-Strain Curves for Forged Composite & Hybrid Composite Materials.

4.3. Flexural Test Results :

Three point bending (flexural) test results for un-forged and forged materials as shown in Figure (6). It is observed that the flexural strength of composites and hybrid materials increases with forged process 17%, 26% , 36%, 46% and 50% for matrix, 5% SiC, 10% SiC, 15% SiC and 20% SiC composites respectively, and by 57 %, 58%, 60 %, and 57%   for hybrid composites respectively. This improvement because of the products manufactured by powder metallurgy has defects such as lower ductility, fatigue strength, and impact strength. Therefore, forging process has been introduced as an idea to overcome such defects; which lead to increase flexural strength and generally mechanical properties [9].

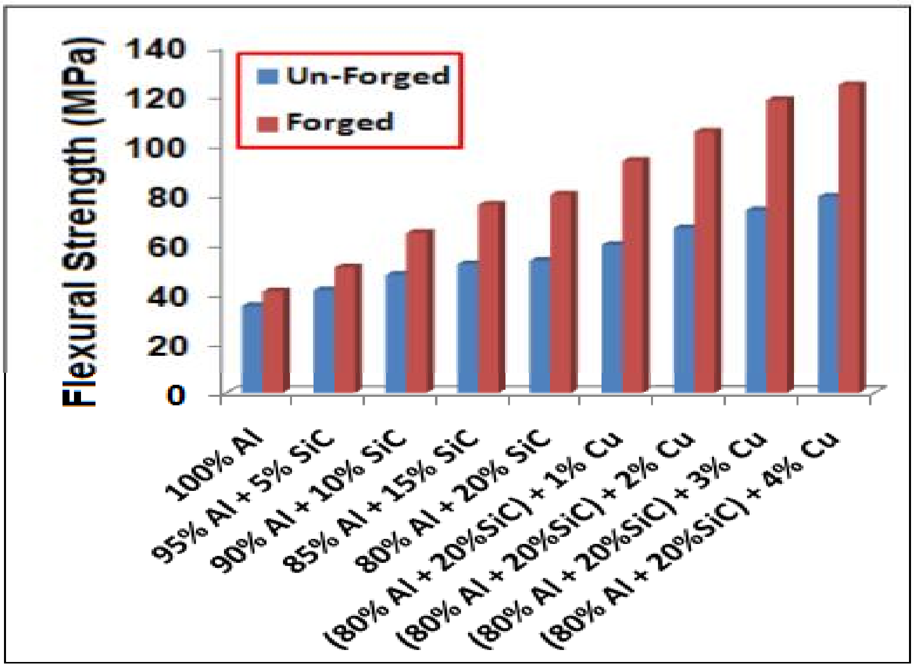


Figure (6): Flexural Strength for Forged and Un-Forged (Al/SiC-Composite) and (Al/SiC/Cu Hybrids Composite).

4.4. Compression vs. Hardness Strength :

Hardness (HRB) can be estimated for un-forged and forged composites and their hybrids. Equations (1) and (2) are a Sinusoidal fit model which is the best model (high correlation coefficients 0.991 and 0.993 for un-forged and forged composites and their hybrids respectively through more than thirty models. This model describes mathematically the increasing in compressive strength lead to increase the hardness value after and before forging process. Improved hardness results in increase leads to decrease in wear rate, finer the grain size better is the hardness and strength of composites leading to lowering of wear rates, which lead to increase mechanical properties [10].

$$\sigma_c=\left[145.52972+31.3835\ \cos\left(0.06622\ HRB-0.61582\right)\right]_{-3.264830176}^{+2.768252386} \quad \ldots\ldots\ldots\ldots (1)$$

$$\sigma_c=[360.72991+238.24609\ \cos(0.023802\ HRB+1.6796237)]_{-8.46129}^{+8.26171} \quad \ldots\ldots\ldots\ldots (2)$$

The effect of forging on compression strength related to hardness is sown clearly in Figure (7) which illustrates the increasing in compression and hardness is more than that for un forged.

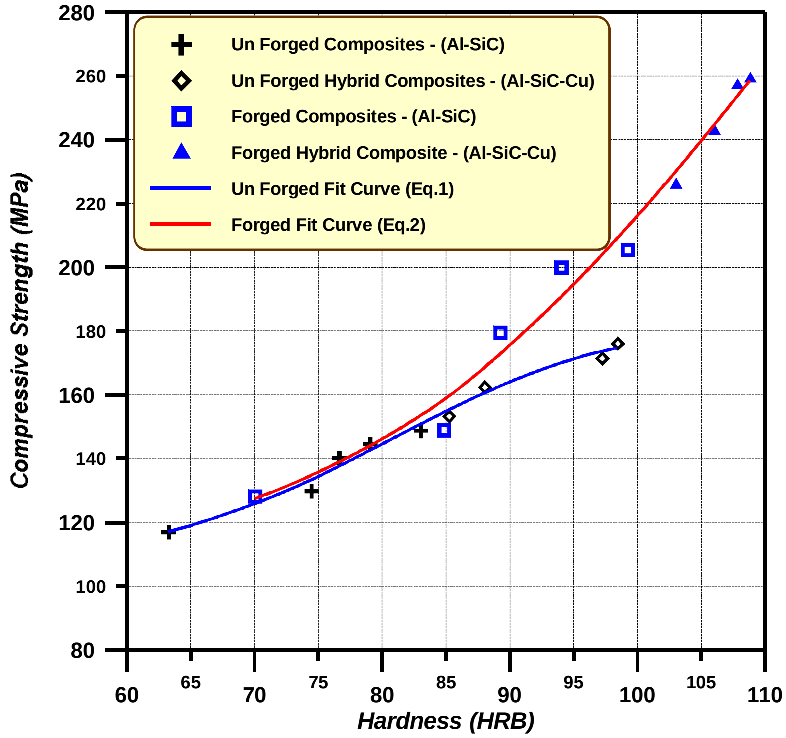


Figure (7): Effect of Hot Forging on Relationship of Compressive Strength vs. Hardness for (Al-SiC)-Composites and their Hybrids (Al-SiC-Cu).

5. Conclusion :

Al-SiC and Al-SiC-Cu (various concentrations) composites were successfully fabricated by powder metallurgy process and modified the mechanical properties for these materials hot forging process.

Based on the experimental observations the following conclusions have been drawn:

1. Maximum and minimum differences between simulation and experimental work for maximum applied forging load are (9.5%) and (1.5%) respectively.
2. The results of compressive tests shows that the properties (compressive strength, proof stress, and modulus of elasticity) for hybrid is best than composites and for forged best than un-forged. The forged hybrid [96% of (80%Al+20%SiC) + 4% Cu] have the highest values for the previous compressive properties by (74 %, 133%, and 349%) respectively relative to (148.92 MPa, 84.11 MPa and 3005.9 MPa) respectively for (80% Al + 20% SiC) un-forged composites.
3. The same previous indication was obtained in flexural strength from three-point bending tests. The forged hybrid (80%Al+20%SiC) + 4% Cu have the highest flexural strength value by (132%) relative to 53.5 MPa for (80% Al + 20% SiC) un-forged composites.
4. The hardness (HRB) can be estimated from compressive strength using Sinusoidal mathematical model equations (1) and (2) for forged and un-forged composites and their hybrids. So these composites can be used in applications where to a great extent weight reductions, endures high strength and hardness are desirable.

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