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Fabrication and investigation of the deformation behaviour of Al-10Si-TiB2 composites

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Abstract- Light weight metal matrix composites based on aluminum alloy and TiB_2 particulates has emerged as an important class of materials and finding increasing applications in automobile, aero-space and space industries, in their quest for achieving better fuel economy. In order to fabricate a kind of high strength particulate reinforced aluminum alloy matrix composites, a high strength aluminum-10silicon alloy was selected as a matrix and composites reinforced with varying amounts of TiB_2 particles from 2 to 10% were synthesized using stir casting method. The deformation behaviour was analyzed. Stress of base Al -10Si alloy and its TiB_2 composites in the as cast condition has increased with increase in deformation in both samples of aspect ratio 1 and 1.5. Load required to deform of base Al -10Si alloy and its TiB_2 composites in the as cast condition increased with increase in reinforcement content as well as with aspect ratio. The increase in the properties could be attributed to be good bonding of TiB_2 particles and aluminum matrix. Stress of base Al -10Si alloy and its TiB_2 composites in the as cast condition has increased with increase in deformation in both samples of aspect ratio 1 and 1.5. But hardness has decreased with with increased aspect ratio. Strength coefficient (K) and strain hardening exponent (n) of Al-10Si-10TiB_2 considered in the present investigation was found to be 386.1 and 0.493 shows that the material has good flow stress per unit strain, good formability and can be work hardened at higher rate compared to its base Al -10Si alloy and its composites. Bulge diameter for base Al-10Si alloy and its composites increased with increasing degree of deformation, due to friction at contact surfaces, where as radius of curvature of bulge decreased with increasing degree of deformation.

Index Terms- Al -10Si alloy,TiB2, MMC, Stir casting, Deformation, Radius of curvature of bulge.

I. INTRODUCTION

Many operations in manufacturing processes such as forging, rolling, extrusion etc are performed with the work piece, subjected to compressive forces. Specimen subjected to a compressive load gives information useful for these processes [1-2]. Uni-axial compression of cylinders is a standard test, determines the ability of material to be forged either in cold or warm conditions without cracking. This test is important and gives a representative behaviour during metal forming at room temperature.

In uni-axial compression testing, the presence of frictional constraints between the dies and the work-piece has a direct effect on the plastic deformation of the later. When a solid cylinder undergoes axial compression between the top and bottom platen, the work-piece undergoes heterogeneous deformation, resulting in the “barrelling” of the cylinder. Friction at the faces of contact causes a retarding effect on the plastic flow of metal on the surface and in its vicinity. As a result, a conical wedge of a relatively undeformed metal is formed next to platens, while the rest of the cylinder suffers high strains and bulges out in the form of a barrel. This demonstrates that the metal goes easily towards the nearest free surface which is said as the point of least resistance, a well-known principle of plastic deformation [2].

II. LITERATURE REVIEW

Many investigators have carried out a series of investigations on uniaxial compression testing/cold forging of solid cylinders. Because of its relevance in many metal forming applications, comprehensive review of literature has been published by Johnson and Mellor [3]. Another major aspect of uniaxial compression from the standpoint of testing the mechanical properties of metals is its estimation of their forming limits up to plastic instability and subsequently fractures. *Narayanasamy R*, et al. [4-5] studied the cold upset forming for different materials and different shapes. A new geometrical shape factor (GSF) has been established based on the dimensions of the deformed specimens. It was reported that the measured barrel radius of curvature follows a straight line relationship with the GSF. Narayanasamy R and Pandey K S et al. [6] studied the effect of barrelling in aluminium solid cylinders during cold upset forming and found that the measured radius of curvature of the barrel exhibited a straight-line relationship with the new geometrical shape-factor, irrespective of the aspect ratios of the cylinders. Sowerby R, Banerjee J.K et al. [7, 8] showed theoretically that the barrel radius can also be expressed as a function of axial strain and subsequently confirmed the same through experimental verification. Kulkarni and Kalpakjian et al. [9] conducted experiments on 7075 aluminium specimens with three aspect ratios to examine the arc of barrel and lead to conclusion that it may be a circular or parabolic. Schey A, Narayanasamy R et al. [10-11] presented a comprehensive report on the different geometrical factors that affect the shape of the barrel and concluded that the expansion of the original end face was highly sensitive to friction and the material’s strain hardening characteristics. Yang *D et al*. [12] developed an upper bound solution for the determination of forging load and also deformed bulged profile during upset forging of cylindrical billets under the dissimilar frictional conditions at flat die surfaces. Male A T and Cockcroft M G et al. [13] developed ring compression test, which is most commonly, employed method for determining friction characteristics. The test involves the compression of a hollow thick walled cylinder, or ring, and the determination of the variation of the internal bore diameter with the height reduction. Shaw M C et al. [14] studied the significance of axi symmetric compression from the stand point of mechanical/manufacturing properties of materials and estimated the forming limits up to plastic instability and fracture. Malayappan S et al. [15] also made analysis on effect of friction and concluded that the final shape of the work-piece after the upsetting process can be divided into two geometries namely a barrelled portion and a truncated cone portion and the new hoop strain slope is found to increase accordingly with increasing aspect ratio. Sljapic V [16] studied fracture in axi-symmetric and three dimensional cold upsetting of brass and concluded that the material exhibit a transition from ductile to brittle behaviour under the room temperature quasi-static test conditions. Kobayashi S [17] studied the deformation characteristics and ductile fracture of 1040 steel in simple upsetting of solid cylinders, and also calculated the ring compression tests to evaluate the friction factor.

Extensive studies have been reported by various authors on the compression of solid cylinders where the initial height/diameter (H_0/D_0) ratio equals or exceeds unity. Though there are many works on friction studies, little attention has been given to the compression of taller cylinders, due to the height of the specimen and ductility of the material. To be comprehensive and practical, a model of the forging process should permit the determination of the platen forces, the friction between the platens and work piece, pressure distributions affecting tool life, the internal flow of the forging influencing die-design, forging sequence and the properties of final product dictating in-service performance.

Banerjee and Narayanasamy et al. showed theoretically that the barrel radius can also be expressed as a function of axial strain and subsequently confirmed the same through experimental verification [18,19,20]. Narayanaswamy et al, have done experimental work on workability behaviour of aluminium, Al-Al_2O_3 [20], Al-Fe [21,], Fe [22] and Fe-TiC [23,] during cold upsetting. S Dikshit et al. [24] carried out cold upsetting experiments under unlubricated condition on cast and homogenized AA 2014/SiC composites to study the effect of homogenization on deformation behavior.

Present work attempts to discuss the deformation behaviour of Al-10Si alloy and Al-10Si -TiB_2 composites under uni axial compression, which had a direct relevance to the experimental results.

III. EXPERIMENTAL METHODS

A. Fabrication of composites

Al-10Si alloy was melted at 775^{0}C under the protection argon atmosphere. The reaction slag was skimmed from the surface of melt. TiB_2 particles were added in to the vortex formed during stirring. Al-10Si alloy basedcomposites were produced by varying the TiB_2 content from 2% to 10% in the form of 8inch long x 25mm dia. and 8inch long x 22mm dia. castings. The composites were quenched in water at room temperature.

The cylindrical test specimens of size 25mm length x 25mm diameter with aspect ratio 1 and 37.5mm length x25mm diameter for aspect ratio 1.5 were machined from the castings for deformation studies. Hardness studies were carried out on Vickers micro hardness tester (micro vickers hardness tester, Model: LV 700) hardness testing machine.

B. Compression Test

The upset tests were performed at room temperature between two flat platens on a UTM of 100 KN capacity universal testing machine (Model: UTM/E100). The compression dies of EN-31 grade are used for compression and the sample was placed axi-symmetrically in between the dies. The tests were conducted at 10%, 20%, 30%, 40% and 50% deformations on the top surface of the Al-10Si alloy and its TiB_2 composites with a constant cross head speed to assess the deformation behaviour for two limiting values of aspect ratio 1.5 (to avoid buckling) and 1.0 (which is used in most of the forging applications).

Fig.1.(a): Al-10Si alloy specimens showing bulge profiles at various deformation stages under compression testing at aspect ratio 1.0.

Fig.1(b): Al-10Si-2%TiB_2 composite specimens showing bulge profiles at various deformation stages under compression testing at aspect ratio 1.0.

Fig.1.(c): Al-10Si-4%TiB_2 composite specimens showing bulge profiles at various deformation stages under compression testing at aspect ratio 1.

Fig.1.(d): Al-10Si-6%TiB_2 composite specimens showing bulge profiles at various deformation stages under compression testing at aspect ratio 1.

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Fig.1. (e): Al-10Si-8%TiB_2 composite specimens showing bulge profiles at various deformation stages under compression testing at aspect ratio 1.

Fig.1.f: Al-10Si-10%TiB_2 composite specimens showing bulge profiles at various deformation stages under compression testing at aspect ratio 1.0

Fig.2. (a): Al-10Si alloy specimens showing bulge profiles at various deformation stages under compression testing at aspect ratio 1.5.

Fig.2. (b):Al-10Si-2%TiB_2 composite alloy specimens showing bulge profiles at various deformation stages under compression testing at aspect ratio 1.5.

Fig.2.(c):Al-10Si-4%TiB_2 composite specimens showing bulge profiles at various deformation stages under compression testing at aspect ratio 1.5.

Fig.2.(d):Al-10Si-6%TiB_2 composite specimens showing bulge profiles at various deformation stages under compression testing at aspect ratio 1.5.

Fig.2.(e): Al-10Si-8%TiB_2 composite specimens showing bulge profiles at various deformation stages under compression testing at aspect ratio 1.5.

Fig.2.(f): Al-10Si-10%TiB_2 composite specimens showing bulge profiles at various deformation stages under compression testing at aspect ratio1.5.

IV. RESULTS AND DISCUSSION

A. Compressive behaviour

Compressive properties of the alloy and composites have been studied from the load-displacement curves.

Figure 3 and 4 shows the true stress–true strain curves of alloy and composites with aspect ratios of 1.0 and 1.5 respectively.

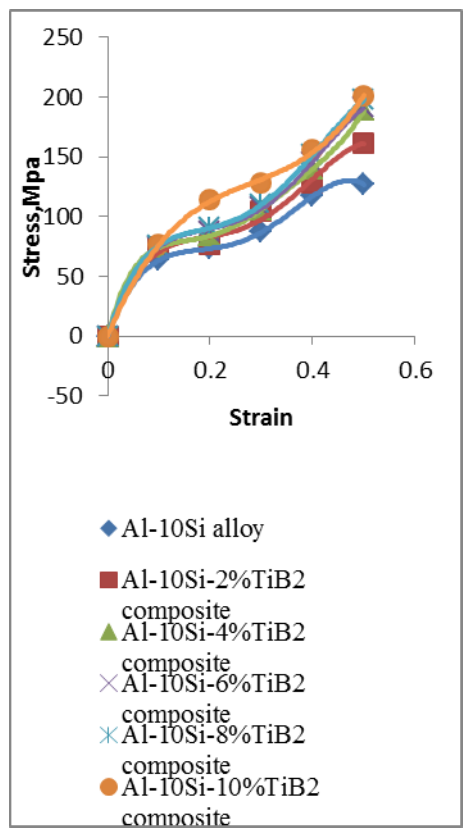

Fig.3.variation of compressive stress and strain in Al-10Si alloy and composites (aspect ratio 1)

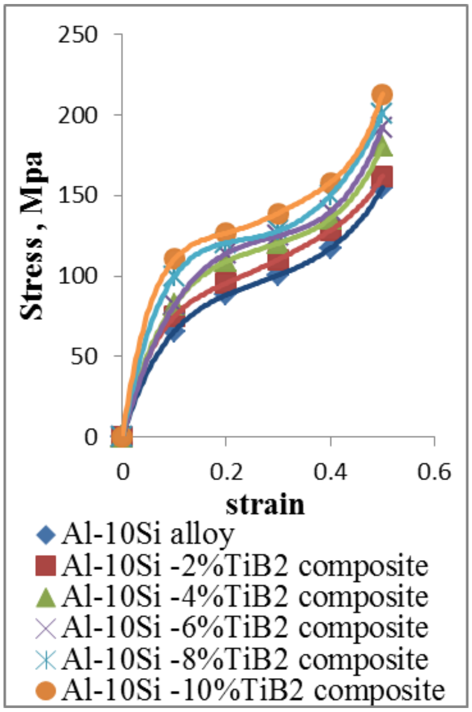

Fig.4: variation of compressive stress and strain in Al-10Si alloy and its composites (aspect ratio 1.5)

Both alloy and composites exhibit strain hardening behaviour showing increase in load with increasing displacement. The composites show higher loads than the alloy and the increase in load increases with the increasing reinforcement contents, indicating increased work hardening due to the presence of reinforcements and its corresponding weight fractions.

Erik Parteder [25], Khlaghi F [26] and Valdez S [27], reported, the strength of the MMC is expected to increase by addition of solid particles due to the strengthening effects occurred in particulate reinforced composites. These effects include the transfer of stress from the matrix to the particulate, the interaction between individual dislocations and particulates, grain size strengthening mechanism due to reduction in composite matrix grain size, and generation of a high dislocation density in the matrix of the composite as a result of the difference in thermal expansion between the metal matrix and particulates.

Figure 5 and figure 6 shows the effect of aspect ratio1 and 1.5 on load taken by the specimen up to 50% deformation. The increase in aspect ratio decreases the load required for the same amount of deformation. For a fixed diameter, a shorter specimen will require a greater axial force to produce the same percentage of reduction in height, because of the relatively larger undeformed region [28].

From the above observations it is evideint that stress of Al-10Si alloy and its composites in the as cast condition increased with increase in degree of deformation in both samples of aspect ratio 1 and 1.5. Further it was also observed that the load required to deform Al-10Si alloy & composites in the as cast condition increased with increase in reinforcement content as well as with aspect ratio.

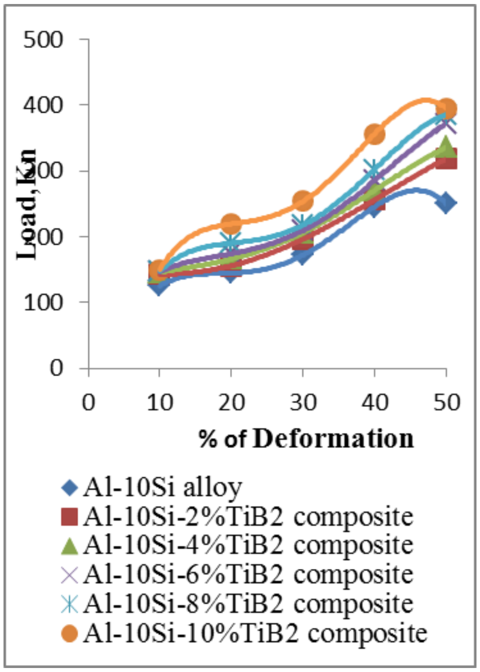

Fig.5:Effect of load on deformation of samples with aspect ratio1.

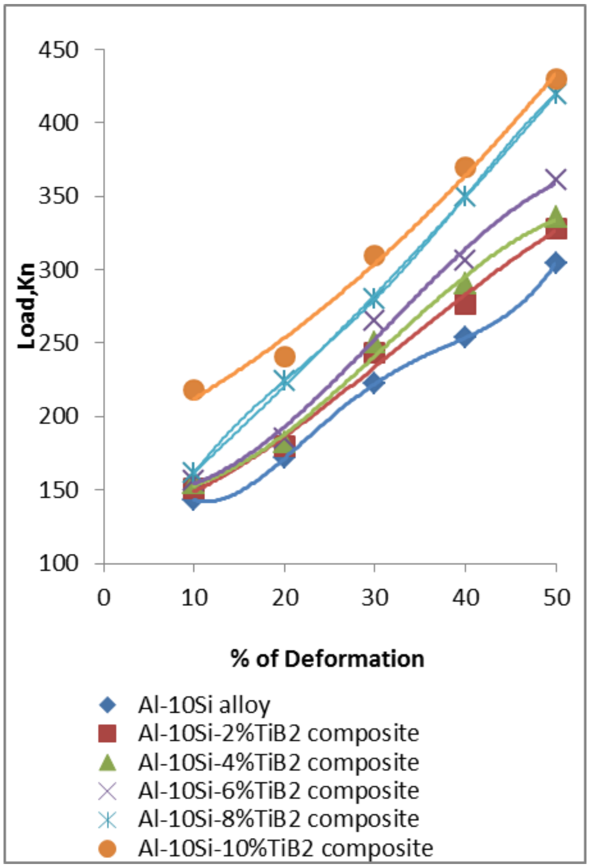

Fig.6: Effect of load on deformation of samples with aspect ratio 1.5.

From the above observations it is evideint that load required to deform the alloy and its composites in the as cast condition has increased with increase in deformation, in the both samples of aspect ratio 1and 1.5. Further it is also observed that the load required to deform the alloy & composites in the as cast condition is reduced with increased aspect ratio

A. Hollomon power law parameters

In the absence of thermal action, such as recrystalization or recovery, during the deformation process, the exponent ‘n’ was a measure of the work hardening. This represents the increase of flow stress $\bar{\sigma}$ with increase in natural strain $\bar{\varepsilon}$. Based on this phenomenon, the work hardening coefficient ‘n’ was a measure of achievable maximum formability for different materials during forming with the same external restraints. A higher work hardening coefficient means a higher uniform elongation value, thereby reducing the tendency for local straining in the material. Although slip planes occasionally cross grain boundaries, especially if the crystals have twin orientation or close to it as a rule deformation stops whenever a change of orientation is present not only grain boundaries but also sub boundaries acts as barriers for movement, and a pile-up of dislocations with distortion of the crystal results (29-31)

The calculated true stress vs. true strain was fit into the equation of Holloman power law [28-33] given by:

$\bar{\sigma} = K\,\bar{\varepsilon}^{n}$ ------------------ (1) Where $\bar{\sigma}$ = true stress, $\bar{\varepsilon}$ = true plastic strain, K= strength coefficient, and
n = strain hardening exponent

Hollomon parameters ‘K’ and ‘n’ are used widely to assess the behaviour of metals in both uni axial tension and compression at room temperature [34-36]. These constants have also been used to relate properties in metal forming [37-43]. The strength coefficient (K) gives the flow stress at unit strain and it is the measure of elastic spring-back. The strain hardening exponent ‘n’ is an important parameter in metal forming. It signifies the strain hardening or work hardening characteristic of a material, that is, the higher the value of ‘n’, higher is the rate at which the material work hardens. A material with high value of ‘n’ is preferred for process which involves plastic deformation. The larger the ‘n’ value, the more the material can deform before instability [43]. To validate the calculations, the plastic region of the curve.

In order to study the effect of reinforcement content on strength coefficient (K) and strain hardening exponent (n), calculations have been made taking base alloy value as zero. Figure.7. and figure.8. shows the effect of reinforcement content on strength coefficient (K) and strain hardening exponent (n). As the reinforcement content increases, a continuous increase in K values have been observed. Increased fabrication time of composites may be one of the reasons for the formation of thick interface between the matrix and the reinforcement, inhibiting effective transfer of load from matrix to the reinforcement.

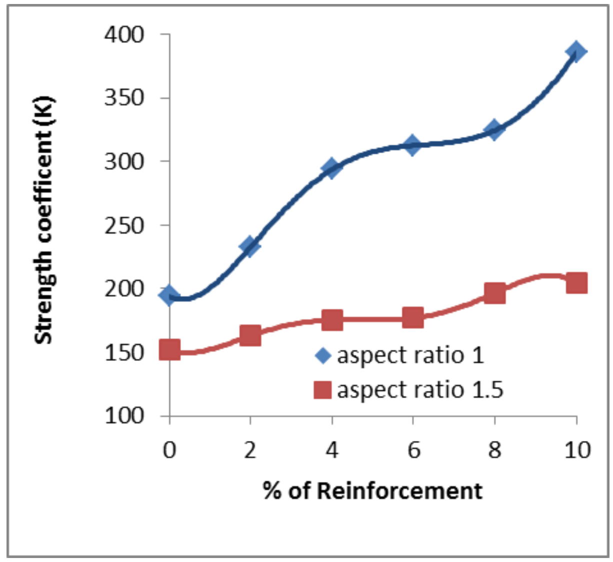

Fig.7: variation of strength coefficient (K) with respect to content.

It is evideint that strength coefficient (K) and strain hardening exponent(n) of the Al-10Si alloy and its TiB_2 composites in the as cast condition as well as after deformation has increased with increased reinforecement content in the both samples of aspect ratio 1 and 1.5. But it was observed that the samples with aspect ratio 1 are found to have higher values of strength coefficient (K) and strain hardening exponent (n) than that of the samples with aspect ratio 1.5.

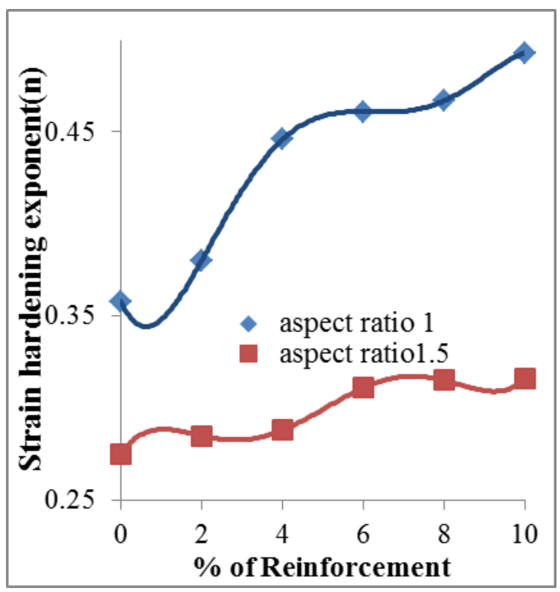

Fig.8: Variation of strain hardening exponent (n) with reinforcement content.

Venugopal et al [44] reported that, decrease in strength coefficient (K) value is due to occurance of bulk forming & mass constancy. Composites with higher reinforcements offer higher resistance towards deformation. Narayanaswamy R [23] reported that composites with smaller particles, offer higher value of strength coefficient. Samuel K G et al [45] reported that, the larger the strain hardening exponent (n) value, the more the

material can deform before instability. A material with high vaue of n was preferred for process, which involve plastic deformation. The strain hardening exponent found to be increasing with increase in aspect ratio. The increase in strain hardening exponent (n) with increasing aspect ratio shows the material can take more plastic deformation before instability.
An effective interface is one which transfers quickly from the matrix to the reinforcement in the smooth way, and this effectiveness holds good only when a uniform interface is formed between the matrix and reinforcement. Formation of thicker interfaces not only impedes load transfer (diminishing 'K') but also minimizes the dislocation mobility (diminishing 'n').

Hollomon parameters 'K' and 'n' are used widely to assess the behavior of metals in both uniaxial tension and compression at room temperature [33-35]. These constants have also been used to relate properties in metal forming [36-42]. The strength coefficient (K) gives the flow stress at unit strain and it is the measure of elastic spring-back. The strain hardening exponent 'n' is an important in metal forming. It signifies the strain hardening or work hardening characteristic of a material, that is, the higher the value of 'n', higher is the rate at which the material work hardens. A material with high value of 'n' is preferred for process, which involves plastic deformation. The larger the 'n' value, the more the material can deform before instability [43].

It is evident that strain hardening exponent (n) of the Al-10Si -TiB2 composites in the as cast condition has increased with increased reinforecement content in the both samples of aspect ratio 1and 1.5. Further it is also observed that the strength coefficient (K) and strain hardening exponent (n) of the Al-10Si alloy TiB_2 composites decreased with increased aspect ratio.

B. Hardness behaviour during work hardening

Hardness was found to be increasing with increasing deformations and also with increasing reinforcement content. Work hardening of material due to increased dislocation density during deformation is the reason for the increase in hardness. As the dislocation density increases, resistance to the mobility of dislocations increases, resulting in a continuous increment in hardness values.

In order to substantiate the compressive behaviour with the aspect ratio (H/D), hardness testing was conducted. Figure.9. shows the effect of deformation on hardness, for the Al-10Si alloy and its TiB_2 composites. The hardness values were found to be low for samples with aspect ratio 1 when compared to that of 1.5. This behavior indicated was in tune with that of compressive behavior, as discussed in the earlier paragraphs.

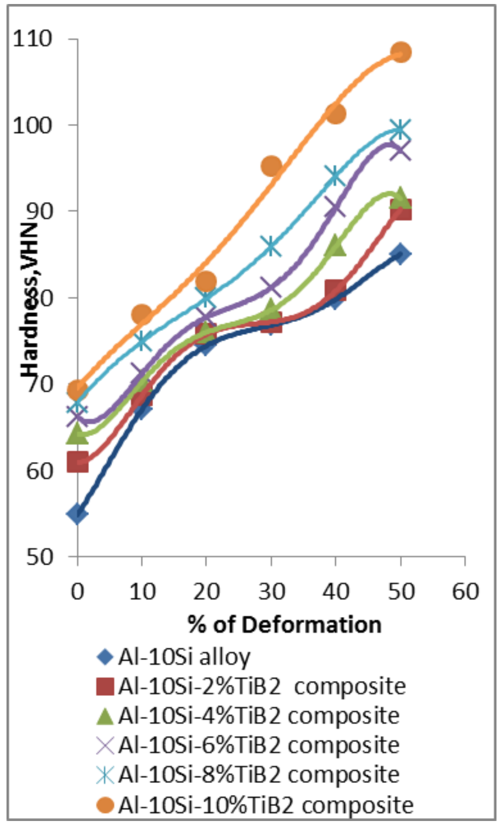

Fig.9:Effect of deformation on hardness of samples with aspect ratio1.

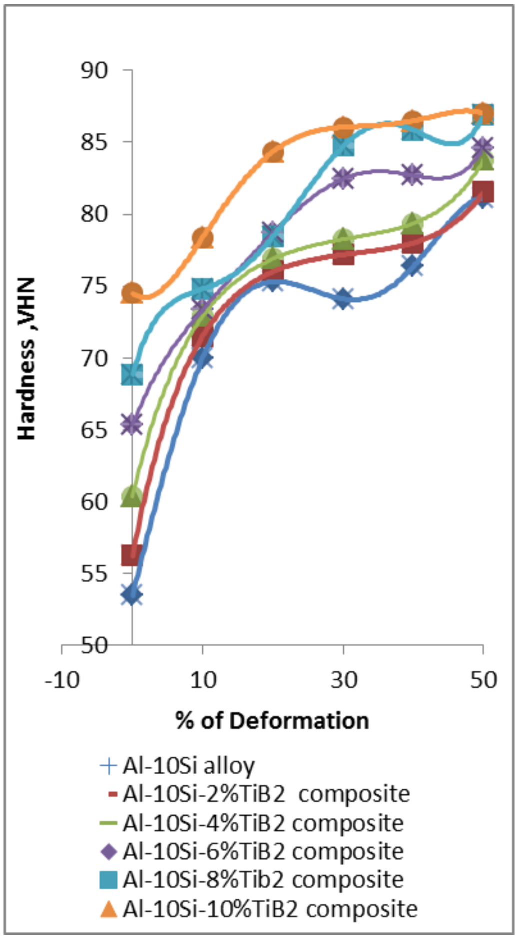

Fig.10: Effect of deformation on hardness of samples with aspect ratio1.5.

From the above observations it is evideint that hardness of alloy and its composites in the as cast condition has increased with increase in deformation, in both samples of aspect ratio 1 and 1.5, and the same decreased with with increased aspect ratio.

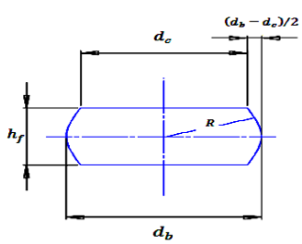

Fig.11: Effect of deformation on bulge diameter

Bulging is the phenomenon when the faces under uni-axial compression get deformed to result in a bulge shaped profile with bulge diameter attaining a maximum in the middle of the height of the deformed specimen. The bulge profile observed in this particular case of Al-10Si alloy subjected to uni axial compression at room temperature bears a close resemblance to that one shown in figure 11.

Fig.12. shows the effect of deformation at the centre of the samples. The diameter at the centre increases more compared to the ends of the cylinder (sample) due to friction free volume that is available at the centre compared to the restricted deformation at the contacts. The bulge diameter is found to be increasing with increasing deformation

Radius of curvature of Bulge = $R = h_f^2 / 4(d_b - d_c)$ ---------2

Where h_f = height of the sample after deformation
d_b = bulge diameter of the sample after deformation
d_c = top diameter of the sample after deformation

Fig.12:specimens under different deformations with their bulge profiles.

C. Radius of curvature of bulge

Fig.13. Shows the effect of reinforcement content on radius of curvature of bulge. Radius of curvature of bulge decreases with increase in reinforcement content. This effect is much more pronounced with decreasing aspect ratio.

Height of the specimen after deformation, the bulge diameter and the top diameter of the specimen after each and every deformation are measured in each case. Kulkarni et al [9] reported that the profile of the bulged surface is approximately by an arc of a circle, figure.12.The radius of curvature of bulge is calculated basing on the formula given below as equation 1..The radius of curvature of bulge plotted as a function of percentage of deformation is shown in the figure 13.The radius of curvature of bulge found to be decreasing with increasing deformation. As the deformation proceeds, the flow of the metal at the top and bottom platens will increase with respect to the middle and hence the radius of curvature seems to be decreased.

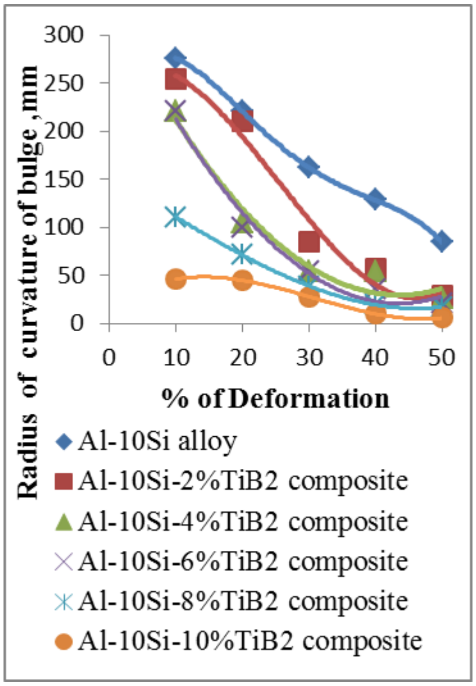

Figure.13: Effect of deformation on radius of curvature of bulge (aspect ratio 1).

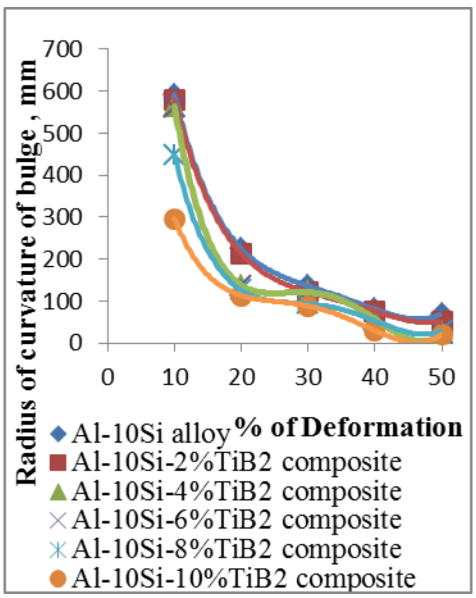

Figure.14: Effect of deformation on radius of curvature of bulge (aspect ratio 1.5).

From the above observations it is evideint that radius of curvature of bulge of Al-10Si alloy and its TiB_2 composites in the as cast condition decreased with increase in deformation in the both samples of aspect ratio 1and 1.5 and the same is reduced with increased aspect ratio.

V. CONCLUSIONS

1. Stress of base Al -10Si alloy and its TiB_2 composites in the as cast condition has increased with increase in deformation in both samples of aspect ratio 1 and 1.5.
2. Load required to deform of base Al -10Si alloy and its TiB_2 composites in the as cast condition increased with increase in reinforcement content as well as with aspect ratio.
3. Hardness of base Al -10Si alloy and its TiB_2 composites in the as cast condition has increased with increase in deformation, in both samples of aspect ratio 1 and 1.5, and the same decreased with with increased aspect ratio.
4. Strength coefficient (K) of Al -10Si-10%TiB_2 considered in the present investigation is found to be 386.1 shows that the material has good flow stress per unit strain compared to its base Al -10Si alloy and its composites.
5. Strain hardening exponent (n) of Al-10Si-10%TiB_2, considered in the present investigation, is found to be 0.493, shows that the material has good formability and can be work hardened at higher rate compared to base Al -10Si alloy and its composites.
6. Bulge diameter for base Al -10Si alloy and its composites is increasing with increasing degree of deformation, due to friction at contact surfaces.
7. Radius of curvature of bulge for base Al -10Si alloy and its composites is decreasing with increasing degree of deformation.

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