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Analytical, numerical and experimental approach for design and development of optimal die profile for the cold extrusion of B_4C DRMM Al 6061 composite billet into hexagonal section †

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Abstract

Aluminium based matrix composites with boron carbide as particle reinforcement called Discontinuous reinforced metal matrix composites (DRMMs) possess high specific strength, high elastic modulus, good wear resistance, damping capacity and thermal stability. But during the development of DRMM composites, compression process like extrusion is an advisable secondary process for homogenous structure. This research work investigates the metal flow behavior of Al-B_4C based DRMM composite through six different die profiles namely third order polynomial, fourth order polynomial, cosine, elliptical, hyperbolic and conical geometry. Extrusion load, stress and strain distribution, and metal flow for above said die profiles are predicted by using analytical approach upper bound technique and compared with finite element method. Cosine and third order polynomial profiles are found to be most optimal in terms of homogenous and minimal extrusion load requirement. To validate the results, specially made Al-B_4C composite through stir casting route was extruded from round to hexagon through an exclusively fabricated cosine die. Results observed from the experiment have good agreement with both analytical and numerical.

Keywords: Stir casting; Metal matrix composites; Nanoindentation; Upper bound technique; DEFORM-3D; Cosine profile die

1. Introduction

Advanced material development in the field of engineering applications has made revolutionary changes in the life of engineering components. Metal matrix composites are important materials and recently emerged as an alternative to conventional monolithic alloys. Aluminium based metal matrix with ceramic materials like SiC and Al_2O_3 are the widely used reinforcement materials for aluminium in particulate form are technically known as Discontinuous Reinforcement Metal Matrix composites. Boron carbide found to be an alternative for SiC and Al_2O_3 due to high hardness and low density. This specific combination of Al-B_4C DRMM composites have an incredible physical and mechanical properties such as high modulus, yield strength, wear resistance, damping capacity and thermal stability.

Because of these properties, they have unique applications in aerospace, automobile, absorption of neutron, bulletproof armor and other fields.

As a primary processing technique to develop the metal matrix composite, either stir casting route or powder metallurgy technique has been followed. But these processing techniques often develops the composites with defects like porosity, non uniform grain structure, inhomogeneous reinforcement distribution and weak bonding between matrix and reinforcement materials due to low wettability and density different between matrix and reinforcement materials. These defects are rectified or relieved, when the composite are fed into extrusion, hence the extrusion of the metal matrix composites with particle reinforcement is an inevitable secondary process for their microstructure development. Extrusion not only deforms the materials into desired shape but also refines the microstructure in terms of homogeneous reinforcement and bonding.

A number of literature research works have been carried out on streamlined extrusion. R.Narayanasamy and R. Venkatesan [1] have suggested the streamlined extrusion die by taking the die profile as cosine function and have analysed through upper bound technique and compared the results with concave and straight tapered die, but they have considered the material as Aluminium. R. Naraynasamy et al. [2] did the same analysis for streamlined die by considering the die profile as Bezier curve. N. Venkata Reddy and P. M Dixit [3] have attempted to find an optimal die profile for axisymmetric extrusion through

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a pure analytical approach of a combined upper bound and slab method. They have compared the results of eight different die profile shapes and they have concluded that the cosine and fourth order polynomials are the best amongst the profiles considered. Joseph S. Ajiboye [4, 5] have utilised the upper bound technique to predict the extrusion pressure in three dimensional forward extrusion process using square/rectangular sections and the effect of selected parameters on temperature distribution in axisymmetric extrusion. Y. H. Seo, C. G. Kang [6] have conducted a research work regarding the influence of die profile over the mechanical properties of silicon carbide reinforced aluminium composite fabricated by melt stirring. They have concluded that the tensile strength of extruded billet has been increased by 20% to 30% and also homogeneous distribution of reinforcement has been improved. E. Mohammad sharifi, F. Karimzadeh, M. H. Enayati [7] have carried a charectrization and tribological study by fabricating Al-B_4C nanocomposite through ball mill and powder metallurgy route. They have concluded that the wear resistance of the nanocomposite increases significantly with the increase in B_4C content.

Influence of particle reinforcement of Al_2O_3 with aluminium as matrix material has been studied by E. M. Herba and H. J. McQueen [8] using DEFORM package, finally they have validated that the higher load stroke curve were recorded for higher content of Al_2O_3 particle. Effect of dead metal zone over the tribological interaction between the die and billet deformation of Sic reinforced Al 6063 composite have been investigated by Fehmi Nair, M. Baki Karamis [9]. These researchers have stressed and predicted that there are two sections of dead metal zone developed during deformation of Al-Sic composite wherein there is no material flow in one zone, while other zone observed very small material flow. M. Schikorra et al. [10] have analysed the microstructure and grain size distribution of three different grades of aluminium alloys after the extrusion to show the metal flow, dynamic and static recrysatallization. Three dimensional forward extrusion of square section from a round billet through a straight converging die was analyzed using both updated Lagarangian and the combined Eulerian-Lagarangian finite element formulations by B. P. P. A. Gouvia, J. M. C. Rodrigues [11] and co authors. They have come up with the results, that the combined Eulerian- Lagarangian mesh models are more efficient for the analyses of steady state metal forming process. Design of streamlined extrusion die to extrude a aluminium round billet into hexagonal section has been carried out by this same authors C. Venkatesh and R. Venkatesan [12] using upper bound technique and finite element method, and they compared the results with the experimental results to validate the cosine profile is a best streamlined profile.

Most of the previous research work focused to register the benefit of streamlined profile through various techniques by considering the billet as aluminium or any other metals, but only, very few attempts have been made towards the extrusion of DRMM composite. In this study keen attention was paid to bring out an exact and efficient die profile with proper specifications to extrude an advanced material like boron carbide reinforced metal matrix composite. More over this study has diverted into an industrially benefited hexagonal section as extrudate. To investigate the optimal profile, there are six different die profile geometry of fourth order polynomial, third order polynomial, cosine, elliptical, hyperbolic, and conical were utilised.

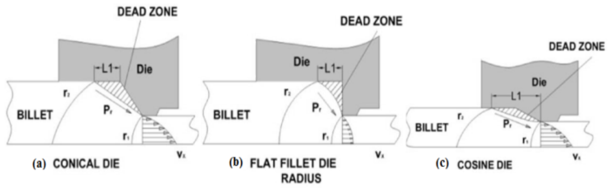


Fig. 1. Extrusion through various dies.

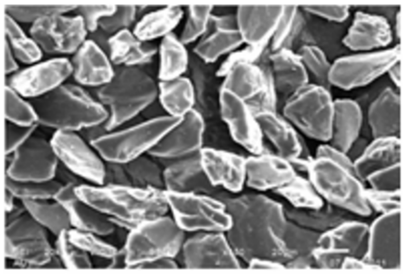


Fig. 2. SEM image of B_4C particles.

2. Geometry of die profile

In extrusion, mechanical properties of the billet material, extrusion ratio, frictional condition between die-workpiece interface, and the die profile are the predominant parameters that directly influences the product quality. Study of frictional condition and effect of die profile to impart a homogeneous deformation of material flow becomes very complex in analytical way. Reduction of dead metal zone and frictional effect between die- workpiece interfaces ensures the homogeneous metal flow, this has been proved by many researchers by redesigning the die profile. But most of the research articles and B. Avitzur [13] dealt with conventional conical die with different cone angle. The effect of dead metal zone during extrusion schematically depicted in a, b and c of Fig. 1.

3. Material and method

3.1 Development of composite billet

The Al-B_4C DRMM composite was manufactured through stir casting route. AA 6061 aluminium alloy whose properties has been tabulated in Table 1 was used as a matrix material and B_4C granules with particle size of 85μm with volume fraction 10% shown in Fig. 2 used as a reinforced material. The properties of B_4C particles have also been presented in Table 2.

Table 1. Properties of aluminium 6061.

Density	Elastic modulus	Yield strength	Thermal conductivity	Melting point	Hardness BHN
2.7 gm/cm^3	68.9 GPa	276 MPa	167 W/mK	652°C	95

Table 2. Properties of boron carbide.

Density	Elastic Modulus	Yield strength	Thermal conductivity	Melting point	Hardness (Vickers)
2.5 gm/cm^3	460 GPa	569 MPa	42 W/mK	2763°C	38 GPa

Fig. 3. Stir casting setup.

Fig. 4. Al- B_4C composite.

During the stir casting process as shown in Fig. 3 first AA6061 matrix material was melted at a 750°C in a graphite crucible coated with wolfra coat, within the resistance heated furnace. Next, B_4C particle preheated up to 500°C were added with degassing tablets and magnesium covered with Al foil into the molten bath of AA6061. The B_4C particles were stirred by a wolfra coated stirrer at 400 rpm for about 30 min for a homogeneous mixture. After completing the stirring process, the material mixture was cast in to a metallic mould at 750°C to 850°C. The material was allowed to cool in open atmosphere, and then the material was machined to a 10 mm diameter and 25 mm in length of cylindrical section which is shown in Fig. 4.

3.2 Microscopic examination

The part of the casted composite material was finished to a size of 1 cm cube. The specimen material was fully ground to maximum surface finish and then cleaned by acetone. To extract the elastic modulus and the hardness of the material, the nano-indentation set up was employed. The prepared specimen was mounted on a metal base with mounting adhesive under the Berkovich type indenter. More than 40 indentations were made over the surface of the specimen at various places with the load ranging from 11 mN to 67 mN. The depth of penetration beneath the specimen surface was observed and recorded for every indentation from the nano-indenter in nanoscale as shown in Fig. 5. From the extracted results, the load displacement curve has been plotted as shown in Fig. 6.

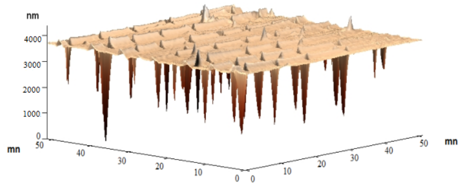


Fig. 5. Morphology of nanoindentor.

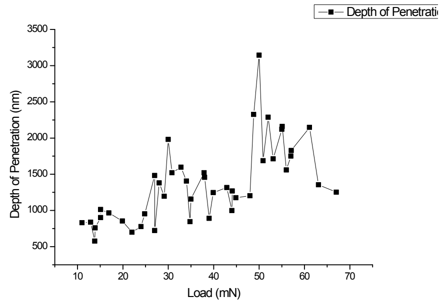


Fig. 6. Load- displacement curve.

The known geometry of the indenter then allows the size of the area of contact to be determined. Elastic modulus and hardness of the specially developed composite were calculated from the results of nano-indenter through Anthony C. Fischer [14], which in turn leads to allow the magnitude of the yield strength to be determined.

4. Upper bound analysis

4.1 Derivation of velocity and strain rate fields

While applying the upper bound solution to analyze plastic deformation, a properly constructed admissible velocity field is deemed to be an essential to ensure the accuracy of the final solution. To be kinematically admissible, the velocity components must fulfill the conditions of incompressibility.

For the steady state plastic flow through a rigid curved shaped die, the die profile and the axis of symmetry are streamlined. Since the billet material is assumed to be rigid at outside the entry and exit of die section, the axial velocity profiles at this section are assumed to be uniform. Further it is assumed that the flow pattern in the deformation zone can be

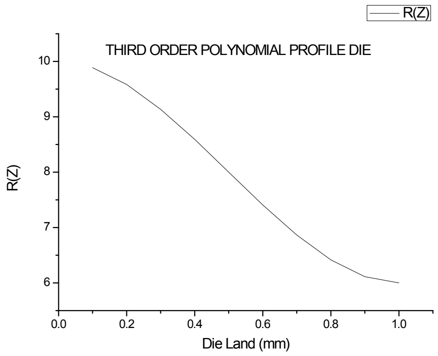


Fig. 7. Third order polynomial profile.

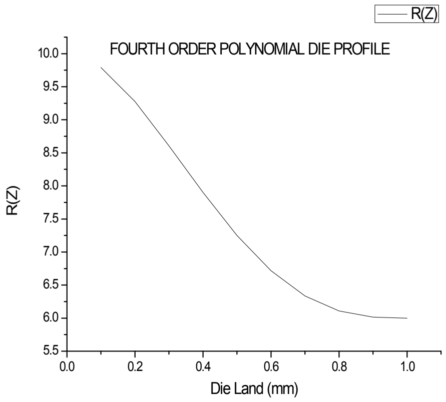


Fig. 8. Fourth order polynomial profile.

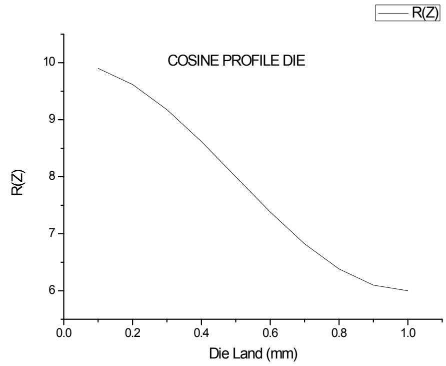


Fig. 9. Cosine profile.

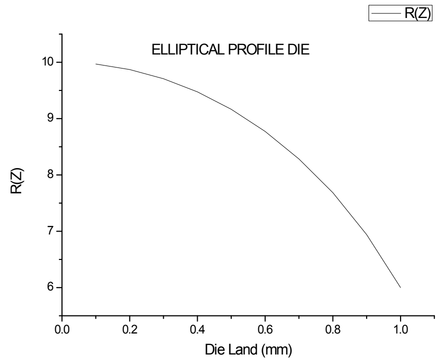


Fig. 10. Elliptical profile.

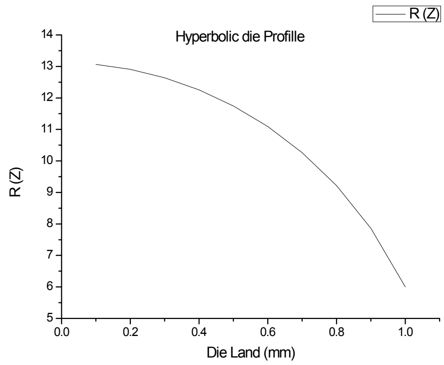


Fig. 11. Hyperbolic profile.

represented in the same functional as the die profile. In the present work, the geometric shape of the die profile is considered to be a key variant for optimal effect. Hence, six different die profile geometries have been considered.

4.1.1 Third order polynomial die profile

This die profile is shown in Fig. 7 and is represented by the function

$$R(Z) = R_1 + (R_1 - R_2)\left[2\frac{Z^3}{L^3} - 3\frac{Z^2}{L^2}\right]. \tag{1}$$

4.1.2 Fourth order polynomial die profile

This die profile is shown in Fig. 8 and is represented by the function

$$R(Z) = R_1 + \frac{6ZK(2-3Z)}{L^2}Z^2 + \frac{4K(3Z^2-1)}{L^3}Z^3 + \frac{3K(1-2Z)}{L^4}Z^4 \tag{2}$$

4.1.3 Cosine die profile

This die profile is shown in Fig. 9 and is represented by the function

$$R(Z) = \frac{R_1 + R_2}{2} + \frac{R_1 - R_2}{2}\cos\frac{\pi z}{L}. \tag{3}$$

4.1.4 Elliptical die profile

This die profile is shown in Fig. 10 and is represented by the function

$$R(Z) = \sqrt{R_1^2 - (R_1^2 - R_2^2)\frac{Z^2}{L^2}}. \tag{4}$$

4.1.5 Hyperbolic die profile

This die profile is shown in Fig. 11 and is represented by the function

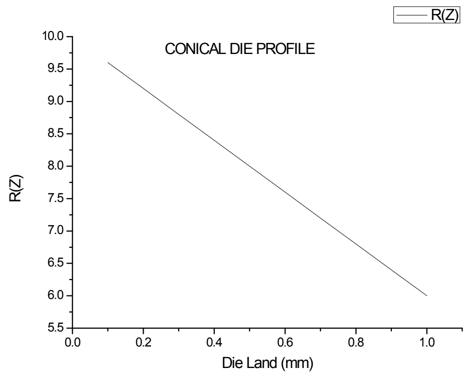


Fig. 12. Conical profile.

$$R(Z) = \sqrt{R_2^2 - (R_1^2 - R_2^2)\frac{Z^2}{L^2}} \;. \tag{5}$$

4.1.6 Conical die profile

This die profile is shown in Fig. 12 and is represented by the function.

$$R(Z) = R_1 + \frac{R_2 - R_1}{L} Z \,. \tag{6}$$

Since the steam function has to be satisfy the condition of uniform axial velocity V_O at the entry section (Radius R_1) and the symmetry condition at $\zeta = 0$, it can be assumed as

$$\psi = \frac{V_O R_1^2 \xi^2}{2} \;. \tag{7}$$

The velocity components V_r, V_θ, and V_z are derived in terms of the die profile from the spatial derivatives of the stream functions for the six different profile function as

$$V_Z = \frac{1}{r}\frac{\partial \psi}{\partial r} = \frac{V_O R_1^2}{R^2(Z)} \tag{8}$$

$$V_r = -\frac{1}{r}\frac{\partial \psi}{\partial z} = \frac{\xi V_O R_1^2 R^1(Z)}{R^2(Z)} \tag{9}$$

$$V_Z = \frac{V_r}{r} = \frac{\xi^2 V_O R_1^2 R^1(Z)}{R(Z)} \;. \tag{10}$$

From the velocity field Eqs. (7)-(10) the strain rate components can be derived as

$$\varepsilon_{rr} = \frac{\partial V_r}{\partial r} = \frac{V_O R_1^2 R^1(Z)}{R^3(Z)} \tag{11}$$

$$\varepsilon_{zz} = \frac{\partial V_Z}{\partial z} = -2\frac{V_O R_1^2 R^1(Z)}{R^3(Z)} \tag{12}$$

$$\varepsilon_{\theta\theta} = \frac{1}{r}\left[\frac{\partial V_\theta}{\partial \theta} + V_r\right] = 2\frac{V_O R_1^2 R^1(Z)}{R^3(Z)} \tag{13}$$

$$\varepsilon_{r\theta} = \frac{1}{2}\frac{\partial V_\theta}{\partial r} - \frac{V_\theta}{r} + \frac{1}{r}\frac{\partial V_r}{\partial \theta} = -\frac{V_O R_1^2 R^1(Z)}{2R^2(Z)}\frac{1}{R(Z)} - 3\xi \tag{14}$$

$$\varepsilon_{\theta z} = \frac{1}{2}\frac{\partial V_\theta}{\partial Z} + \frac{1}{r}\frac{\partial V_Z}{\partial \theta} = -\frac{3V_O R_1^2 R^{II}(Z)}{2R^4(Z)} \tag{15}$$

$$\varepsilon_{rz} = \frac{1}{2}\frac{\partial V_r}{\partial r} + \frac{\partial V_z}{\partial r} = \frac{-V_O R_1^2 R^I(Z)}{R^3(Z)}\left[1 + \frac{1}{\xi}\right] \tag{16}$$

where $R^I(Z) = \frac{dR(z)}{dz}$ and $R^{II}(Z) = \frac{d^2R(z)}{dz^2}$.

4.2 Upper bound theorem

The total power consumption (J) required to deform the circular billet into hexagonal section through the six different die profile is denoted as the sum of the power losses due to the plastic deformation inside the die (W_i), due to the velocity discontinuities at the entry (W_e), at the exit (W_f) and due to the frictional resistance at the interface between die and material (W_s)

$$J = W_i + W_e + W_f + W_s \,. \tag{17}$$

But as far as stream lined die profile is concerned, there is no velocity discontinuities at the entry and exit, then the equation becomes as

$$J = W_I + W_s \,. \tag{18}$$

Power loss due to internal deformation:

$$W_i = \frac{2\sigma_y}{\sqrt{3}} \iint_v \sqrt{\frac{\varepsilon_{ij}\varepsilon_{ij}}{2}}\, dv \tag{19}$$

$$W_i = \frac{2\sigma_y}{\sqrt{3}} \int_0^z\int_0^r\int_0^\theta \sqrt{\frac{\left(\varepsilon_{rr}^2 + \varepsilon_{\theta\theta}^2 + \varepsilon_{zz}^2\right) + \left(\varepsilon_{r\theta}^2 + \varepsilon_{\theta z}^2 + \varepsilon_{rz}^2\right)}{2}}\, d\theta\, dr\, dz \,. \tag{20}$$

Power loss due to frictional resistance:

$$W_s = \frac{m\sigma_y}{\sqrt{3}} \int_0^z\int_0^\theta \sqrt{V_r^2 + V_\theta^2 + V_z^2}\, \sec\alpha \left|\frac{\partial(r,z)}{\partial(\theta,z)}\right| d\theta\, dz \,. \tag{21}$$

The angle α is the angle of inclination of the element of the die surface for all six die profiles with respect to the projected surface of the element on the rz plane.

Knowing the velocity components, strain rate components of the individual die profile of the six different profiles, the

Table 3. Extrusion and frictional load through UBT.

S. No	Name of the profile	Extrusion load (KN)	Frictional load(KN)
1	Third order	134.57	2.975
2	Fourth order	218.23	3.816
3	Cosine	95.78	2.675
4	Elliptical	578.12	16.56
5	Hyperbolic	1545.12	21.31
6	Conical	425.13	13.31

volume integral was carried out using Simpson one third techniques. The yield value of the material has substituted from the microscopic results of the nano indenter apparatus. The determined power can be converted to the average extrusion load (P_{ave}) and relative stress (R_s) as follows

$$P_{ave} = \frac{W_i}{\pi R_1^2 V_0}$$
$$R_s = \frac{P_{ave}}{\sigma_0}. \quad (22)$$

The results computed by solving the Eqs. (20)-(22) are tabulated in Table 3.

5. Finite element analysis

Significance of optimal die profile is insisted by drawing a comparison between six different geometry of profile like fourth order polynomial, third order polynomial, cosine, elliptical, hyperbolic and conventional conical through finite element method. To analyze the die profiles in FEM, DEFORM 3D V6.1 [15] software was utilized. The die geometry containing hexagonal and cylindrical portions were created as solid model using ProE. The inter-junction between the cylindrical and hexagonal portion was extended as die land measuring a length of 1. The profile of die land was made by the above said six different curves. All the six solid model of die profiles were exported to DEFORM 3D V 6.1 as STEP file.

A B_4C-Al composite billet measuring 25 mm long and 10 mm diameter was meshed into 36767 tetrahedral elements where the aspect ratio was kept as unity. Instead of developing a material model for the specially made composite, mechanical properties of the composite which have been derived using nanoindentor setup were loaded as material properties in DEFORM database. A friction factor of 0.3 was assumed by anticipating the partial lubrication condition of die-billet interfaces during actual industrial practice, for all six types of profiles and the ram velocity was set as 1. The time step was 0.004 sec for a total of 100 steps.

Once the model was run to completion, the next step was to extract the data from the FEM analysis and to assemble it for the evaluation of each distortion criterion. The criteria to minimize average axial displacement, average shear strain, and average effective strain required the data to be extracted along a distorted grid line. The point tracking option in the DEFORM-3D post-processor was used to extract the appropriate data.

6. Results and discussion

It is well understood from the literature of extrusion deformation that the rate of deformation from the die entrance to the exit is diminishing. Similarly the force required to extrude the billet also decreasing from the peak point at the die entrance to zero at the die exit. Strain rate and shear deformation are utmost peak point at the die entrance hence the die entrance zone is the highest deformation zone. Inhomogeneous strain gradient at the outer and central part of the billet causes the dead metal zone near the die entrance.

But during the B_4C DRMM composite extrusion, the boron carbide particles are forced to move along with the matrix material. Majority of the particles tend to flow with a matrix material, where in some of them move with abrading action at the die- billet interface. Abrading behaviour of these particles causes the scratching effect on the die land surface because of extreme hardness property of B_4C standing second in hardness ranking.

Also few of the B_4C particles forced to deform, imposes a challenge by developing a huge friction between the die- billet interfaces. It is observed from the previous study and the microscopic image shown in Fig. 16 that the die surface is found to be scratched due to the flow of B_4C particles and matrix materials, further some of the B_4C particles propagates the scratches into micro grooves. Some of the B_4C particles are embedded into the wear mark or groove scratched by the previous particles either in the die entrance or in the die bearing surface. If they keep their location, some matrix material and the B_4C particles may be collected behind these embedded particles and acts as a part of the die profile, thereby increasing the extrusion load and affecting the surface properties of the extrudate.

It is keenly observed from the Figs. 7 and 9 third order polynomial and cosine profiled die geometry has got a initial curvature effect at the die entrance which facilitates the free flow of both matrix and reinforced B_4C particles without causing any adhering and scratch. But the Figs. 10-12 enlightens the fact that the absences of initial curvature effect on conical, elliptical, hyperbolic die profiles causes the flow of matrix and the B_4C particles with adhering behaviour and scratch effect on the die entrance and the bearing surfaces. This damage mechanism prevails on these profiles reserves the negative factor such as higher extrusion load requirement, development of friction and non homogeneous material flow and strain development. The comparative graph plotted for the frictional load calculated using upper bound technique shown in Fig. 13 depicts the frictional load requirement for the six different profiles. Cosine profiled die is declared to be a optimal die by encountering a very lesser average frictional load of 2.675 KN

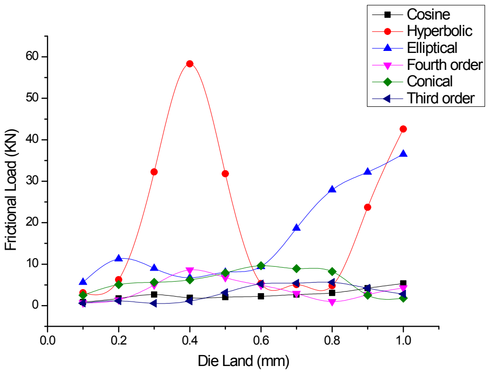
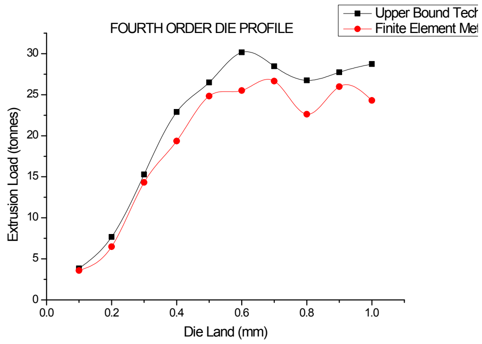
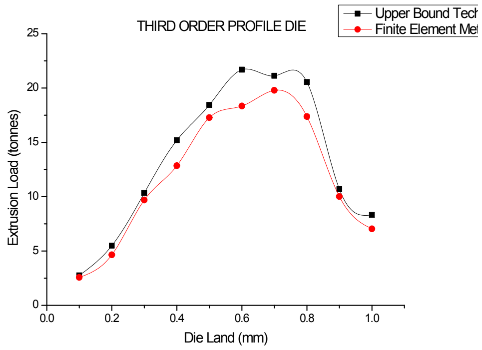


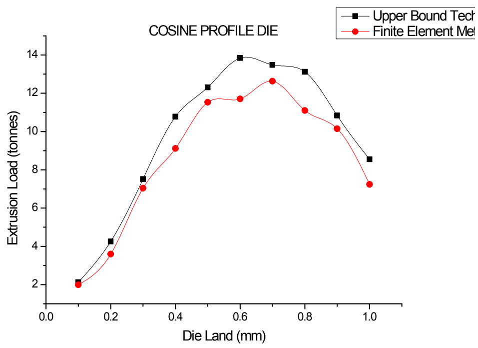
Fig. 13. Frictional load graph for various profiles.



(a)

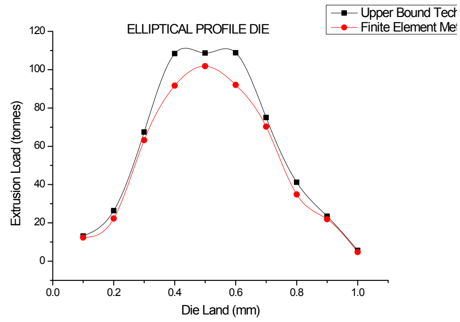


(b)

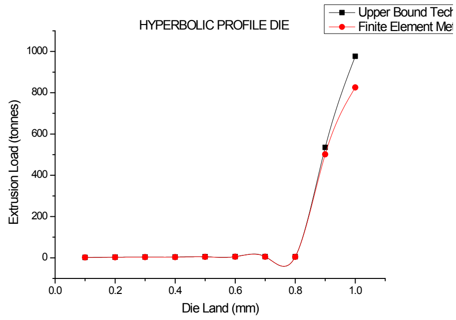


(c)

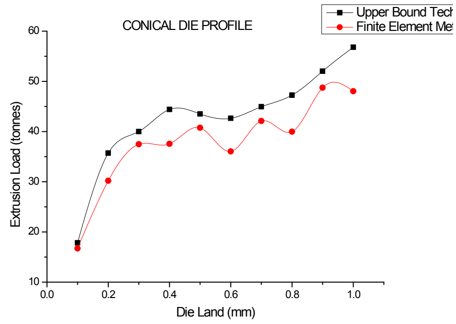
Fig. 14. Extrusion load curves: (a) fourth order; (b) third order; (c) cosine.



(a)



(b)



(c)

Fig. 15. Extrusion load curves: (a) elliptical; (b) hyperbolic; (c) conical.

than the highest average frictional load of 21.31 KN of hyperbolic die. This analytical result earned from upper bound technique acknowledges the above said literature fact.

It is also comprehended from the research literature, during extrusion of composite material, development of dead metal zone near the die entrance has got two different sections as shown in Fig. 17. Area A shows the real dead metal zone in which there is no material flow, the compressed inactive material acts as funnel to direct the material towards the die entrance. Area B is called as secondary dead metal zone comes after A in which the material flows very slowly to the die bearing. The B_4C particles in this zone participates in agglomeration of their own group which in turn acts as barrier for uniform flow and also increase friction effect from the die entrance to die land.

The different load curves arrived from UB and FEM methods for six different profiles shown in Figs. 14 and 15 assures

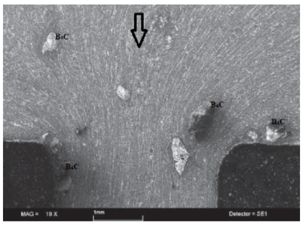


Fig. 16. Effect of B4C particles.

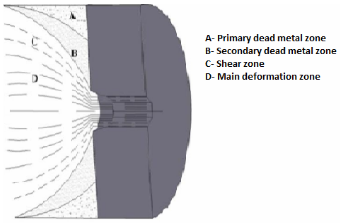


Fig. 17. Development of dead metal zone.

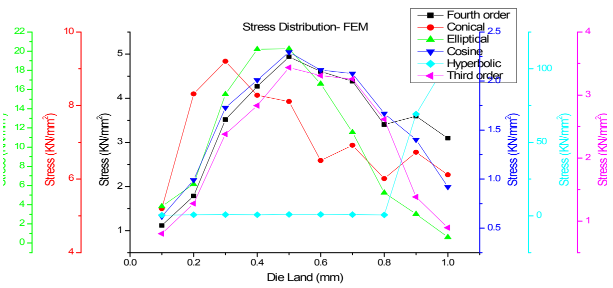


Fig. 18. Stress distribution for six different profiles through FEM analysis.

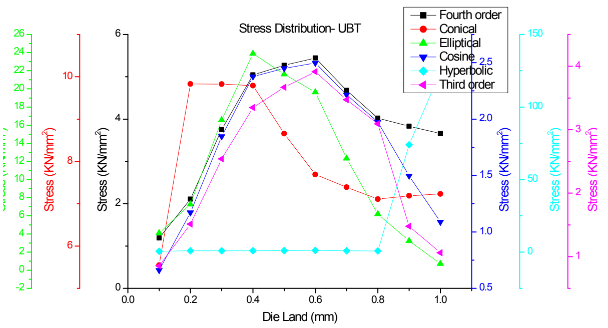


Fig. 19. Stress distribution for six different profiles through UBT analysis.

the fact that development of friction, extrusion load requirement, inhomogeneous material flow and strain gradient are in lesser effect for cosine profile than the rest of five different die profiles. It is firmly learnt that the cosine die is the best among the rest of the dies by consuming a lesser extrusion load of 14.5 tonnes by enhancing the homogeneity of metal flow.

From the simulation results shown in Fig. 20. the material flow and strain gradient are in lower magnitude and homogeneous for cosine and third order die profile because the effect of agglomeration of the B_4C particles near the die entrance and the impact of two dead metal zone A and B is very minimal than the rest of the die profiles. The nature of profile with uniform curvature of cosine and third order die ensures the homogeneity in plastic deformation and material flow by averting the probability of agglomeration of B_4C particles near the die entrance. From the Figs. 18 and 19 which emphasizes the stress development for each and every die profile throughout the entire die length computed through upper bound and finite element method. The material experiences the huge plastic deformation develops the stress in lower magnitude when it is extruded through cosine and third order polynomial profile where as stress development is in higher magnitude when it is flowing over the rest of four die profiles. Higher dead metal zone accompanying with greater frictional force causes the deformation of the outer zone much higher than the central zone which in turn develops the higher stress values.

This inhomogeneous deformation phenomenon stimulates the higher load requirement to deform the central zone further. The effect of uniform curvature of cosine and third order polynomial die profiles ensures the lesser extrusion load requirement, lesser frictional effect, and homogeneous strain gradient and homogeneous material flow.

7. Experimental study

To carry out an experimental study, the hexagonal extrusion die with cosine profile as die land geometry was made out of chrome-vanadium tool steel through CAD/CAM using wire cut EDM machine as shown in Fig. 21. The billet made out from B_4C DRMM Al-6061 composite casted through stir casting route is machined for 9 mm diameter and 25 mm length was fed into 45 Tonne capacity cranked type SEYI make press to extrude the required hexagonal shape. The extruded product is shown in Fig. 22.

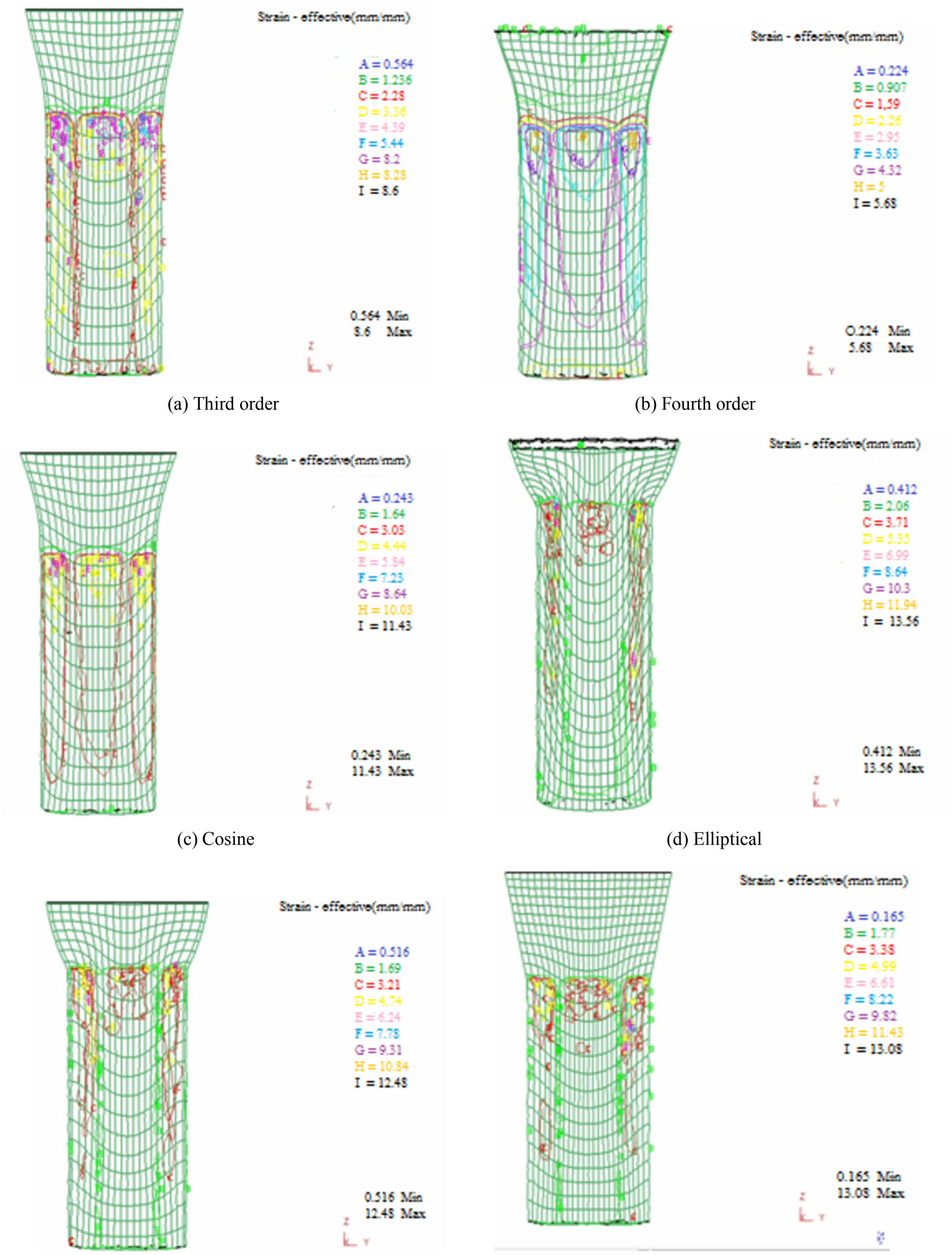
Fig. 23 shows the graphical representation of load requirement versus die land for the results incurred through the upper bound technique, simulation and the experiment. Higher load consumption in experimental study than the simulation reveals the lubrication complication prevailing over the die surface. Experimental results have not incur any significant deviations from the analytical and simulation.

8. Conclusion

After an exhaustive study of extrusion of B_4C reinforced Al composite through UB, FEM and experiment method for six various die profiles, the following conclusions have been arrived.

(1) By means of a suitable design of the die geometric shape, it is possible to obtain a favourable positioning or a dead zone size reduction. This determines an importance of reduction of friction in the deformation zone and of the extrusion load as well.

(2) It is concluded that during the extrusion of B_4C DRMM composite, the B_4C particles reinforced with Al6061 matrix material moves in two ways. They flow either with the matrix



(a) Third order (b) Fourth order

(c) Cosine (d) Elliptical

(e) Hyperbolic (f) Conical

Fig. 20. Strain distribution for six different profiles.

material or move with an abrading action over the die surface.

(3) The B_4C particles moving at the outermost layer of the matrix material adhere to the die entrance and scratch the die bearing surfaces thereby inducing a higher frictional effect.

(4) Development of dead zone found to be in two sections as primary and secondary dead zone. Higher development of dead zone accompanying with greater frictional force causes the outer most layer of the billet into more severe deformation than the central part.

(5) Higher dead metal zone, adhering and agglomeration of B_4C particles, development of scratches are concluded as the potential constraints, when the B_4C particle reinforced billet is

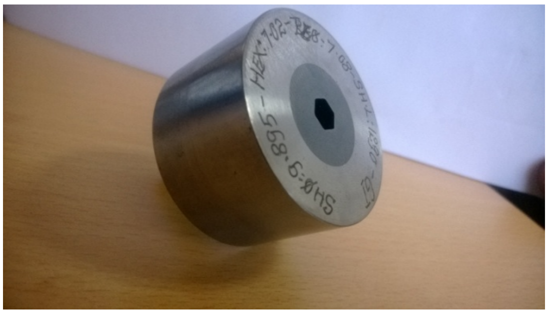


Fig. 21. Specially fabricated extrusion die with cosine profile.

Fig. 22. Extruded hexagonal section.

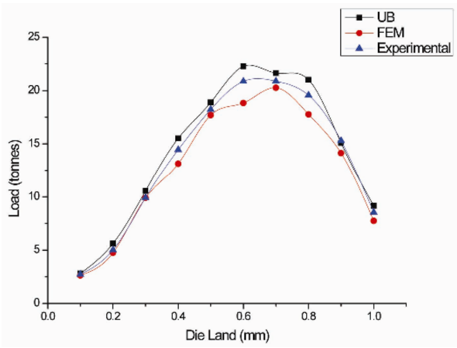


Fig. 23. Extrusion load curve (comparative).

forced into extrude.

(6) Uniform curvature effect right from starting to end of the cosine curve profile facilitates the homogeneous flow of MMC material with negligible effect of adhering and agglomeration of B_4C particles, scratching the die entrance and bearing surface, and higher dead metal zone.

(7) Benefit of cosine die profile over the rest of five different profiles is learnt from the metal flow analysis through upper bound technique, Finite element technique and the experimental study.

(8) It is realised that the cosine profile die is the most optimised die profile for extrusion of B_4C DRMM composite because the results obtained for the six various profiles from upper bound technique, Finite element technique and experimental method have not incur any significant deviations to each other.

Notation

L : Length of the die
m : Friction factor
P_{ave} : Average extrusion pressure
r,θ,z : Cylindrical coordinate system
$R(z)$: Die profile
$R^{I}(z)$: First derivative of R(z)
$R^{II}(z)$: Second derivative of R(z)
R_1 : Radius at the entry
R_2 : Radius at the exit
V_0 : Ram velocity
V_r, V_θ, V_z : Velocity components in r,θ and z respectively
ε_{ij} : Strain rate tensor
ζ : Stream function constant
σ_y : Yield stress value of the material
ψ : Stream function

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