Processing of materials—monolithic to composites

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Abstract. A multimillion rupee 500-ton hydraulic extrusion/forging facility established at NPL, New Delhi, has been used to undertake extensive studies in forming, the process of plastically deforming, which is the most important way of shaping materials. Wrought materials are used extensively for making useful products employing extrusion and forging, the two important secondary processing techniques used to convert materials into useful shapes and sizes and also to improve the mechanical and metallurgical properties. The success of these processes depends on the proper control and eventual optimization of different process variables.

Different ferrous and non-ferrous materials including 316 and 321 stainless steels (using glass lubrication), aluminium brass, admiralty brass and 70/30 and 90/10 cupro nickels have been extruded at a lab-scale production level to determine the influence of different extrusion variables such as temperature, strain rate, extrusion ratio, different die design and several different compositions of lubricants on pressure requirement and surface quality of the products.

In the case of ferrous extrusions, the choice of billet-container lubricant has a marked effect on the shape of pressure-distance curves by influencing the effective coefficient of friction and heat transfer coefficient. Temperature, extrusion ratio and strain rate mainly influence the level of pressure-distance curves. Significance of specially designed dish shaped dies, avoiding the dead metal zone and the importance of extrusion limit diagrams for different materials on the available press capacity has also been highlighted.

Deformation behaviour of the hi-tech materials; discontinuously reinforced metal matrix composites (MMCs) and aluminium-lithium alloys using hot extrusion and closed die forging, have been carried out. Parameters have been optimized to extrude rods and thin walled circular MMC tubes of aluminium alloy (2124/6061)-SiCp MMCs having varying volume fractions of SiCp. This developmental work has been carried out using powder metallurgy, liquid metallurgy and spray atomization and deposition routes, in joint collaboration with several R & D organizations.

Hot extrusion being an important production technique, results of these experiments can be directly transferred to industries. Similar deformation studies either by closed die or by isothermal forging have been made to develop components.

The pilot plant level facility is available for any industry for carrying out developmental R & D work. NPL welcomes such collaboration.

Keywords. Composites; forming; extrusion; metal matrix composites; aluminium-lithium alloy.

1. Introduction

The process of plastically deforming the metal is called metal forming process. Most of the metals can be deformed or reshaped within limits by the application of suitable forces without thereby disturbing or damaging their inner structures. The deformation proceeds by a sliding or slipping movement within the individual crystals. The plasticity of a metal thus depends on the ability of the single crystal to allow this inner slip in certain definite directions once a certain critical stress is exceeded without disturbance of the bond between the slipping layers. Different forming operations are used to transform solid or quasi-solid workpieces into solid products by plastic deformation without generating chips. Different forming processes are used for producing a wide variety of products. There are a large

Figure 1. Typical deformation processes.

number of such products and it is impossible to list the end products. Typical deformation processes used for making wide variety of components are shown in figure 1.

‘Work piece material’ does not distinguish one forming method from another but the know-how and equipments for forming operations are often largely dependent upon the material to be deformed/worked. Forming operations are generally tool and machine dependent to a large extent.

1.1 Working temperature and speed

‘Working temperature’ and ‘working speed’ together with ‘deformation’ and ‘stresses’ are the fundamental parameters that are closely related to the strain increment, strain rate, mean hydrostatic pressure and temperature. These are decisive for engineering features of the operation and the resultant product properties.

The strain rates and temperatures are never uniform within the work piece and can be determined only at an enormous expense either by calculations or experimentally. We are thus contented with the preheat or average deformation temperature for the 'working temperature' and with the average or maximum strain rate for 'working speed'. Taking the combined effect of temperature and strain rate, the forming processes can be classified into those without work hardening (hot forming), with partial work hardening (warm forming), and with permanent work hardening (cold forming).

1.2 Deformation

Deformation is the essence of the forming operation. Deformation is visible while stresses are invisible. They are either the means to generate deformation or the result of deformation. Deformation reveals a lot of information that is relevant to an operation under consideration. The extent of the deformation zone within a workpiece is one of the important classification.

1.3 State of stresses

The state of stresses are the primary requirement for any forming process to be understood. But these stresses are invisible and are extensively dependent upon strain. If we know the constitutive equation of the workpiece material, the hydrostatic stresses and accordingly, the stress components can be derived from the prescribed strain rate, temperature and one of the normal stress component. It is needless to say, however, that the stresses are of paramount importance in assessing the machine capacity, energy consumption, tool life, limit of deformation, dimensional accuracy and properties of the products.

2. Facilities available at NPL

The National Physical Laboratory (NPL), New Delhi has set up with UNDP and British Colombo Plan assistance, a pilot and demonstration plant in metal forming with the following major objectives:

- * Develop process technology for the forming of tubes, shapes and sections in ferrous, non-ferrous metals/alloys and composite materials, using hot extrusion.
- * Develop cold forging/closed die warm forging for near net shape components.
- * Batch production of the above materials for consumer accessibility trials.
- * Design and fabricate laboratory/pilot plant equipments in metal forming.

Several organizations have already used this facility for developing components such as tubes, shapes and sections in ferrous, non-ferrous and other hi-tech materials as well as to study hot deformation characteristics of advanced materials such as discontinuously reinforced metal matrix composites (MMCs), aluminium–lithium (Al–Li) and other high strength alloys.

The pilot plant is equipped with the following metal forming equipments:

- * 500 ton vertical hydraulic press (figure 2) being used to develop hot extrusion and closed die forging for near net shape components. The press is equipped with the instrumentation used for measuring and recording extrusion pressure and speed.

Figure 2. Pictorial view of 500-ton press.

- * Induction furnace along with conveyor system for preheating billets (up to approximately 1300°C and ~ 8 kg in weight) and transferring them to the extrusion container, prior to hot extrusion.
- * 50,000 lbs hydraulic draw bench.
- * Swaging machine.
- * Spray atomization unit (under fabrication).

The ancillary facilities include:

- * 5 ton 'Instron' make Universal Testing Machine.
- * A well equipped tool room having various facilities such as: Deckel, milling machine; cylindrical, surface, centreless, tool and cutter grinder (monoset); honing machine, drilling machine, deep-hole drilling machine, and various heavy-duty lathe machines etc.
- * Inspection equipments including perthometer and hydrotester.

- * Heat-treatment and product-anneal furnaces; salt bath furnaces, solutionizing and ageing furnaces, electrical resistance type muffle furnaces etc.
- * Hardness testers.
- * Lapping and polishing machines.
- * A well equipped metallographic laboratory including Carl Zeiss Metallurgical optical microscope with micro-hardness testing attachment.
- * A sophisticated electronic balance with density measurement facility.
- * Experimental set up for volume fraction analysis of MMCs.

3. Hot extrusion

Hot extrusion is a metal forming process in which a cylindrical slug of material called the billet, is heated above the recrystallization temperature of the material to be extruded. The hot billet is then forced by pressure applied on the top surface of the billet to pass through a die opening to take the desired shape. The process is of great industrial importance and a large number of products of consumer and industrial importance are hot extruded (Cox *et al* 1960; Sabroff 1963; Cox 1964; Cook 1972). These include rods, strips, solids and hollow sections in a wide variety of ferrous, non-ferrous metals/alloys and their composites (popularly known as metal matrix composites). The materials of particular interest to Indian industries are high strength aluminium alloys, copper and copper alloys—specially aluminium and admiralty brasses, 70/30 and 90/10 copper nickels; stainless steels 316, 321; and aluminium alloy matrix composites.

3.1 Tooling

Tooling is the most important component of the hot extrusion process. These tools operate under severe conditions of temperature, pressure and abrasive wear and choice of proper steel is necessary for the optimum utilization of tooling. Since hot extrusion is carried out at temperatures in excess of 400 °C, the steel most widely used are hot work die steels. The steels frequently employed for tool fabrication meeting the above requirements are H11, H13 and H21 steels, heat treated to 50 HRC (Cox *et al* 1960; Cox 1964). An important factor used in the die design is well balanced flow of metal in the die and avoidance of the dead metal zone. Specially designed dish shaped die, avoiding the dead metal zone, has been used for most of the investigations as it leads to minimum pressure requirement and best surface finish.

3.2 Lubrication and lubricating techniques

Lubrication is necessary to reduce friction at the billet-liner, billet-die and billet-mandrel interface to reduce the pressure requirement, die wear, and also to improve dimensional tolerances of the extruded products. The lubricating techniques are different for ferrous and non-ferrous metals/alloys and their composites.

Graphite based lubricants (graphite + MoS₂) are generally used for the extrusion of non-ferrous metals. The lubricant is applied on the die, the mandrel and on the inside of the container. Alternatively, the lubricant can be sprayed on the toolings.

The most serious problem faced in the extrusion of ferrous materials was the seizing between the hot metal and the tooling, in particular the die. The use of heat resistant die steel did not bring about any noticeable improvement in the situation. Conventional lubrication either melted or vaporized at high temperature involved, 1100–1300°C and conventional solid lubricants remained solid under extrusion conditions and acted as harmful abrasives. The conclusion was then reached that the lubricant should neither be solid nor liquid but should be viscous at the operative temperature. A technological breakthrough was made by Sejournet when he found that glass could act as a satisfactory lubricant (Sabroff 1963; Cook 1972).

Satisfactory extrusions of ferrous materials were then possible with the development of these glass lubrications (Sabroff 1963; Cook 1972). The billet-die lubrication was achieved by using pressed glass powder pads; the most effective way of lubricating the surface of billet was to sprinkle glass powder on an inclined table and let the hot billet pick up the powder during rolling on the table. To lubricate the inner surface of the hollow billet, glass powder was inserted through a half cut flute, inside the billet before it started rolling down the inclined plane. Details of lubricating techniques employed are described in detail elsewhere (Gupta *et al* 1980).

Different materials require different glasses to be used depending on the preheat temperature range of the material to be extruded and the softening point of glasses (Sejournet 1956; Rogers and Rowe 1967). Thus temperature-viscosity characteristics of the glasses are of prime importance. Glasses softening at 1/2 to 2/3 of the billet temperature are usually recommended (Sejournet 1956; Rogers 1962), softening being taken as a viscosity of the 10^{7-6} poise. The lubricating layer of glass which adhere to the extruded products has to be removed before the extruded product is further processed. There are many alternative methods available for removing these adhered glasses and the most common way is either to shot blast or by employing pickling. The ideal thickness of glass on the extruded products, both with regard to surface quality and for ease of removal is probably 25–100 μm .

3.3 Process variables

The hot extrusion process represents a complex interrelationship between extrusion ratio, preheat temperature, pressing speed, lubrication and die design. These variables need to be optimized within the constraints of the press and the material itself to achieve a satisfactory extrusion. Although a wide variety of materials are being successfully extruded on an industrial scale, very little published information is available on the influence of these variables on the pressure requirement and surface quality of the product. The problem does not lend itself to an analytical approach and the optimum process parameters have to be determined empirically for each material and thus the present investigation.

4. Monolithic materials

In the present paper, a systematic study of the effect of extrusion parameters for type 321 stainless steel, 70/30 cupro-nickel, aluminium brass and high strength aluminium alloys including aluminium-lithium on their actual component development are reported. All these experimentations have been carried out on a 500 ton 'Wellman Enesco Press' using hot extrusion and close die forging techniques.

4.1 Stainless steel (321)

Detailed experiments were conducted using different pressing speeds (50–200 mm/sec), preheat temperatures (1070–1280°C), extrusion ratios (4:1, 9:1, 16:1 and 36:1), use of different die design and varied varieties of glass powders. Important results of the comprehensive experimental programme undertaken to produce rods, sections and tubes are summarized below:

4.1a *Effect of variables on extrusion pressure:* In the glass-lubricated hot extrusion of stainless steel, the pressure rises sharply to a peak and falls to a running pressure

Figure 3. Extrusion pressure distance curves for stainless steel (321) billets, reheated to 1170°C and extruded with B46 F1237 glass lubrication and different extrusion ratios at different ram speeds. (a) 190 mm s⁻¹ and (b) 50 mm s⁻¹.

Figure 4. Extrusion pressure-distance curves for stainless steel (321) billets, extruded with extrusion ratio of 16:1 and B46-F1237 glass lubrication at different temperatures and ram speeds. (a) 190 mm s^{-1} and (b) 50 mm s^{-1} .

which is either constant or can fall or rise during the stroke. Typical examples of these form of curves are shown in figures 3 and 4. In this work the initial running pressure was found to be $18 \pm 4\%$ lower than the peak pressure, with no systematic trend with regard to speed, temperature, lubrication, or extrusion ratios.

Pressure–distance curves for billets reheated to 1170°C and extruded with a range of extrusion ratios at both fast and slow pressing speeds are given in figure 3. These show that the high pressing speed led to high peak pressures coupled with running pressures which remained nearly constant throughout the stroke. At low pressing speed, the peak pressure was lower but the running pressure rose during the stroke, generally to a level which was higher than the peak pressure for fast extrusion. These general forms of curves were also encountered when billets were reheated to 1280°C , although the running pressure did not rise as sharply at slow extrusion speed. At a reheating temperature of 1070°C , the running pressure was nearly constant at slow speed but had a downward slope at fast speed, as indicated in figure 4.

Data from figures 3 and 4 and other pressure–distance curves have been used to derive the points given in figure 5, which show peak and initial running pressures (at 30 mm after upsetting) for all the reheating temperatures and extrusion ratios at fast and slow speeds. For fast speed, the relationship between temperature and pressure is nearly linear and independent of extrusion ratio, except for the lowest extrusion ratio. At slow speed, the temperature dependence is similar above 1170°C but below that, the

Figure 5. Temperature dependence of peak pressure and initial running pressure (30 mm ram travel after upset) for type 321 stainless steel extruded at different ram speeds. (a) 190 mm s^{-1} and (b) 50 mm s^{-1} .

Figure 6. Effect of die angles on peak and initial running pressures for stainless steels reheated to 1170°C and extruded with extrusion ratio of 16:1 and B46-F1237 glass lubrication at different ram speeds. (a) 190 mm s^{-1} and (b) 50 mm s^{-1} .

temperature dependence increases significantly, particularly at high extrusion ratios, where peak pressures were higher than those at high speed.

Figure 6 shows the effect on peak and initial running pressures of reducing the die angle from 90° to 60° , 45° , and 30° for both type 321 and type 316 stainless steels reheated to 1170°C and extruded with a ratio of 16:1 at fast and slow speeds.

As shown in figures 3 and 5, increasing the extrusion ratio had the effect of increasing both the peak and running pressures at a given reheating temperature. Figure 7 shows peak pressure plotted against the logarithm of the extrusion ratio for fast and slow pressing speeds. Substituting the standard pad glass (B46) by other soda lime glasses of similar softening point (F239S or C7216) and substituting the standard tray glass (F1237) by a borosilicate glass of rather higher softening point (C6496) had significant effects on the extrusion behaviour. Extrusion carried out at slow speed from a reheating temperature of 1170°C , the substitute glasses usefully reduced the peak pressure and flattened running pressures. In terms of peak pressure, this benefit decreased with decreasing extrusion ratio (11% at 16:1 to 6% at 4:1 for glass C7216) and with

Figure 7. Dependence of peak extrusion pressure on extrusion ratio for type 321 stainless steel extruded with B46-F1237 glass lubrication at different ram speeds. (a) 190 mm s^{-1} and (b) 50 mm s^{-1} .

increasing reheating temperature (2% at 1280°C); even so, the running pressure rose less steeply than with the standard glasses under all the conditions examined. When extrusion was carried out at fast speed, the pressure-distance curves for all the glasses were almost identical.

The use of harder 'Pyrex' borosilicate glass for both pad and tray at reheating temperatures of 1280 and 1230°C resulted in high peak pressures followed by fall in running pressures. When a 'Pyrex' glass pad was used with C6496 tray glass for a reheating temperature of 1230°C the pressure requirement was similar to that for standard glasses. 'Pyrex' glass pads were rather fragile and die suffered more wear.

When a pad of glass wool used with dish-shaped dies and C6496 tray glass, the resultant pressure-distance curves for a reheating temperature of 1170°C were almost identical with those obtained with C7216-C6496 glasses using a flat die.

4.1b Effect of variables on product surface: The surfaces of all extruded rods of type 321 stainless steel were examined visually and classified both before and after the removal of lubricating glass by shot blasting or pickling.

None of the rods was burnt, nor was there any evidence of cracking or tearing, the defects being limited to varying degrees of roughness or scoring. Typical examples of the surfaces, both before and after the removal of glass, are shown in figure 8.

Figure 8. Effect of various glass pad-tray lubricants on surface quality of type 321 stainless steel extruded to round bars at slow (S) and fast (F) pressing speeds.

Figure 9. Extrusion limit diagram for 76 mm dia. billets of types 321 and 316 stainless steels; pressing speeds 190 and 135 mm s⁻¹, maximum available pressure 1300 N mm⁻², glass lubrication (B46 pad, F1237 tray), flat die.

4.1c Extrusion limits: Using techniques described elsewhere (Hughes *et al* 1974), the data given here have been used to construct an extrusion limit diagram for type 321 stainless steel extruded at fast speed. This is given as figure 9. The pressure limits are based on peak pressures as indicated by the solid lines in figure 7a. In calculating the temperature limits, the solidus temperature has been taken as 1400 °C and the observed difference of 18% between peak and initial running pressure has been used. The extrusion limits for type 316 stainless steel, derived from other data (Hughes *et al* 1974), are also included. The diagram is strictly valid only for 76 mm dia billets extruded to round sections; the extrusion limits will be wider for larger billets but extrusion of shapes will require a higher pressure for a given extrusion ratio (Hughes 1973). An extrusion limit diagram has not been constructed for the slow pressing speed because the running pressure can rise to a value above the peak as a result of the fall in billet temperature during extrusion. However, where larger diameter billets are used the fall in temperature is less (Hughes and Sellars 1972, 1974; Whiteman *et al* 1995) and extrusion limits wider than those that would be expected for the high pressing speed.

4.1d Discussion: The form of extrusion pressure–distance curves shown in figure 3 is typical of those reported previously (Hughes and Sellars 1974) where it was shown that a quantitative description can be given in terms of the relationship:

$$P = \alpha \sigma \ln \operatorname{Re} \exp(4\mu L/D) = \alpha \sigma \ln \operatorname{Re}(1 + 4\mu L/D),$$

where P is the instantaneous value of pressure during extrusion to an extrusion ratio Re , when length L of a billet of diameter D remains in container; μ is the effective coefficient of friction between the billet and container, previously found to be 0.005–0.01 for glass-lubricated extrusion (Sabroff 1963; Cockroft 1969; Hughes and Sellars 1972), α is a factor which allows for friction at the die and for redundant work, and for glass-lubricated extrusion, when μ is low, was previously found to be constant and ~ 1.34 (Hughes *et al* 1974); σ is the mean flow stress of the material and is a function of mean extrusion temperature (T_{ext} , K) and strain rate $\dot{\epsilon}$ of the form

$$\sigma = [1/B \ln(\dot{\epsilon}/A) + Q/R T_{\text{ext}}],$$

where A , B and Q are constants for the material and R the gas constant. Values of the constants for type 304 (Barraclough and Sellars 1974) stainless steels are, respectively, $A = 1.52 \times 10^{13}$ and $1.34 \times 10^{14} \text{ s}^{-1}$, $B = 0.047$ and $0.057 \text{ mm}^2 \text{ N}^{-1}$, and $Q = 410$ and 460 kJ mol^{-1} . T_{ext} is a function of reheating temperature, heat loss to the container, and work done during extrusion (Hughes 1972; Whiteman 1995).

The influence of these variables on the extrusion pressure–distance curve is shown schematically in figure 10. If the coefficient of friction were zero ($\mu = 0$) and there were no radical heat loss to the container ($\Delta T_r = 0$), the running extrusion pressure would be constant at a level determined by the reheating temperature, Re , and α for a given material. With increasing μ , but $\Delta T_r = 0$, the peak and initial running pressures are increased but there is little effect on the final pressure (discard length 20 mm). If $\mu = 0$ but the radical heat loss during steady-state extrusion (ΔT_r)₄₀^{1.70} increases, as a result of increasing heat-transfer coefficient to the container or decreasing ram speed (Whiteman 1995), the running pressure rose proportionately.

4.1e Summary: The level and form of the extrusion pressure–distance curves for a given extrusion ratio directly reflect the influence of temperature and strain rate on

Figure 10. Schematic extrusion pressure–distance curves showing influence of coefficient of friction and heat loss between billet and container.

flow stress and the influence of lubrication conditions on friction and heat transfer to the container. The overall level of the pressure curves is significantly reduced by improved lubrication at the die. Lubrication of the billet/container interface is markedly influenced by the chilling effect of the container and high softening point (F1237, 460°C) glass. B46/F239S as glass pad lubrication and F1237 for billet surface lubricants gave best surface finish and achieving lower pressures. The extrusion pressure for circular tubes were found to be 15% higher than for circular solids.

The appearance of glass-coated extrusion does not correlate simply with the surface quality of the products. In general, the effect of extrusion speed on the surface quality is small, but fast speeds and lower temperatures in the normal reheating range, as defined by the extrusion limit diagram, tend to give better quality. Surface quality was considerably improved by the use of dish-shaped dies.

4.2 Copper–nickel–iron (70/30) alloy

It is well known that extensively used non-ferrous materials in the construction of power generating equipments, particularly in the fabrication of heat exchangers, are copper–nickel–iron (Cu–Ni–Fe) alloys. Copper–nickel tubes and sections required for power generating equipments are thus of immediate interest to the Indian industries. The published literature on hot extrusion of this material was scanty and, therefore, a detailed study was undertaken to determine the optimum parameters for a satisfactory extrusion. This section gives the results of a study made on Cu-32.2 Ni-0.39 Fe-0.1 Mn, on lines similar to the one carried out on several other alloys (Gupta *et al* 1980).

The hot extrusion process for copper and copper based alloys is of two types: lubricated and non-lubricated. In the former, lubrication is achieved by the use of heavy greases containing graphite to which a small quantity of molybdenum disulphide is sometimes added. The lubricant is applied to the tooling (liner, mandrel, and die orifice) prior to the insertion of the hot billet into the press liner (Gupta and Hughes 1979). Back extrusion is prevented by the use of an alloy steel pressure pad with a close fit in the liner. In the non-lubricated process, the lubricant is occasionally applied to the die orifice and to the mandrel. The details of the process is described in § 4.3.

Lubricated extrusions were used for Cu–Ni–Fe alloy in these investigations as it seemed to be the usual procedure when extruding this alloy. Of all the copper based alloys, the 70/30 Cu–Ni–Fe alloy is known to possess the highest resistance to deformation (Pearson and Parkins 1961). The pressure encountered, tooling used and operating techniques are in consequence, may be considered similar to those pertinent to steel extrusions. The recommended temperature range of extrusion for 70/30 Cu–Ni–Fe alloy is 1000–1100°C (Pearson and Parkins 1961). These temperatures are slightly lower than those normally used for steel but are at a high enough level where scale is formed. However, copper oxide is a lubricant and, therefore, is less harmful than steel scale. It is, however, considered that anything more than a light covering is undesirable and billets are heated in an induction furnace or in a furnace having non-oxidizing atmosphere.

This section describes results of experiments aimed at examining the effect of various extrusion parameters on pressure requirements and surface quality of the extruded products and its extension to circular tubes.

4.2a Effect of ram travel: Extrusion pressure vs ram travel curves were as expected; an initial peak followed by a fall to a nearly constant running pressure. This is a feature which is common to both ferrous and non-ferrous extrusions (Gupta *et al* 1980). The difference between the pressure patterns of these two classes of metals is that while in the case of ferrous metals the running pressure rises at slow speeds, but it remains almost constant for non-ferrous metals.

4.2b Effect of extrusion ratio: The utility of laboratory scale extrusion experiments lies in their ability to predict extrusion pressure (P_0) required in conventional productions. Data obtained in the present set of experiments can be used for such a prediction based on

$$P_0 = \bar{\sigma}(K_1 + K_2 \ln Re),$$

for graphite based lubricated extrusion (Cockroft 1969; Hughes and Sellars 1974). K_1 and K_2 are constants which have been evaluated to be 0.88 and 1.30 respectively. $\bar{\sigma}$ is the mean flow stress of the material under the same conditions which can be determined from tension or compression tests and Re is the extrusion ratio. Taking the value of σ from Liversey and Sellars (1984), the relationship between P_0 and Re can be obtained as shown in figure 11.

One can also verify these experimental data obtained on the extrusion of 70/30 Cu–Ni alloy. Liversey and Sellars made a detailed study of hot tensile tests from the extruded samples made by Gupta (Gupta 1994; Liversey and Sellars 1984). The equivalent tensile stress–strain curves were prepared from this data. Assuming that the

Figure 11. Comparison of observed and calculated running pressures for extrusion of 70 Cu-30 Ni-Fe alloy reheated to 1050°C and extruded at a pressing speed of 43 mm s⁻¹.

peak stress σ_p follows a relationship with strain rate ($\dot{\sigma}$) and absolute temperature T of the form:

$$\bar{\epsilon} = A \exp(B\sigma_p) \exp(-Q/RT),$$

the constant B and activation energy Q can be estimated from the experimental data. From this value of activation energy, the values of Zener-Hollomon parameter Z has been determined using the following expression and are plotted against σ_p :

$$Z = \bar{\epsilon} \exp(Q/RT).$$

A plot of Z vs σ_p reveals that over the stress levels used in these experiments, Z is independent of $\bar{\epsilon}$ (Liversey and Sellars 1984). It has also been shown that the drop in flow stress from peak to a steady state running stress is partly due to adiabatic condition of flow, but mostly due to softening produced by dynamic recrystallization.

Based on the above calculations, the actual observed and theoretical values of P_0 are compared in figure 11, showing a reasonable agreement. The calculated curve lies between the observed values for the contoured (dish shaped) and the tapered (60° semi angle) die. It is to be noted that the calculations have been made on the peak flow stresses (Liversey and Sellars 1984). The initial peak pressures are higher than the running pressures by an amount which depends on the longitudinal heat transfer from the front end of the billet (Hughes and Sellars 1974). In a vertical press, the heat loss before upset is greater than in a horizontal press, and this loss also depends on the lubrication conditions and the delay time before upset (Hughes *et al* 1982). Estimation of peak pressures from calculated running pressures is, therefore, best carried out by

multiplying the later by an empirical factor obtained from experience with a particular press and the size of billet.

4.2c Summary

- * Satisfactory extruded rods and circular tubes in Cu–Ni–Fe alloy were produced after optimizing the process parameters. The circular tube was finally approved by BHEL for their use in heat exchangers, required in the construction of power generating equipments. As a consequence of developing Cu–Ni–Fe tubes, a project on the preparation of “Techno Economic feasibility report for setting up a plant in India” was prepared and submitted to the Ministry of Industries for implementation.
- * The calculated and experimentally measured pressures show reasonably good agreement.
- * The use of oxidizing atmosphere led to a rough surface finish on the extruded product, which was probably due to the oxidation of the billet surface during heating. To get satisfactory results, scale free billets, to be heated to 1050°C, are desirable.
- * The best results were obtained with dish shaped die using Dag 1559 lubricant. Pressure requirement for tubes were 15% higher than circular rounds.
- * Experience gained with Cu–Ni–Fe alloy showed that the surface was smooth and clean and no cracking was observed when the pressing speed was increased even to 210 mm/sec coupled to high extrusion ratios.

4.3 Aluminium brass

For hot extrusion of aluminium brass, a pad of smaller diameter than the upset billet is often used so that, when the pressure is applied, the pad shears the bulk of the billet from its outside skin, leaving skull in the container liner at the end of the extrusion stroke. The removal of the skin is to ensure that surface defects on the billet are not carried through the die during extrusion to appear on the product. This seems to be the usual procedure when extruding brasses (Hepworth 1978).

The recommended temperature for aluminium brass, 750 to 850 °C is slightly lower than that at which an oxide scale is formed on the billet during reheating and it is not necessary to use a protective atmosphere. Pressing speeds of 12–50 mm/sec are normally employed for the extrusion of brasses. The alpha brass including aluminium brass are said to be speed sensitive and are usually extruded at an extrusion (emergent) speed of 250–500 mm/sec.

The section describes a short series of experiments aimed at examining the effect of varying lubrication techniques and other process variables on pressure requirements and on the surface quality of the extruded circular rods and tubes. The composition of the material was: Cu 21.0%, Zn 1.89% Al; and 0.06% As.

Most of the work was carried out using full lubrication with Dag 1559 (Dag 1559 is a high temperature grease containing a blend of graphite and MoS₂ – Acheson Colloids Company, Plymouth) graphite grease. In other case, billets were partially lubricated by the application of the lubricant to the die alone; the residual lubricant in the bore provided some billet/liner lubrication. In some cases, sticking friction at the billet/liner interface was introduced by the use of a small diameter pressing pad (72 mm).

4.3a Effect of variables on pressure: Most of the pressure–distance curves were typical of hot forward extrusion having a well defined peak followed by a steady running pressure. The exceptions were when a small pressing pad was used and both the die and liner unlubricated (curve a, figure 12). As expected, the pressure requirement increased as reheating temperature was reduced. When a small pressing pad was used, peak pressures were higher and there appeared to be no relationship between reheating temperature and pressure. In fully lubricated extrusion, the pressure requirement increases with increasing extrusion ratio for both 60° and dish shaped dies at reheating temperature of 775°C. In all cases, the increase is linear with $\log Re$ and the slopes pass sufficiently closer to the origin to allow calculation or extrapolation to be used to give a guide to the maximum extrusion ratio possible within the limits of the press, e.g. about 150:1 for RHT 810°C where the maximum available pressure is 1300 N mm^{-2} .

The lowest pressures encountered at all of the reheating temperatures were when the extrusion was fully lubricated. This shows that for the same temperatures and extrusion ratio, the pressure was highest when the extrusion was unlubricated and a small pressing pad used so that a skull remained in the liner. Curve a in figure 12 is typical of this condition. In this case the running pressure behaved erratically and rose to levels which were significantly higher than the peak pressure. Generally the high level of pressure is because the work necessary to effect shearing is in addition to the work done

Figure 12. Extrusion pressure–distance curves for aluminium brass, showing the effect of different lubricating procedures: reheated to 810°C and extruded (9:1) at a ram speed of 43 mm s^{-1} .

in converting the billet into the product. The erratic nature of the curve was probably due to the occurrence of back extrusion in addition to the skull. This got chilled and was trapped between the pressing stem. The curve was much less erratic when a standard pressing pad was used with no lubrication although the running pressure slope indicated high linear billet friction.

4.3b Summary: Satisfactory extruded rods and circular tubes in aluminium brass were produced after optimizing the process parameters. These tubes were required by BHEL, as condenser tubing.

It was found that changes in temperature and die-entry mode had little effect on the pressure requirement or surface quality. Increasing the extrusion speed—either directly or by increasing the extrusion ratio—resulted in an expected increase in pressure requirement but had little effect on surface quality except for a slight deterioration at the highest extrusion ratio.

When the extrusion was totally unlubricated, pressure requirements were high and the product surfaces, although bright, were scored. Where a small pressing pad was used and a residual skull left in the liner, the product yield was reduced by about 7%.

The application of a lubricant in the form of Dag 1559 led to a dramatic reduction in pressure and to products which had very smooth surfaces but which were discoloured by carbon streaking. By limiting the amount of lubricant, extrusions were produced less discoloured.

4.4 *Aerospace grade aluminium alloy rivet wires*

Riveting is an important joining technique in the aircraft industry. In addition to high quality riveting, the rivet material has to satisfy the stringent quality requirements. Until recently large quantities of certain grades of Al alloy rivets and rivet wires were imported for airframe manufacture, involving a substantial outflow of foreign exchange. HAL, Bangalore decided to indigenize the widely used Al alloy rivet wire materials such as IS:5902-1970, Grade 55000 (BSL-58) and Grade 22500 (BSL-86), jointly with NPL, New Delhi. The process parameters for hot extrusion and cold drawing of Al alloys were optimized (Gupta *et al* 1991) and these rivet wires are being produced at the Foundry and Forge Division, HAL, Bangalore. This contribution has helped in indigenizing the need of aerospace industries as far as Al alloy rivet wires (figure 13a) are concerned.

These rivet wires were characterized and following tests were conducted to evaluate the properties as per IS:5902-1970.

- * Chemical analysis
- * Tensile test
- * Torsion test
- * Upsetting test
- * Macro examination
- * Micro examination

All the test results met the minimum requirements of the specification.

Figure 13. (a) High strength Al alloy components developed at NPL jointly with HAL, Bangalore— aerospace grade aluminium alloy rivet wires and (b) high strength Al alloy components developed at NPL jointly with HAL, Bangalore —light weight inserts of Al-Li.

4.5 Aluminium lithium

Several strategic high strength Al alloys with up to 2.5% lithium (Li) addition have become hi-tech in character, because of the need for special processing techniques. This

alloy was supplied in ingot form from Foundry and Forge Division, Hindustan Aeronautics Limited (HAL), Bangalore and the extrusion process parameters were optimized at NPL (Gupta *et al* 1989). The finished hot extruded 20 mm ϕ cylindrical rods (figure 13b) were supplied to ISRO, Bangalore as light weight inserts. Significantly the properties achieved were better than target properties and are indicated here: UTS (MPa): 350 (300); YS (MPa): 260 (200); and % Elongation: 5 (3).

5. Discontinuously reinforced aluminium (DRA) matrix composites

The attractive physical and mechanical properties that can be obtained with metal matrix composites (MMCs), such as higher specific modulus, strength, thermal stability and improved tribological properties, over their conventional monolithic counterparts, enables the material scientists to find their applications in automobile, aerospace and general engineering industries. MMCs combine metallic properties (ductility and toughness) with ceramic properties (high thermal stability and high modulus) leading to greater strength in shear and compression and higher service temperature capabilities.

It has long been known that two or more widely differing materials can be mixed together to form one solid, which is homogeneous in a macroscopic sense, and is capable of displaying unique combination of properties. However, the fact that the combination should form a homogeneous rigid solid to be of any use to the engineers and technologists, imposes restrictions on the choice of materials. A metal matrix composite can thus be defined as that in which a continuous soft ductile metallic material holds together a strong ceramic material of varying size, shape and quantity in a finely divided form in the former. Accordingly, one defines the former as the 'matrix' material (Al, Mg, Cu, Ti) which holds the 'dispersoids'. The dispersoid is a high strength, high modulus material in either continuous form such as fibres, or discontinuous form such as chopped fibres, whiskers or particulates. These reinforcement materials carry the major stresses and loads while the matrix material holds them together, enabling the loads and stresses to be transferred to the reinforcement materials. Reinforcement materials include carbides, (e.g. SiC, B₄C); nitrides (e.g. Si₃N₄, AlN); oxides (e.g. Al₂O₃, SiO₂), as well as elemental materials (e.g. C, Si) (Forney 1986; Geiger and Jackson 1989).

Discontinuously reinforced MMCs have, therefore, recently attracted considerable attention as a result of the following: (a) availability of various types of reinforcements at competitive costs, (b) successful development of manufacturing processes including powder metallurgy (PM), spray atomization and deposition (SAAD) and liquid metallurgy (LM) to produce MMCs with reproducible structures and properties, (c) offer essentially isotropic properties with substantial improvements in strength and stiffness and (d) availability of standard or near standard metal forming processes (forging, extrusion, rolling and superplastic forming) which can be utilized to form these MMCs into usable products.

Numerous techniques have been developed for the production of discontinuously reinforced MMCs which can be broadly classified as: (a) powder metallurgy i.e. solid phase process, (b) liquid metallurgy i.e. liquid phase process, and (c) spray atomization and deposition technique, i.e. two phase (solid/liquid) process.

Each process has its own merits and demerits and thus finds application in one area or the other. The selection of the process mainly depends upon the performance requirement, matrix-reinforcement compatibility and costs.

Once this material is produced in an ingot form, the problem remains of converting this material into usable shapes and sizes with improved properties. This can be achieved by employing metal forming techniques. There are different processes which can be used but the important ones are hot extrusion, hot rolling, hot forging and closed die forging.

The property-performance characteristics of MMCs are critically dependent on the interface bonding between the matrix and the reinforcement and these secondary processing techniques have a direct influence on this property.

The objective here is to present various aspects pertaining to processing techniques used to synthesize discontinuously reinforced aluminium matrix composites (DRA), different secondary processes used such as hot extrusion and closed die forging, microstructure, mechanical properties and ultimately the fabrication of actual MMC components for aerospace and automobile applications. The matrix used are Al alloy (2124 and 6061) and reinforcements are SiCp. In particular, the development work being pursued at NPL, New Delhi, India jointly with other collaborating institutions are reported in detail.

5.1 Bonding-property correlation

The stiffness, strength and fracture characteristics of MMCs have a direct influence on the interface between the matrix and the reinforcement. A 'good' interface means a strong chemical bond across the interface, which efficiently transfers the stresses from the ductile matrix to the strong and stiffer reinforcement. The increment in the Young's modulus achieved by incorporating ceramic reinforcement in a metallic matrix, is

Figure 14. E_{EXPT}/E_{ROM} for aluminium matrix composites with different reinforcements showing Al/TiC highest ratio (Kuruvilla 1989).

a measure of the interfacial bond integrity between the matrix and reinforcement. A well bonded interface would allow the maximum transfer of load from the matrix to the reinforcement through the interface and is expected to exhibit a high value of $E_{\text{expt}}/E_{\text{rom}}$ ratio, where E_{expt} and E_{rom} are the Young's modulus obtained experimentally and from the rule of mixtures, respectively. The Voight (1928) averaging also known as 'rule of mixture' (ROM) is given as,

$$E_c = V_m E_m + V_p E_p,$$

where, E_c , E_m and E_p are Young's modulus of the composite, matrix and reinforcement particles respectively, while V_m and V_p are volume fractions of matrix and reinforcement particles.

A weakly bonded interface would yield a low $E_{\text{expt}}/E_{\text{rom}}$ value. The results of experiments using different reinforcements (SiC, B_4C , TiC and TiB_2) by Kuruvilla *et al* (1989) suggest that Al/TiC bond is the strongest and Al/ TiB_2 , the weakest among the four studied (figure 14). Mitra and Mahajan (1993) reviewed the literature on interfaces in DRA composites, and suggested that clean interfaces between matrix and reinforcement and metallic bonding results in ideal properties. Strong matrix/reinforcement interface bond also allows attainment of attractive physical properties, such as, low coefficient of thermal expansion (CTE), high thermal and electrical conductivity in MMCs.

5.2 Processing of DRA and experimental details

Several R and D organizations and institutes in India are engaged in the development of MMCs, employing LM and PM routes. The National Physical Laboratory (NPL), New Delhi is setting up a SAAD unit to synthesize MMCs. The NPL, New Delhi is having collaboration with different R and D laboratories/industries such as the Defence Metallurgical Research Laboratory (DMRL), Hyderabad for PM route, the Hindustan Aeronautics Limited (HAL), Bangalore, the Regional Research Laboratory (RRL), Trivandrum, and IISc., Bangalore for LM route. Hot deformation behaviour of this material, using different techniques are being studied at NPL, New Delhi where the facilities exist to study different characteristics using hot extrusion and closed die forging on a 500-ton vertical hydraulic press.

5.2a Powder metallurgy: Powder metallurgy technique involving a series of steps are shown in figure 15a. The process involves blending of SiCp (average particle sizes of 1.9, 3.0 and 14 μm) with 2124 aluminium alloy powder (average particle size 94 μm) in varying volume fractions (10, 15 and 20%). Nominal composition of 2124 Al in wt% are 4.6 Cu, 1.4 Mg, 0.2 Fe, 0.1 Si, 0.03 Mn and balance Al. These blended powders were degassed and subsequently cold isostatically pressed (CIP). These CIPed compacts were then vacuum hot pressed at a temperature above the solidus line of the alloy to achieve 98–99% theoretical density. These PM billets were produced at DMRL, Hyderabad under a joint collaborative research project with NPL. These billets (figure 15b) were subsequently hot pressed/hot extruded/closed die forged at NPL. The mechanical and metallurgical properties of different components are reported in a later section.

Figure 15. (a) Conventional/modified PM route flow chart and (b) PM route billets (2124 Al + SiCp).

5.2b Liquid metallurgy: The matrix material and reinforcements used in the present investigations were 2124/6061 Al-alloy and SiC particulates of average size 23 and 40 μm . DRA billets containing various volume fractions of SiCp were prepared using LM route (stir casting). This technique essentially involves addition of the dispersoid particles into the vortex formed in a pool of mechanically stirred molten alloy at 730–740°C. SiC particulates were sieved and preheated in a separate furnace for about

3 hours at 775°C before addition to the melt. After the reinforcement was incorporated into the melt, stirring was continued for 15 min and then cast into permanent moulds. The time was kept minimum to prevent any reaction between SiCp and liquid metal. Different composite billets were produced using varying volume fractions (5 to 20%).

6061 Al/SiCp DRA were supplied by HAL, Bangalore and RRL, Trivandrum while 2124 Al/SiCp DRA were produced at NPL, New Delhi.

5.2c Spray atomization and deposition: The principle of spray deposition was pioneered during the 1970s by Singer (1970, 1972) at the University College of Swansea, UK. Professor Enrique J Lavernia, University of California (UCI), Irvine, USA, has an excellent set-up to synthesize monolithic and composite materials (Lavernia 1989; Liang and Lavernia 1991). The author had worked on the synthesis of DRA using 6061 Al/SiCp in varying volume fractions and using 3 and 15 μm sizes at UCI.

During spray atomization and deposition process, the matrix material is disintegrated into a fine dispersion of droplets using high velocity inert gas jets, followed by deposition onto a substrate where the droplets impact and accumulate into a preform. A schematic diagram of the spray atomization and deposition facility, used in the present work, is shown in figure 16 (Liang and Lavernia 1991). The process is essentially a rapid solidification one and can be broadly classified into two distinct parts, i.e. spray atomization and deposition.

Spray atomization is a method in which a liquid metal stream is atomized at the impact of a stream of another high velocity gas jet (generally N_2 or Ar gas) coming from an atomizing nozzle. These high velocity jets result in the disintegration of molten metal stream into micro sized droplets. Molten metal flows through a ceramic delivery tube by both gravity and aspiration force resulting from the pressure of atomization gas. The impact of high velocity gas jets on the liquid metal stream occurs at the tip of the delivery tube which contains the molten metal.

Figure 16. Schematic diagram of SAAD unit (Liang and Lavernia 1991).

Spray deposition technique, essentially, rapidly quenches the spray atomized droplets under a tightly controlled atmosphere resulting in the development of liquid dynamic compaction. The general principle of spray deposition is to direct a stream of molten droplets onto a water cooled substrate (collector) which is located in such a position that the sprayed droplets are in a mushy state, i.e. partially solid and partially liquid, upon impact. As the distribution of atomized metallic droplets travel towards the deposition surface, one or more jets of ceramic particles are co-injected into the atomized spray at a previously predetermined flight distance. In the present investigation, coaxial type of injector has been used to induct the SiCp in the flight, as shown in figure 16. The process involves mixing of reinforcement and matrix in a regime of the phase diagram where the matrix contains both solid and liquid phases. During impact, the mushy state droplets along with particulates are flattened and welded, forming a highly dense preform, which can be directly extruded/forged to form a fully dense product. Efforts were made to produce a few large sized DRA spray deposited billets using the above process.

All the DRA billets produced using the three processes i.e. PM, LM, and spray, were hot extruded/forged at NPL using 500-ton press. Details of the results are mentioned in § 5.4.

5.3 Hot deformation behaviour

Hot workability of DRA is one of the most important research topic currently being pursued by various research groups all over the world. Hot working process above the recrystallization temperature not only deforms the material in required shapes and sizes but also refines the microstructure which in turn improves the mechanical properties such as ductility and strength. Another important feature which influences the hot workability is the nature of distribution of the ceramic reinforcement in the matrix material. A non-uniform distribution (clustering of reinforcement) may lead to inhomogeneous flow of the material leading to cracks while a uniform distribution of ceramic reinforcement and equiaxed matrix grain structure leads to homogeneous flow of material. As a result, the load requirements are higher in the former.

However, the process parameters adopted for the standard matrix (monolithic) alloys cannot be directly employed for processing the respective composite materials, due to the incompatible deformation characteristics of the matrix and the reinforcement particulates, as well as the consequent changes in the optimal processing parameters.

The incompatibility between a deforming matrix and a nondeformable particle means that dislocations will be generated at the particles. Humphreys *et al* (1990) studied the microstructure developed and recrystallization behaviour of 1050 Al reinforced with 2–35 vol% of SiCp in the size range of 1–100 μm . In addition to dislocation generation due to deformation incompatibility, the mismatch in the coefficients of thermal expansion of the matrix and the reinforcement also gives rise to dislocation generation.

In addition to the high dislocation densities, the presence of particulates ($> 1 \mu\text{m}$) also leads to particle stimulated nucleation (PSN) of recrystallization in the deformation zones adjacent to the particles (Humphreys 1990). As the ceramic particles used in composites are generally much larger than 1 μm in size, these will be a function

of the particle size and volume fraction. A high volume fraction of fine particles with close interparticle spacing can also pin the grain boundary migration and thereby stabilize the fine grain structure and restrict grain growth. Especially in powder metallurgy composites, the oxide particles exert an additional effect on the kinetics of the recrystallization and grain growth (Humphreys *et al* 1990).

DRA composites produced by either powder metallurgy or liquid metallurgy routes, need to be deformed to achieve the best possible properties. In the case of the powder metallurgy billets, the prior particle boundary (PBB) defects can be eliminated and the distribution of the reinforcement particles are improved by the hot deformation process. The matrix powder particles, especially aluminium powder consist of an oxide layer, which does not allow proper interface bonding between matrix and reinforcement as well as between matrix particles themselves. These can only be broken and redistributed by hot deformation using extrusion and forging involving extensive shear. In the case of powder metallurgy billets, the reinforcement particles usually being finer, as compared to the matrix particles, are distributed around the matrix powder particles forming a necklace like microstructure in the as-hot pressed composites. Although, this situation can be improved to some extent by choosing much closer size-ratio of matrix and reinforcement particles, significant improvement can only be achieved by a hot deformation step involving considerable matrix material flow around the hard reinforcement particles, thereby redistributing them and obtaining a more uniform distribution. Even in the case of composites produced by the liquid metallurgy technique, deformation processing helps in healing the defects like porosities and segregation to a large extent. It also breaks the cast dendritic structure and replaces it with a fine grained microstructure.

5.3a Processing maps in hot working: Deformation processing of MMCs presents its own problems, due to the incompatible deformation characteristics of the matrix and reinforcements. Hot working of MMCs thus requires to be carried out within a certain 'window' of strain rate and temperature in order to achieve defect free parts, microstructure and mechanical properties. Optimization of hot working processing parameters by trial and error is both time consuming and expensive. Different methods such as hot torsion testing, hot tensile testing and actual deformation processing studies can also be used to understand the deformation characteristics. Xia *et al* (1994) adopted hot torsion testing and extensive transmission electron microscopy to study the hot deformation and recrystallization behaviour of 6061 Al/SiCp composites. They have concluded that the higher flow stresses encountered in composites, as compared to the monolithic alloys, is due to the higher dislocation densities due to ACTE and the denser substructure induced by plastic flow around the rigid SiC particle during hot working. The softening effects at high temperature deformation is attributed to increased dynamic recovery and dynamic recrystallization.

Processing maps developed by Prasad *et al* (1984) provide a scientific tool for optimizing process parameters based on simple laboratory hot compression tests. Processing maps are generated based on the dynamic materials model (DMM) developed by Prasad *et al* (1984) and reviewed by Gegel *et al* (1987). The model considers the workpiece as a dissipator of power and the power input to the workpiece is partitioned and dissipated as viscoplastic heat and microstructural changes. The strain rate sensitivity (SRS) m is found to be responsible for the partitioning of power and a dimensionless parameter n is defined as the efficiency of power dissipation

through microstructural processes and derived to be equal to $2m/2m + 1$. This efficiency parameter is plotted as a function of both strain rate and temperature to get the processing map. The different efficiency peaks in the map are then interpreted in terms of different deformation mechanisms and thus help in identifying the safe domains for processing.

Bhat *et al* (1992) studied the hot working characteristics of DRA composites in detail. The conventional Al-alloys having good formability are pressed at high strain rates but their respective composites exhibit flow instabilities at those strain rates. Flow instabilities manifest themselves as extensive cracking at particle/matrix interfaces, adiabatic shear band forming and localized flow due to adiabatic heating.

Figure 17. (a) Effect of extrusion ratio and reheat temperature on pressure requirement (Al2124 + SiCp composites) and (b) extruded rods with different extrusion ratios (Al2124 + SiCp composites).

5.4 Experimental results

The MMC billets employing PM, LM and SAAD techniques were hot extruded/closed die forged at NPL, New Delhi, using different extrusion conditions. Different process parameters such as temperature, pressing speed, extrusion ratio, die design, lubrication and its effect on varying volume fraction of various compositions of DRA have been optimized mainly to investigate their effect on surface quality, pressure requirement and the resultant mechanical/metallurgical properties. Details of experimentation techniques used are reported elsewhere (Gupta and Hughes 1979; Gupta *et al* 1980). The work was extended to produce circular rods, tubes and shapes. These circular DRA tubes find application in automobile and space, and have been discussed in § 5.5.

5.4a PM route: 72 mm diameter PM machined billets were hot extruded using a 500-ton press. Different extrusion ratios (up to 36:1) were employed to produce satisfactory extruded rods, tubes and shapes. These products were characterized for detailed mechanical and metallurgical investigations jointly with DMRL. Figure 17a shows the pressure encountered for carrying out solid extrusions employing different process parameters. Figure 17b shows the pictorial view of these DRA circular rods with different extrusion ratios (9:1, 16:1 and 36:1). Tensile tests were conducted on these samples using an Instron testing machine. Comparison of properties achieved using different extrusion conditions are shown in table 1. All the properties reported are in as-extruded conditions and are likely to be considerably improved in T6

Table 1. Tensile results of as-extruded rods – PM.

ER	Temp. (°C)	YS (MPa)	UTS (MPa)	%Elong.	E (GPa)	Hardness (VHN)
[2124Al + 20% SiCp (14 μm)]						
9:1	450	190	270	3.0	90.7	91.6
	500	197	280	3.3	92.8	
16:1	450	195	275	3.1	93.3	94.2
	500	181	291	3.7	96.0	
36:1	450	210	310	3.0	95.9	105
	500	217	316	3.7	98.8	
[2124Al + 20% SiCp (1.9 μm)]						
36:1	525	300	397	4.8	100	

Table 2. Tensile properties of as-extruded rods – PM.

ER	Temp. (°C)	YS (MPa)	UTS (MPa)	%Elong.	Modulus* (GPa)
[2124 Al + 20% SiCp (14 µm)]					
36:1	525	198	323	7.9	95.56
36:1	500	226	333	5.6	95.65

* Mean of eight readings, obtained by Elastasonic equipment

Figure 18. a-b.

Figure 18. (a) Microstructure showing well distributed SiCp in 2124 Al matrix, (b) MMC circular tubes for structural applications for spacecrafts and (c) MMC circular tube fitted as liner in C. I. Engine block.

Table 3. Tensile properties of composite tubes (T6)-PM.

Property	Experimental	Target
[2124 Al/15% SiCp (1.9 μm)]		
YS(MPa)	380	380
UTS(MPa)	473	480
% Elongation	3.6	4.0
E(GPa)	102	95
Buckling properties (L/D ratio: 2.5)		
Compressive YS	261 (MPa)	
Ultimate buckling stress	453 (MPa)	

condition. Microstructure showing well distributed SiCp reinforcement in the matrix is shown as figure 18a. Modified PM route billets were produced which resulted in the enhancement of properties, especially ductility, as reported in table 2.

This work has been undertaken with an objective to make circular tubes as structural component for space and automobile applications. Typical properties achieved for these DRA tubes are shown in table 3, and figure 18b shows the pictorial view of these tubes.

5.4b LM route: Extrusions were made from the DRA billets (6061 Al + SiCp and HMS 2112 Al + chopped carbon fibres) supplied by RRL, Trivandrum and also billets

received from HAL, Bangalore. The work was extended to produce MMC tubes using these composites. Some of the products do show some extent of porosity. In addition to these materials, Cu-graphite (Gupta *et al* 1994), Al-flyash and lead-flyash have also been secondary processed to circular rods at NPL.

5.4c Spray atomization and deposition route: The properties of the extruded rods exhibited improved ductility (around 6–8%), as compared to the PM process.

Spray forming facilities are being set-up at NPL and it is envisaged that the unit will be used to synthesize Al–Li based MMCs. Due to its high elastic modulus and lower density, Al–Li is a very useful material for aerospace and defence applications and by using it as a matrix material in MMCs, its properties can further be tailored according to the desired applications. However, its high reactivity, owing to oxidation, places severe constraints in the processing of this material and thus this work will be carried out using spray forming facilities. The material so produced will be secondary processed for further component development.

5.4d Processing of DRA—current status:

- * All the products extruded using PM, LM and SAAD routes gave satisfactory results. Efforts are being made to optimize different processing conditions to improve the properties.
- * Extrusion die/container wear is a problem. The problem is more acute using LM route because of coarser reinforcements used.
- * Another major problem, which still needs to be addressed, is the high rate of wear of the tool bits/extrusion saw blades. Efforts are being made to improve their performances.

5.5 Applications of DRA composites, developed at NPL, for space and automobiles

While the United States is taking a lead in the use of MMCs in defence and aerospace, Japan has already introduced this new material for a large number of applications in automobiles. Other countries which have strong activities in this area are, UK, France, Germany, Netherlands, Australia, Canada and China (Rohatgi Pradeep 1993). A number of Indian R and D institutes and industries are actively engaged in the development of this hi-tech material, studying different aspects of the science and technology of these composites. In spite of these developments, this material has still to find its place in the Indian Industries. Some of the opportunities and challenges in this context are highlighted in § 5.6.

As described in the last section, DRA circular tubes have been successfully developed which find different applications in space and automobiles.

5.5a PM processed MMC tubes for satellite applications: DRA are now emerging as cost effective materials, providing designers with a unique combination of design features and properties such as high specific stiffness and strength, controlled coefficient of thermal expansion (CTE), improved elevated temperature properties and superior dimensional stability. Tubular struts for satellites is one such application where high specific stiffness, low CTE and reasonably high thermal conductivity play an important role. The performance indices for optimal selection of materials for the

Table 4. Figures of merit for the selection of material for tubular strut applications.

Material	E (GPa)	ρ (g/cm ³)	Figures of merit	
			$E^{1/2}/\rho$ (Mech.)	k/CTE (Thermal)
2124Al	72	2.78	3.05	5.96
2124Al + 15%SiCp	100	2.84	3.52	7.38
2124Al + 30%SiCp	130	2.86	3.98	8.80

Table 5. Weight savings by use of MMCs and Al–Li alloys for structural applications (failure mode: buckling).

Material (Baseline – 2124 Al)	% Weight savings $[\rho_2/\rho_1(E_1/E_2)^{1/2}]$
8090 Al–Li	13.7
2124 Al/15%SiCp	17.6
2124 Al/30%SiCp	19.6

tubular strut application are both, resistance to mechanical ($E^{1/2}/\rho$), as well as thermal (k/CTE) distortions, where ρ is the density, E the elastic modulus, k the thermal conductivity, and CTE is the coefficient of thermal expansion. MMCs exhibit significantly higher figures of merit as compared to the corresponding unreinforced alloy as shown in table 4. The percent weight savings which could be achieved by substituting conventional 2124-Al alloy with Al–Li alloy or MMCs are indicated in table 5. Table 5 indicates that the use of MMC tubular struts can offer significant weight savings which is a prime requirement for the satellite applications. The properties achieved are mentioned in table 3. Efforts have been made to improve the ductility of these tubes to approximately 5%.

5.5b MMC tubes as drive shafts: Drive shafts in passenger cars offer particularly attractive applications for DRA. The primary driving force for aluminium drive shafts is its significant lower weight coupled with the ease with which it can be balanced. The critical drive shaft speed (N_c) is given as (Allison John and Cole Gerald 1993)

$$N_c = 15\pi/L^2[(E/\rho)g(R_o + R_1)^2]^{1/2},$$

where L is drive shaft length, R_o the outer radius and R_1 the inner radius, E the elastic modulus, ρ the density and g the gravitational acceleration. As is clear the specific modulus (E/ρ) is the only material property that affects the critical speed. Some future vehicles will require drive shafts that are longer than feasible using aluminium or steel. Both steel and aluminium have low specific modulus and the critical speed limitations of these impose severe constraints on the drive shaft lengths. DRA drive shafts

represent a cost effective solution to this problem as the specific modulus of DRA can be significantly higher than that of aluminium or steel.

Manufacturing technologies for the fabrication of drive shafts include consistent material quality, high tolerance tube extrusions and DRA to aluminium fusion welding techniques. Significant utilization of these drive shafts are expected by the late 1990s.

5.5c DRA tubes as cylinder liners: The main emphasis in automobile industry is to reduce vehicle weight. A typical 'rule of thumb' estimates that 10% reduction in vehicle weight yields approximately 5.5% improvement in fuel economy (Allison John and Cole Gerald 1993). To achieve this, conventional cast iron engine blocks are being replaced with aluminium silicon alloy engine blocks. A few of the companies have adopted an interim approach of using cast iron blocks fitted with DRA liners. This will help in achieving improved thermal stability, reduce engine friction by improving block stiffness and dimensional stability. These liners increase weight reduction and wear resistance. The extruded DRA tubes at NPL have been fitted on trial basis in cast iron engine blocks (figure 18c) for a two-wheeler and the performance trials are in progress. These DRA circular tubes also find applications for bicycle frames and golf clubs.

5.5d DRA connecting rod, piston and machined components: Piston and connecting rods have also been successfully produced at NPL and are shown as figures 19a and b, respectively. Improvements are currently underway to enhance the performance of these components.

Conventional tools and machining techniques for MMCs pose serious problems due to abrasive nature of ceramic reinforced in the matrix. A prior knowledge of the machinability characteristics are desirable for its optimum use in any structural or other potential applications. Increase of ceramic reinforcements in the matrix leads to the reduction of ductility and toughness while the hardness of the composite increases significantly. It is the hardness which really decides the cutting speed, depth of cut and feed rate. These parameters have a direct influence on the tool life. Thus a limited work was undertaken at NPL to study some of these machining aspects in a limited way. Some of the billets and components were machined using turning, milling, drilling and grinding operations in 15 and 20% SiCp reinforced MMCs. During the course of this investigation, a few components were machined as shown in figure 19b.

5.5e DRA closed die forged component: An aluminium alloy forged motor body component, is shown as figure 20a and a typical DRA component made by closed die forging, shown as figure 20b. The component was produced mainly to study the maximum percentage of reduction achieved during upsetting operation. The fabrication of component, employed hollow forward and upsetting operations. The distribution of SiCp was reasonably good in the matrix.

5.6 Opportunities and challenges—Indian context

Despite the fact that MMCs are emerging as potential materials for different applications in automobile and general engineering industries, a number of barriers have to be

Figure 19. (a) MMC piston and (b) secondary processed and machined MMC components.

overcome to ensure its widespread introduction. A few of these could be classified as below:

- * MMC finished components will eventually cost more than conventional components because of the higher cost associated with raw materials and processing cost (fabrication and machining).

Figure 20. Closed-die-forged components: (a) Al alloy motor body component and (b) MMC forged component.

- * Recycling of this material is another handicap and needs attention.
- * Lack of design data, particularly the detailed properties of fatigue, creep, wear and corrosion is again a practical problem and requires a comprehensive data generation.

- * Lack of quantitative information on machining tool life and die wear.
- * Product consistency is also an important parameter. Standards are required so that automotive engineers could specify and manufacture components with specified structure and properties that are predictable and stable over long periods.

To overcome these deficiencies, sustained efforts are required to develop near-net shaped forming techniques, rapid and inexpensive machining process and recycling methods.

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