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METAL-MATRIX COMPOSITES

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1. INTRODUCTION

Metal-matrix composites (MMC) are engineered combinations of two or more materials (one of which is a metal) where tailored properties are achieved by systematic combinations of different constituents. Conventional monolithic materials have limitations in respect of achievable combinations of strength, stiffness and density. Engineered metal-matrix composites consisting of continuous or discontinuous fibers, whiskers, or particles in a metal result in combinations of very high specific strength and specific modulus to be achieved (Tables 1A, 1B; Fig. 1A). Structurally, metal-matrix composites consist of continuous or discontinuous fibers, whiskers, or particles in an alloy matrix which reinforce the matrix or provide it with requisite properties not achievable in monolithic alloys. Furthermore, systematic design and synthesis procedures allow unique combinations of engineering properties like high elevated temperature strengths, fatigue strength, damping properties, electrical conductivity, thermal conductivity and expansion coefficient. In a broader sense, cast composites, where the volume and shape of phases is governed by phase diagrams, i.e., cast iron and aluminum-silicon alloys, have been produced by foundries for a long time. The modern composites differ in the sense that any selected volume, shape and size of reinforcement can be introduced in the matrix. The modern composites are nonequilibrium mixtures of metals and ceramics where there are no thermodynamic restrictions on the relative volume percentages, shapes and sizes of ceramic phases.

By carefully controlling the relative amounts and distribution of the ingredients constituting a composite, as well as by controlling the processing conditions, MMCs can be imparted with a tailored set of useful engineering

TABLE 1A

Mechanical Properties of Some Metal Matrix Composites

Material	Vol. Fr. Fiber (%)	Specific Strength (N • m/kg)	Specific Modulus (N • m/kg)
Al_2O_3 (FP)/Al-Li			
0°	60	20000	7.59×10^7
90°	60	4986 - 6000	4.406×10^7
SiC/Ti-6 Al-4V			
0°	35	45337	7.77×10^7
90°	35	10622	-
C/Mg (Thornd)	38	28333	-
C/Al	30	28163	6.53×10^7
6061 Al	-	11481	2.53×10^7
2014 Al	-	17143	2.59×10^7
$SiC_{(f)}$	100	78431	1.567×10^8
$SiC_{(w)}$	100	6.67×10^5	2.19×10^8
$Al_2O_{3(f)}$	100	50000	1.175×10^8
$B_{(f)}$	100	1.538×10^5	1.62×10^8
$C_{(f)}$	100	1.618×10^5	1.35×10^8
$Be_{(f)}$	100	59459	1.68×10^8
$W_{(f)}$	100	14974	1.79×10^7
B/Al 0°	50	56604	7.92×10^7
90°	50	5283	5.66×10^7
SiC/Al 0°	50	8803	1.092×10^8
90°	50	3697	-

TABLE 1B

Mechanical Properties of Cast Metal Matrix Composites

Type of MMC	V_f	Elastic Modules (GN/m^2)
Al Matrix	0	3.79
Continuous SiC Fiber (Al-4.5 Cu Matrix)	0.35	10.85
Continuous SiC Fiber (Al-11.6 Si Matrix)	0.35	10.50
Continuous SiC Fiber (Al-4.8 Mg)	0.35	10.25
Discontinuous SiC Fiber (Al Matrix)	0.44	11.6

properties which can not be realized with conventional monolithic materials (Figs. 1A, 1B).

Composite materials are attractive since they offer the possibility of attaining property combinations which are not obtained in monolithic materials and which can result in a number of service benefits. These could include increased strength, decreased weight, higher service temperature, improved wear resistance, higher elastic modulus, controlled coefficients of thermal expansion and improved fatigue properties. The quest for improved performance has resulted in a number of developments in the area of metal-matrix composites. These include the preparation of the reinforcing phases and development of fabrication techniques.

Reinforcement phases for metal-matrix composites fall into three important categories--continuous or discontinuous filament, whiskers and particulate. The greatest improvements in mechanical properties are obtained from filaments in the direction of filament alignment, with whiskers and particulate offering descending strength, but greater isotropy, in that order.

A number of composite fabrication techniques have been developed that can be placed into four broad categories: those involving liquid metallurgy; those involving powder metallurgical techniques; those involving diffusion bonding of foils; and those involving vapor phase infiltration. The liquid metallurgy techniques would include unidirectional solidification to produce directionally aligned metal-matrix composites, suspension of reinforcements in melts followed by solidification, compocasting and pressure infiltration. The liquid metallurgy techniques are least expensive and the multi step diffusion bonding techniques are most expensive.

From a technological standpoint of property-performance relationship, the interface between the matrix and the reinforcing phase (fiber or particle) is of central importance. Processing of metal-matrix composites sometimes allows tailoring of the interface between the matrix and the fiber in order to suit specific property-performance requirements. The cost of producing cast metal-matrix composites has come down rapidly, especially with the use of low cost particulate reinforcements like graphite and silicon carbide. Low cost composites like metal-silicon carbide particle and metal-graphite particle are now commercially available. In recent years considerable activity has taken place in the area of metal-matrix composites, and Table 2 shows the different fibers and matrices combined to date, the fabrication techniques and the potential fields of application. Table 3 gives more recent data of the same type for cast composites, most of which are particulate.

2. STRENGTHENING CONSIDERATIONS

Composite materials technology offers unique opportunities to tailor the properties of metals and metal alloys. Under ideal conditions the composite exhibits mechanical and physical properties defined by the rule-of-mixture. That is:

$$P_c = P_m F_m + P_r F_r \tag{1}$$

where:

P_c = the properties of the composite material

P_m = the properties of the matrix phase

P_r = the properties of the reinforcement phase

F_m = the volume fraction of the matrix phase

$F_r = 1 - F_m$ = the volume fraction of the reinforcement phase.

By combining matrix and reinforcement phases exhibiting the appropriate properties, dramatic changes can be made in strength, elastic modulus,

TABLE 2

Fibers, Matrix, Fabrication Techniques and Fields of Application of Metal Matrix Composites

Fibers	Matrix	Fabrication Method	Field of Application
SiC coated B	Al	Powder metallurgy; the composite article is clad with a sheet of Ti by diffusion bonding	Turbine blades
C (graphite, amorphous carbon)	Ni/Co aluminide	Coating C fibers with Ni or Co; mixing with Ni-Co-Al powder; hot pressing	
C coated with boride of Ti, Zr, Hf	Al or Al alloys, Mg, Pb, Sn, Cu, Zn	Melt impregnation	
	Al alloy containing carbideforming metal, e.g., Ti and Zr	Melt impregnation	
SiC with W core	Al-Cu alloy	Coating the filaments with Cu; passing the Cu-coated filaments through an Al melt	
C	Mg or Mg alloy	Melt impregnation; the molten Mg matrix contains small amounts of magnesium nitride to enhance wetting of the fibers	Turbine fan blades, pressure vessels, armor-plates
SiC	Be or alloys with Ca, W, Mo, Fe, Co, Ni, Cr, Si, Cu, Mg, and Zr	Vacuum impregnation; with molten Be or plasma spraying fibers with Be and consolidation by metallurgical process	Aerospace and nuclear industries
B + stainless steel; Borsic + Mo fibers	Al, Ti	Impregnation, spraying combination of high-strength ductile and brittle fibers	Aerospace industry

TABLE 2 (continued)

Fibers, Matrix, Fabrication Techniques and Fields of Application of Metal Matrix Composites

Fibers	Matrix	Fabrication Method	Field of Application
SiC	Ti or alloy Ti-3 Al-2.5V	Hot pressing of interlayers of fibers and matrix sheets; SiC fibers are previously coated with Zr diffusion barrier layer	Compressor blades, airfoil surfaces
Carbides of Nb, Ta, and W	Ni-Co and Fe-Cr alloys	Unidirectional solidification	Aircraft industry
SiC containing 0.01-20% free carbon	Cr-based alloys	Powder metallurgy; the free carbon reacts with the Cr to form carbides, thus improving bonding	High-strength, heat resistant material, e.g., vanes and blades for turbine, rocket nozzles
SiC containing 0.01-30% free carbon	Co or Co-based alloys	Powder metallurgy or melt impregnation: carbide formation between the fibers and the Co matrix	High-strength, heat-resistant material, e.g., vanes and blades for turbines, rocket nozzles
SiC containing 0.01-20% free carbon	Mo-based alloys	Powder metallurgy	High-strength, heat-resistant material, e.g., vanes and blades for turbines, rocket nozzles
C coated with carbides	Ni or Ni alloys	Melt impregnation	Aeronautical industry
B	Cu-Ti-Sn alloy	Liquid phase sintering	Cutting tools
C	Bronze	Various processes	Bearing materials
C	Cu alloy	Powder metallurgy; the fibers are mixed with a slurry of Cu powder and 2% of a carbine-forming metal powder (Ti or Cr)	High strength, electrically conductive materials

TABLE 2 (continued)

Fibers, Matrix, Fabrication Techniques and Fields of Application of Metal Matrix Composites

Fibers	Matrix	Fabrication Method	Field of Application
C coated with Ti boride	Al, Cu, Sn, Pb, Ag, Zn, and Mg	The matrix contains alloying elements of Ti and B to prevent deterioration of the TiB coating of the fibers	Aeronautical industry
C coated with Ni	Metals with melting point lower than that of Ni	Melt impregnation	
C coated with SiO_2 + SiC	Al, Mg, Ti, and Ni	Melt impregnation, powder metallurgy	
Monocarbides of Ta, Ti, and W	Al, Al-Si alloy Ag or Ag alloys, and Cu or Cu alloys	Melt impregnation	Abrasion-resistant materials
B-SiC	Ag or Ag alloys		Electrical Conductors contacts
C	Si	Powder metallurgy	Abrasive materials
SiC	Al		
C coated with TiB	Mg,Pb, Zn, Cu, and Al	Melt impregnation	

fracture toughness, density, and coefficient of expansion. The key to control of these properties depends in part on successful selection of the reinforcement phase, and the bonding between the matrix and the reinforcement. Examples of the range of some of the mechanical properties attainable in aluminum metal-matrix composites are shown in Fig. 1 as a function of reinforcement phase strength, elastic modulus, and volume loading.

The above discussion is based on the assumption that the rule-of-mixtures is followed by the composite material. In fact, this can be the case for certain properties like modulus, when continuous filament is used as the reinforcement phase, and matrix-to-reinforcement phase interfacial reactions are controlled to provide good bonding without degradation of the reinforcement phase. An example of the agreement between the strength predicted by the rule-of-mixtures and that measured in stainless steel reinforced aluminum is shown in Fig. 2A.

Based on the agreement shown in Fig. 2A between the rule-of-mixtures prediction and measured properties, it would be desirable to fabricate all metal-matrix composites using continuous filament as the reinforcement phase, if properties mainly in one direction are required. Practically speaking, however, there are significant restrictions imposed by the use of continuous reinforcement in metal-matrix composites. The preparation of continuous filament is a complex and expensive process as shown in the lay-up process for continuous filament within the metallic matrix (Fig. 2B). In addition, continuous filament reinforcement is currently limited to simple geometries such as planar or symmetric shapes as discussed previously. Consequently, continuous filament-reinforced metal-matrix composites are being evaluated only for limited, high value-added applications, especially for aerospace applications.

As a result, alternative reinforcement phase morphologies are being investigated to reduce the cost of metal-matrix composites while still retaining the attractive properties. These approaches typically involve the use of less expensive, discontinuous reinforcement phases and powder metallurgy or casting techniques. Unfortunately, in the quest for lower cost, a price has to be paid in generally lower levels of property enhancement.

The short-fall in mechanical properties compared with continuous fiber reinforcement results from the decreased transfer of stress from the matrix to the reinforcement phase. As shown in Fig. 3, the efficiency of stress transfer is related to the length (l) of the reinforcement phase compared with its critical length (l_c) by the relationship:

$$S_c = S_f[V_f*(1-l_c/2*l) + E_m/Ef*(1-V_f)] \tag{2}$$

where:

S_c = composite strength

S_f = reinforcement strength

V_f = volume fraction of reinforcement phase

l_c = minimum reinforcement phase length for full load transfer from the matrix to the reinforcement

($l_c = d*S_f/S_m$) where

d = fiber diameter and

S_m = matrix strength

l = actual reinforcement phase length

E_m = elastic modulus of the matrix

E_r = elastic modulus of the reinforcement phase.

Figure 3 reveals that for fiber lengths near the critical fiber length, relatively modest increases in strength are realized. As the ratio of l/l_c

increases, however, the efficiency of load transfer from the matrix to the reinforcement increases. For example, if $l/l_c = 16$, the discontinuously reinforced composite will exhibit approximately 96 percent of the increase in strength exhibited by a continuously reinforced composite.

Despite these theoretical advantages, there are significant practical problems associated with maintaining the integrity of high-aspect-ratio discontinuous fibers during fabrication and working. Thus, there is a high level of development activity in the use of particulates as composite reinforcement materials. However, particulate material has an aspect ratio of only about one and there is a trade-off to lower properties when using particulate reinforcement as compared with high aspect ratio fibers. There are other mechanisms between the matrix and the dispersoid which contribute to an overall increase in the strength and modulus of particulate composites. Recent studies have indicated that dislocation densities are very high in the matrix near the interface which may be responsible for strength. In addition to the length, the shape of the dispersoids also has a major influence on the properties (Fig. 3B); there are indications that flakes may be more effective than particles.

3. POWDER METALLURGY-BASED METAL-MATRIX COMPOSITES

Powder metallurgy techniques offer the following advantages over liquid metallurgy techniques of fabricating metal-matrix composites.

Lower temperatures can be used during preparation of a P/M-based composite compared with preparation of a liquid metallurgy-based composite. The result is lesser interaction between the matrix and the reinforcement when using the P/M technique. By minimizing undesirable interfacial reactions, improved mechanical properties are obtained.

In some cases P/M techniques will permit the preparation of composites that cannot be prepared by liquid metallurgy. For instance, fibers or particles of silicon carbide will dissolve in melts of several metals like titanium, and such composites will be difficult to prepare using liquid metallurgy techniques.

However, powder metallurgy techniques remain expensive compared to liquid metallurgy techniques for composites like Al-SiC particle composites. In addition only small and simple shapes can be produced by powder metallurgy techniques.

A number of P/M composite preparation methods have been studied. The conventional powder metallurgy techniques of blending metal powders and ceramic powders, followed by pressing and sintering, have been used extensively to produce composites. In certain instances sintering is done in the presence of pressures at temperatures where there is partial melting for better bonding. The powder produces composites which can be subsequently forged and rolled.

Several companies are currently involved in the development of powder metallurgy-based metal-matrix composites using either particulates or whiskers as the reinforcement phase. Three of these companies are DWA (Delowey, Webb and Associates, Chatsworth, CA), the American Composites, formerly ARCO and Silag (Greenville, SC), and Novamet, a part of INCO Mechanically Alloyed Products Company (Wyckoff, NJ). Each of these companies has a unique feature associated with their process/product that differentiates it from the other two. Brief descriptions of these processes are shown in Figs. 4 to 6. DWA uses a proprietary blending process to combine particulate with metal powder. Silag also uses a proprietary blending process to combine its composite components. The distinction between the two is that Silag uses SiC whiskers, which are manufactured from rice hulls, as the reinforcement phase rather than particulate. Novamet, similar to DWA, uses particulate as the reinforcement phase, but employs mechanical alloying techniques to combine the reinforcement and matrix constituents.

Despite the differences in reinforcement or processing methods, all of these products show similarities. All are currently intended for high value-added applications, such as military or aerospace, and all are quite expensive relative to similar, noncomposite products, i.e., \$50-\$100/pound versus \$5-\$10/pound as billet. Additionally, the relation of the mechanical properties to volume fraction reinforcement is similar. As shown in Fig. 7, the measured values of elastic modulus follow closely the predicted values for continuous filament reinforcement. However, the measured strength values are lower than the values predicted by the continuous filament reinforcement model, although they are generally above the discontinuous reinforcement model predictions, at least at the lower volume loadings.

The shortfall in strength relative to the behavior of the elastic modulus is a typical problem that currently plagues all discontinuous metal-matrix composites. It is most likely a result of decohesion between the reinforcement and matrix phases. While some of the continuous reinforcement filaments have near surface chemistries that are specially tailored to enhance this interfacial bond, similar progress has not yet been made in the case of the discontinuous reinforcement phases. This aspect of composite technology must be addressed to achieve the optimum properties attainable from discontinuous reinforcement.

In the following, two novel powder processes are described.

3.1 In-Situ Composites

In this approach to metal-matrix composite fabrication, elongated reinforcement phases are created by deformation processing of the composites, which consist of samples of elemental powders. During the working process, which may be extrusion, drawing or rolling, the constituents acquire an elongated, fibrous or lamellar morphology. To accomplish this, the reinforcing phase must be ductile under the deformation processing condition used.

The strength of nickel and tungsten in-situ composite is at least as great as a similarly worked directionally solidified alloy of the same composition. The nickel Tungsten in-situ composite contains Tungsten particles which are elongated into fibers during deformation.

The in-situ composite fabrication technique is not universally applicable to all metallic systems, and some restrictions apply to the properties of the second phase, particularly if the second phase is brittle at the working temperature.

Another factor that affects the ability to fabricate in-situ composites is the disparity in the flow stress of the constituents. Reinforcing-phase (i,e., the minor constituent) particles having a much higher flow stress than the matrix phase will not elongate into fibers or platelets during working, even when very high plastic strains are imposed. An example of such a system is Cu-11.3 weight percent Mo which, at true strains of approximately 7, still retained the molybdenum particles at near their original morphology. Presumably, if the matrix phase possessed a high work hardening rate, its flow stress could have been increased during working to the point where it would have caused deformation of the molybdenum particles.

Despite the above limitations, fibrous composites made using this technique can show unexpectedly large positive deviations in strength compared with rule-of-mixtures as shown by the Cu-16 volume percent Fe system. Significant deviations in strength from the rule of mixtures begin as early as true strains of approximately 2; and, at a true strain of approximately 5-6, the observed strength can be as much as 50 percent above the rule-of-mixture value.

For certain composite materials applications, the approach described above may offer significant advantages such as the following:

- The metallic constituents making up the composite are inexpensive relative to nonmetallic reinforcement.
- The composite can be formed by traditional metalworking operations.
- Thermal expansion mismatch between the metallic reinforcement and matrix is minimized, compared with nonmetallic reinforcement in a metallic matrix.
- Much higher strengths than predicted by the rule-of-mixtures can be achieved.

3.2 Spray Casting

Singer and Osprey processes, involving spray casting techniques, are based on conventional gas-atomization technology. In these processes, a molten metal stream is impinged by a gas stream to create particulate. Rather than allowing the particulate to solidify, as is done in the gas atomization of metal powders, a substrate is placed in the path of the particulate. The molten particles collide with the substrate and a metallic preform is built up. These techniques can be classified as either powder or casting techniques since they combine both processes.

Recently, Singer and Ozbeck used a spray codeposition process to prepare particulate reinforced composites. In their study they introduced various reinforcement phases into the atomized stream of molten metal. In this way they were able to build up a spray-cast strip structure that contained the reinforcement phase in a fairly uniform dispersion with the metallic matrix.

Incorporation of the reinforcement phase into the matrix does not occur until the reinforcement phase is trapped by molten matrix particles impinging the substrate. When impingement occurs, heat extraction from the splatted matrix particles is very rapid; and the fairly high solidification rate, combined with the fact that the reinforcement phase is in contact with the molten metal for only a very short time, greatly reduces the amount of interfacial reaction that can occur. This in turn minimizes the formation of brittle interfacial phases that sometimes degrade the properties of a composite.

Full density is not achieved during spray codeposition, and subsequent hot and cold rolling need to be used to densify the material. The distribution of all the phases tried, including sand, graphite and silicon carbide, appeared to be quite uniform despite the density variations. This feature of the process results from introducing the reinforcement phase into the atomized metal stream and entrapment of the reinforcement when the two components impinge on the substrate.

4. SOLIDIFICATION PROCESSING OF METAL-MATRIX COMPOSITES

Solidification processing of metal-matrix composites represents one of the simplest methods of producing metal-matrix composites. Cast irons and aluminum-silicon alloys are in a sense phase diagram redirected metal-matrix composites. Unidirectional solidification of eutectics can produce fiber reinforced composites in a single step. However, these are phase diagram restricted.

Modern cast metal-matrix composites which are not restricted by phase diagrams are made by introducing fibers or particles in molten or partially solidified metals followed by casting of these slurries in molds. Alternately, a preform of fibers or particles is made and it is infiltrated by molten alloys, which then freeze in the interfiber spaces to form the composite. In both these processes wetting between molten alloys and dispersoids is necessary. The cast metal composites made by dispersing pretreated particles in the melts followed by solidification are given in Table 3. In addition, several short fiber and long fiber reinforced metal-matrix composites have been made by casting techniques.

Continuous fiber reinforced Gr/Mg, Gr/Al, and several other cast FRMs are valuable structural materials since they combine high specific strength and stiffness, with a near-zero coefficient of thermal expansion, and high electrical and thermal conductivities. The primary difficulty with fabricating these cast fiber-reinforced metals is the poor wetting and bonding between fibers and metals. However, compatibility and bonding between the fiber and the metal in these systems are induced by chemical vapor deposition of a thin layer of Ti and B, or oxides like silica or metals like nickel, onto the fibers to achieve wetting. The flexible coated fibers may then be wound or laid-up and held in place with a removable binder for selective reinforcement. They are then incorporated into Mg by casting near-net shape structures by pressure infiltration of Mg. Complex structural components with high volume fraction graphite fibers can be fabricated in this manner in a foundry. High-strength, high-stiffness fiber FP (100% polycrystalline

TABLE 3A

Selected Potential Applications of Cast Metal-Matrix Composites

Composite	Applications	Special Features
Aluminum/graphite	Bearings	Cheaper, lighter, self-lubricating conserve Cu, Pb, Sn, Zn, etc.
Aluminum/graphite, aluminum/aAl_2O_3, aluminum/SiC-Al_2O_3	Automobile pistons, cylinder liners, piston rings, connecting rods	Reduced wear, antiseizing, cold start, lighter, conserves fuel, improved efficiency
Copper/graphite	Sliding electrical contacts	Excellent conductivity and anti-seizing properties
Aluminum/SiC	turbocharger impellers	High-Temperature use
Aluminum/glass or carbon microballoons		Ultralight material
Magnesium/carbon fiber	Tubular composites for space structures	Zero thermal expansion, High-temperature strength, good specific strength and specific stiffness
Aluminum/zircon, aluminum/SiC, aluminum/silica	Cutting tools, machine shrouds, impellers	Hard, abrasion-resistant materials
Aluminum/char, aluminum/clay	Low-cost, low-energy materials	

TABLE 3B

Matrix-Dispersoid Combinations Used to Make Cast Particulate Composites

Matrix	Dispersoids	Size	Amount
Aluminum Based	Graphite Flake	20-60 μm	0.9-0.815%
	Graphite Granules	15-100 μm	1-8%
	Carbon Microballoons	40 μm, thickness 1-2 μm	
	Shell Char	125 μm	15%
	Al_2O_3 Particles	3-200 μm	3-30%
	Al_2O_3 Discontinuous	3-6 mm long, 15 μm dia	0-23 Vol.-%
	SiC Particles	16-120 μm	3-20%
	SiC Whiskers	(5-10 μm)	10%, 0-0.5 Vol.-%
	Mica	(40-180 μm)	3-10%
	SiO_2	(5-53 μm)	5%
	Zircon	40 μm	0-30%
	Glass Particles	100-150 μm	8%
	Glass beads (spherical)	100 μm	30%
	MgO	40 μm	10%
	Sand	75-120 μm	36 Vol.-%
	Tic Particles	46 μm	15%
	Boron Nitride Particle	46 μm	8%
	Si_2N_4 Particle	40 μm	10%
	Chilled Iron	75-120 μm	36 Vol.-%
	ZrO_2	5-80 μm	4%
	TiO_2	5-80 μm	4%
	Lead		10%

TABLE 3B (continued)

Matrix-Dispersoid Combinations Used to Make Cast Particulate Composites

Matrix	Dispersoids	Size	Amount
Copper Based	Graphite		
	Al_2O_3	11 µm	Vol fraction 0.74
	ZrO_2	5 µm	2.12 Vol.-%
Steel	TiO_2	8 µm	
	CeO_2	10 µm	
	Illite Clay	753 µm	3%
	Graphite Microballoons		

α-Alumina)/Mg composites containing up to 70 vol. % fiber FP have been prepared by a pressure infiltration process.

For non-wetting metals, fiber FP is coated with the metal by vapor deposition or by electroless plating, prior to infiltration. Coatings of Ti-B also have been used for Gr/Al, fiber FP/Al and FP/Pb metal-matrix composites. However, from the standpoint of ease of fabrication and cost, modification of matrix alloy by addition of small amounts of reactive elements like Mg, Ca, Li or Na is preferred. Fiber FP reinforced Al, Cu, Pb and Zn composites as well as several particle filled metal-matrix composites have been synthesized by using reactive agents.

Continuous adherent metallic coatings (e.g., Cu and Ni) on several non-wetting particles such as graphite, shell char and mica improve the melt-particle wettability and allow high percentages of these[1] particles to be introduced in the solidified castings. The wetting properties of ceramics by liquid metals are governed by a number of variables such as heat of formation, stoichiometry, valence electron concentration in the ceramic phase, interfacial chemical reactions, temperature and contact time.

Therefore, while metal-matrix composites are not restricted by phase-diagram considerations (viz., fixed proportions, chemistry and morphology of solidifying phases), thermodynamic free energy and kinetic barriers still exist in their processing in the form of poor wettability and rates of mixing, and they need to be addressed for synthesizing these composites.

4.1 Casting Techniques, Microstructures, and Properties

A basic requirement of foundry processing of MMCs is initial intimate contact and intimate bonding between the ceramic phase and the molten alloy. This is achieved either by premixing of the constituents or by pressure infiltration of preforms of ceramic phase. As mentioned earlier, due to poor wettability of most ceramics with molten metals, intimate contact between fiber and alloy can be promoted only by artificially inducing wettability or by using external forces to overcome the thermodynamic surface energy barrier and viscous drag. Mixing techniques generally used for introducing and homogeneously dispersing a discontinuous phase in a melt are:

1. Addition of particles to a vigorously agitated fully or partially solidified alloy. Figure 8 shows a schematic diagram of an agitation vessel using rotating impeller.
2. Injection of discontinuous phase in the melt with the help of an injection gun.
3. Dispersing pellets or briquettes, formed by compressing powders of base alloys and the ceramic phase, in a mildly agitated melt.
4. Centrifugal dispersion of particles in a melt. This has been done for carbon microballoons.
5. Spray casting of droplets of atomized molten metals along with particulates.on a substrate. This technique has been described in the previous section.

In all the above techniques, external force is used to (i) transfer a non-wettable ceramic phase into a melt, and (ii) create a homogeneous suspension in the melt. The uniformity of particle dispersion in a melt prior to solidification is controlled by the dynamics of particle movement in agitated vessels.

The melt-particle slurry can be cast either by conventional foundry techniques such as gravity or pressure die casting, centrifugal casting or by novel techniques such as squeeze casting (liquid-forging) and spray codeposition, melt spinning or laser melt-particle injection. The choice of casting technique and mold configuration is of central importance to the quality (soundness, particle distribution, etc.) of a composite casting since the suspended particles experience buoyancy driven movement in the solidifying melt until they are encapsulated in the solidifying structure by crystallizing phases. Particles like graphite, mica, talc, porous alumina, and hollow microballoons are lighter than most Al alloys and they tend to segregate near the top portion of gravity castings, leaving behind a particle-impoverished region near the bottom of the casting. Similarly, heavier particles such as zircon, glass, SiC, SiO_2, TiO_2 and ZrO_2 tend to settle down and segregate near the bottom portion of the gravity castings.

The spatial arrangement of the discontinuous ceramic phase in the cast structure principally determines the properties of the cast composite. The distribution of phases depends on the quality of melt-particle slurry prior to casting and the processing variables, including the cooling rate, viscosity of solidifying melt, shape, size and volume fraction of particle, particle and melt specific gravities, and their thermal and chemical properties, interactions of freezing solid with particles and presence of any external forces during solidification. The various techniques used to solidify melt-particle slurries are discussed below.

4.1.1 Sand Castings

The slow freezing rates obtained in insulating sand molds permit considerable buoyancy-driven segregation of particles. This leads to preferential concentration of particles lighter than Al alloys (e.g., mica, graphite, porous alumina) near the top surface of sand castings and segregation of heavier particles (sand, zircon, glass, SiC, etc.) near the bottom part of castings. These high-particle-volume fraction surfaces serve as selectively reinforced surfaces, for instance, tailor-made lubricating or abrasion-resistant contacting surfaces, for various tribological applications.

4.1.2 Die Castings

The relatively rapid freezing rates in metallic molds generally give rise to more homogeneous distributions(-SOUTH-)cles in cast matrix. Figures 9 and 10 show a microstructure of a permanent mold gravity die casting of Al alloys containing dispersions of graphite and zircon particles.

4.1.3 Centrifugal Castings

Solidification in rotating molds of composite melts containing dispersions of lighter particles, like graphite, mica, and porous alumina, exhibits two distinct zones--a particle rich zone near the inner circumference for lighter particles and a particle-impoverished zone near the outer circumference. The outer zone is particle rich if the particles like zircon or silicon carbide are heavier than the melt (Fig. 11); the outer zone is abrasion resistant due to these hard particles.

Due to centrifugal acceleration in rotating molds, the lighter graphite and mica particles segregate near the axis of rotation producing high particle volume-fraction-surfaces for bearing or cylinder liner applications. The thicknesses of these particle rich zones remain adequate for machining. Up to 8% by weight mica and graphite, and up to 30% by weight zircon, particles could be incorporated in selected zones of Al alloy castings by this technique.

4.1.4 Compocasting

Particulates and discontinuous fibers of SiC, alumina, TiC, silicon nitride, graphite, mica, glass, slag, MgO and boron carbide have been incorporated into vigorously agitated partially solid aluminum alloy slurries by a compocasting technique. The discontinuous ceramic phase is mechanically entrapped between the proeutectic phase present in the alloy slurry which is held between its liquidus and solidus temperatures. Under mechanical agitation, such an alloy slurry exhibits "thixotropy" in that the viscosity decreases with increasing shear rate and appears to be time-dependent and reversible. This semi-fusion process allows near net-shape fabrication by extrusion or forging since deformation resistance is considerably reduced due to the semi-fused state of the composite slurry. Figure 12 is a scanning micrograph of a compocast composite showing a random planer arrangement of alumina fibers.

4.1.5 Pressure-Die Casting

Pressure die-casting of composites allows larger-sized, more intricately shaped components to be rapidly produced at relatively low pressures ($\leq$ 15 MPa). Pressurized gas and hydraulic ram in a die-casting machine have been employed to synthesize porosity-free fiber and particle composites. It has been reported that high pressures, short infiltration paths and columnar solidification toward the gate produced void-free composite castings. The pressure die cast particle composites exhibit lower bulk and interfacial porosities, more uniform particle distribution, and less agglomeration of particles. High concentrations (60 wt. % or more) of zircon ($ZrSiO_4$) particles can be achieved in pressure die-cast Al-Si-Mg alloys. Pressure die castings of LM 13* - 7 wt. % graphite and Al-(4-12%)Si-(0.5-10%)Mg-alumina particle composites showed considerable improvement in particle distribution, particle-matrix bonding and elimination of porosities.

4.1.6 Squeeze Casting

Squeeze casting or liquid forging of metal-matrix composites is a recent development which involves unidirectional pressure infiltration (pressures ~ 70-200 MPa) of fiber-preforms or powder-beds by alloy melts, to produce void-free, near net-shape castings of composites (Fig. 13). The Saffil fiber reinforced pistons of aluminum alloys made by Toyota have been in use for several years in heavy diesel engines. The processing variables governing evolution of microstructures in squeeze cast MMCs are:

(i) fiber and melt preheat temperature, (ii) infiltration speed and pressure, and (iii) interfiber spacing.

If the metal or fiber temperature is too low, poorly infiltrated or porous castings are produced; high temperatures promote excessive fiber/metal reaction leading to degradation of casting properties. A threshold pressure is required to initiate liquid metal flow through a fiberous preform or powder-bed to overcome the viscous friction of molten pressure moving through reinforcements and the capillary forces if there is inadequate wetting between the melt and the fibers. Several theoretical analyses to model and analyze the frictional forces have been proposed. These relate the infiltration velocity to applied pressure, capillarity, viscosity and interfiber spacing as well as fiber preform permeability, length, diameter and geometry.

Alternatively, whiskers or particles may be mixed with molten metal prior to squeeze casting. Al alloy composites containing SiC and Al_2O_3 powders, σ-Alumina (Saffil) fibers, and silicon nitride whiskers have been fabricated by the squeeze casting process.

SiC whiskers (0-10 μm dia. 5.50 mm in length) have been dispersed in cast Al-(4-5)% Cu alloy matrix by a squeeze casting technique. The wettability problem was overcome by codispersing SiC whiskers and Al alloy powder (200 μm avg. size) in an aqueous solution of isopropyl alcohol, followed by infiltration, compaction into small briquettes and vacuum degassing. These briquettes were disintegrated into a mechanically stirred base alloy melt followed by squeeze casting under a pressure of 207 MPa. The resulting strengthening effects of composites are attributable to several factors, e.g., fine grain size, elimination of bulk and interfacial porosities, increased solid solubility due to hydrostatic pressure and the presence of high-strength SiC whiskers. Figure 13 shows a schematic diagram illustrating the principle of a squeeze casting process for particle composites.

Plate and tubular composites of Al alloys containing continuous or discontinuous SiC fibers (nicalon) can be synthesized by a squeeze casting technique. The SiC yarn consisting of about 500 monofilaments (13 μm avg. dia.) is mechanically wound around a steel frame or aligned undirectionally in an Al vessel. In the case of discontinuous SiC fibers, fiber can be chopped and packed in the vessel. The vessel with fiber is preheated in air for good penetration of molten metal matrix into interfiber space. Then the vessel is put into the mold which is preheated to 500 - 700 K. The fiber volume fraction of composites is controlled by selecting the winding conditions (for continuous fiber) or packing conditions (for discontinuous fibers) before casting.

4.1.7 Vacuum Infiltration Process

Several fiber reinforced metals (FRM) are prepared by the vacuum infiltration process. In the first step the fiber yarn is made into a handleable tape with a fugitive binder in a manner similar to producing a resin matrix composite prepreg. Fiber tapes are then laid out in the desired orientation, fiber volume fraction and shape, and are then inserted into a suitable casting mold. The fugitive organic binder is burned away and the mold is infiltrated with molten matrix metal.

The liquid infiltration process used for making graphite/Al composite differs from the above process of preparing fiber FP/Al composites. Graphite fibers are first surface treated and then infiltrated with molten metal in the form of wires and these coated graphite wires are then diffusion bonded together to form larger sections.

4.1.8 Investment Casting

In investment casting of metal-matrix composites, filament winding or prepreg handling procedures developed for fiber reinforced plastics (FRPs) are used to position and orient the proper volume fraction of continuous fibers within the casting. The layers of reinforcing fibers are glued together with an appropriate plastic adhesive (fugitive binder) which burns away without contaminating either the matrix or the fiber-matrix interface. These layers are stacked in the proper sequence and orientation, and the fiber preform thus produced is either infiltrated under pressure or by creating a vacuum in the permeable preform. Continuous graphite fiber reinforced Mg has been produced by this method.

4.1.9 Microstructures

The primary solid (α-Al) grows by rejecting solute in the melt while the discontinuous ceramic phase tends to restrict diffusion and fluid flow; α-Al tends to avoid it as shown in Fig. 9. Primary silicon and the eutectic in Al-Si alloys tend to concentrate on particle or fiber surface.

The discontinuous ceramic phase also tends to modify or refine the structure, e.g., eutectic Si in Al-Si alloys gets modified whereas primary Si is refined when solidification occurs in the presence of high volume fraction of ceramic phase. At sufficiently slow cooling rates when the secondary (DAS) in the unreinforced alloy is comparable to interfiber spacing, the grain size becomes large in comparison with interfiber spacing. In this case fibers do not enhance the nucleation of the solid phase. With a further decrease in the cooling rates, the extent of microsegregation is reduced; and, at sufficiently slow cooling rates, the matrix can be rendered free of microsegregation.

4.1.10 Properties and Applications

Modern fiber-reinforced or particle-filled metal-matrix composites produced by foundry techniques find a wide variety of applications due to the low cost of their fabrication and the specificity of achievable engineering properties. Some of these properties are high longitudinal strengths at normal and elevated temperatures, near-zero coefficients of thermal expansion, good electrical and thermal conductivities, excellent antifriction, antiabrasion, damping, corrosion and machinability.

The high temperature strength of MMCs is enhanced by reinforcements such as SiC fibers or whiskers or continuous Borsic (B fibers coated with SiC) fibers. Carbon/Al MMCs combine very high stiffness with a very low thermal expansion due to almost zero expansion coefficient of C fibers in the longitudinal direction. Graphite/Mg composites also have a nearly zero expansion coefficient.

In the case of particle-filled MMCs, the mechanical properties are not significantly altered, but tribological properties show marked improvements. Soft solid lubricant particles like graphite and mica improve antiseizing properties of Al alloys whereas hard particles like SiC, alumina, WC, TiC, zircon, silica, and boron carbide greatly improve the resistance to abrasion of Al alloys. Particle additions can also give rise to better damping and conductivity of the matrix alloy. For example, the damping capacity of aluminum and copper alloys is considerably enhanced when graphite powder is dispersed in them. Hitachi, Ltd., of Japan has produced a high damping MMC of graphite/Al or Cu under the name (GRADIA) whose damping capacity is considerably more stable at high temperatures than conventional vibration insulating alloys, including cast irons. Sliding electrical contacts made from the same alloy GRADIA (Cu-20 graphite) perform better than sintered materials of the same materials generally used, since the alloy combines excellent resistance to seizure with high electrical conductivity.

Figures 14 and 15 show photographs of fan bushes, journal bearings and several other components made from cast Al-Si-graphite particle composite and cast Al-Si-silicon carbide composite. The use of graphite in automobile engine parts considerably reduces the wear of cylinder liners as well as improves fuel efficiency and engine horsepower at equivalent cost. The most promising application of cast graphitic-aluminum alloys is for bearings which would be cheaper and lighter in addition to being self lubricating compared to the bearings currently being made out of Cu, Pb, Sn and Cd containing alloys. Cast aluminum-graphite fan bushes experience considerably reduced wear as well as temperature rise during trial at 1400 rpm for 1500 hrs.

Cast aluminum-graphite alloy pistons used in single cylinder diesel engines with a cast iron bore reduce fuel consumption and frictional horse power losses. Due to its lower density, the use of aluminum graphite composite in internal combustion engines reduces the overall weight of the engine. Such an engine does not seize during cold start or failure of lubricant due to excellent antiseizing properties of graphitic-aluminum alloys.

Alloys with a dispersed ceramic phase are finding applications in impellers and other tribological systems which run at high temperatures where there is a possibility of failure of liquid lubricant. Cast Al alloys reinforced with ceramic phase are being tried out as turbocharger impellers which run at high temperatures.

5. THE CENTERS OF METAL-MATRIX COMPOSITE MATERIALS IN THE UNITED STATES AND SOME OF THE DEVELOPING COUNTRIES

The United States is one of the most actively involved countries in research in metal-matrix composites. University-based centers in the United States with substantial activity in processing metal-matrix composites include the Center for Processing and Characterization of Composite Materials at the University of Wisconsin--Milwaukee, the Massachusetts Institute of Technology, and the University of Virginia. Other university-based centers for composites include Drexel University, Carnegie Mellon University, University of Illinois, Michigan State University, Renesslaer Polytechnic, Pennsylvania State University, University of California at Santa Barbara, University of Texas, and Witchita State University. Several other universities are in the process of opening centers on composite materials with activity in metal-matrix composites.

The companies and organizations that are very active in the metal-matrix composites in the United States and Canada include the following:

- Aluminum Company of Canada, Dural Corporation, Kaiser Aluminum, Alcoa, American Matrix
- Northrup Corporation, McDonald Douglas, Allied Signal, Advanced Composite Materials Corporation, Textron Specialty Materials
- DWA Associates, MCI Corporation, Novamet
- Martin Marietta Aerospace, Oakridge National Laboratory, North American Rockwell, General Dynamics Corporation, Lockheed Aeronautical Systems
- Dupont, General Motors Corporation, Ford Motor Company, Chrysler Corporation, Boeing Aerospace Company, General Electric, Westinghouse

- Wright Patterson Air Force Base, Dayton, Ohio
- Naval Surface Warfare Center, Silver Spring, Maryland

While the United States had a lead in the use of metal-matrix composites in aerospace and defense weapon applications, Japan has taken the lead in using metal-matrix composites on a widespread basis and in large applications such as automotive. Toyota was the first company in the world to incorporate metal-matrix composite pistons in high speed diesel engines. There is intensive activity in metal-matrix composites in several other corporations and universities in Japan.

In Europe, recently a consortium on composite materials has been formed involving all European countries, with a special emphasis on metal-matrix composites. The countries which have strong activities in composites include England, France, Italy, Norway, Sweden and West Germany.

Among the developing countries, China and India have well established research activities in metal-matrix composites. China has set up a very large institute in composite materials with a heavy emphasis in metal-matrix composites. This year's international conference on composites materials, which is one of the major biannual worldwide meetings in composites, is being hosted in China. In China, work is going on in the area of casting and powder metallurgy processes for making metal-matrix composites.

India has had substantial activity in cast and powder produced metal-matrix composites. It has leadership in cast aluminum graphite composites for automotive applications, and can offer this technology to other developing countries. India has the requisite technology base in the metals industry and it can get into large-scale manufacture of metal-matrix composites, especially particulate composites. It has laboratory scale production capability for production of carbon fibers for metal-matrix composites.

List of a Few Institutes Working on Metal-Matrix Composites in a Developing Country (India)

National Physical Laboratory, CSIR, New Delhi, India
Indian Institute of Technology, New Delhi, India
Indian Institute of Technology, Kanpur, India
Regional Research Laboratory (Bhopal), CSIR, Bhopal, India
Regional Research Laboratory (Trivandrum), CSIR, Trivandrum, India
National Aeronautical Laboratory, CSIR, Bangalore, India
Vikram Sarabhai Space Center, Trivandrum, India
Indian Institute of Science, Bangalore, India
Banaras Hindu University, Varanasi, India
University of Roorkee, Roorkee, U.P., India

6. STATE OF THE ART IN METAL-MATRIX COMPOSITES AND RELEVANCE TO DEVELOPING COUNTRIES

Intensive research in metal-matrix composites started about thirty years ago to meet the increasing requirements of properties in aerospace materials to achieve higher speeds and higher temperature engines for higher efficiencies. Much of this research was concentrated on ceramic and carbon fiber reinforced metals made by processes of plasma spray and vapor disposition or diffusion bonding of foils with interspersed layers of fibers followed by hot pressing (Fig. 28). These multi-stage processes involve several steps, and combined with the cost of long expensive fibers like Boron and carbon, the cost of metal-matrix composites thirty years ago was several hundred thousand U.S. dollars per pound. Most of these metal-matrix composites were used in aerospace applications where weight savings were of paramount importance, and to some extent in selected weapons systems, where cost was no concern (Table 2).

During the last few years, several developments have occurred in metal-matrix composites which have great relevance to developing countries.

For instance, the costs of metal-matrix composites has come down enormously during this period. The costs of metal-matrix fiber reinforced composites has come down from several hundred thousand dollars per pound to order of a thousand dollars per pound at this time due to decrease in costs of continuous fibers. The continuous fiber reinforced metal-matrix composites, therefore, still remain quite expensive for wide spread use in developing countries, except for certain critical applications where enormous savings in energy or resources can be made. However, there has been a more dramatic decrease in the cost of metal-matrix discontinuous fiber composites. The costs of particulate composites like aluminum-silicon carbide have come down to the level of two to ten dollars per pound due to the feasibility of using inexpensive particulate reinforcements and the possibility of using conventional casting processes to produce these composites.

In the early part of development of metal-matrix composites, organizations had captive research and production, or contracted small scale production of small quantities of metal-matrix continuous fiber composites. For the first time in the last five years, there are some producers and suppliers of metal matrix-silicon carbide composites both by powder metallurgy processes and by castings route. For instance, one could today obtain aluminum matrix silicon carbide composites for two to five dollars per pound from Aluminum Company of Canada. In fact in the last six months, Alcan has announced putting up of two plants with a capacity to produce twenty five millions pounds of aluminum silicon carbide or aluminum alumina composites per year in Canada and USA, and it can ship ingots of composites which can be melted in conventional foundries and cast into components very much the same way as conventional aluminum alloys are cast from shipped primary ingots. Norsk Hydro in Europe also plans to become a supplier of cast aluminum-silicon carbide composites. A number of components including pistons, impellers, brake systems, and housings have been cast out of aluminum - silicon carbide composites. This type of cast composite will be the forerunner for widespread use of metal-matrix ceramic particle composites, and could make possible secondary processing and use of these composites even in the developing world. Dow Chemical can supply small samples of cast magnesium-silicon carbide or magnesium-alumina composites. Likewise DWA Associates and American Composites can supply powder metallurgy produced aluminum-ceramic particle, whisker and fiber composites. In addition, companies like Textron can supply metal-matrix composites with higher melting metals as matrices. There are also a large number of research laboratories which can supply small samples of high melting metal-matrix composites, and composites with intermetallic compounds as matrices.

In the area of applications, the first application in large scale automotive sector was by Toyota in Japan, which put out a ceramic fiber reinforced squeeze cast aluminum piston for high speed diesel engines. This has triggered a flurry of activity in making engine components out of cast metal-matrix components. There is a great deal of activity in trying to make pistons, connecting rods and other engine parts out of aluminum-ceramic fiber composites using conventional pressure casting. In fact, Dupont had done a considerable amount of work in this area several years ago involving squeeze infiltration of FP alumina fiber, and now there is intense activity in Japan. In addition to Toyota, several companies are producing squeeze cast pistons where the combustion bowl area of the pistons (which is subjected to very high temperatures) and the ring groove area (which is subjected to high wear) are reinforced by discontinuous ceramic fibers placed in the molds as preforms before casting. These low cost, large scale mass manufacturable cast metal-matrix composites represent the biggest potential for metal-matrix composite activity in developing countries. The ingredients to make these composites are available in, or can be imported into, most of these developing countries and the composite products made will be of immediate use in many developing countries. For instance, aluminum-silicon carbide composites can save considerable amounts of energy and fuel when used in transportation systems, and can free several of these developing countries from the requirements of importing critical strategic minerals and oil that are presently not available in many of these developing countries.

Another metal-matrix composite of relevance to developing countries is cast aluminum-graphite particle composites, which has been developed in India, U.S., Europe and Japan during the last fifteen years for anti-friction applications. It has been demonstrated that pistons, cylinder liners, and bearings can be made out of cast aluminum-graphite particle composites. The use of pistons and liners of aluminum-graphite particle composites has been shown to save considerable amounts of fuel in the internal combustion engines and reduction in wear of the pistons, rings, and the liners. Aluminum graphite particle composites can replace much more expensive and heavier bearings made out of bronzes and babbit metals. Many of todays bearing materials rely on dispersions of toxic metals like lead in the matrix of copper or tin alloys. The use of graphite in place of lead can eliminate the need for lead, therefore, reducing the cost, weight, and toxicity of presently used bearing alloys. While aluminum-graphite particle composites have not been produced in the U.S.A. and Europe, they will be very useful in most of the developing countries where petroleum and metals like lead, tin, and copper, are available at very high cost and have to be imported. The technology of aluminum-graphite particle composites consists of stirring pretreated graphite particles in the melts of aluminum alloys using very conventional foundry equipment, followed by casting, either in permanent molds, or centrifugal casting machines or in pressure diecasting; most of these technologies are available in most of the developing countries and therefore, such a technology can be practiced and can be productionized in the developing world without much difficulty, and the products could be immediately used in the local industry. Japan has production facilities to make aluminum-graphite and copper-graphite composites, and India and China have the requisite research base to get into production of these alloys.

In addition to the current use of metal-matrix composites in aerospace applications, weapon systems, in the last few years in the developed world, there is interest in using these components in automotive applications, in bicycles and sporting goods like tennis rackets and golf clubs. The developing world should watch the application of metal-matrix composites in these sectors, and derive lessons to use these composites in other sectors critical to raising the standards of living in respective countries instead of leisure goods. The needs of developing world are more in the area of housing, in the area of energy generation and transportation, instead of in faster cars or airplanes, or sporting goods, or aerospace or defense systems which are driving the development of metal-matrix composites in the developed world. There is a very large increase in metal-matrix composites research in some developing countries like China, India, Egypt, and some Latin American Countries like Brazil and Argentina. Exchanges of information between developing countries themselves will be of great value, since their experience would be of greater relevance to each other. The agencies concerned with International development, like U.N. and the World Bank, could greatly facilitate this exchange.

Another area of concern in developing countries in the composite materials area, is the lack of availability of reinforcements. The continuous fiber reinforcements remain very expensive, and their production cannot be set up easily in the developing world. The developing world should initially concentrate on in-situ composites made by unidirectional solidification or powder extrusion, where the reinforcements are produced in-situ during the processing itself, thus eliminating the need for expensive reinforcements. In addition, the developing world should concentrate on short fibers, or better yet on particle reinforced metal-matrix composites which are inexpensive and have large scale application possibilities. For instance, emphasis should be given on graphite particle reinforced metal-matrix composites since graphite is available either in mineral form or in manufactured form in a large number of developing countries; with the relatively easy availability of aluminum, the production of these composites can be set up very easily. Likewise attempts should be made to learn to use readily available mineral based fibers in these developing countries, for instance, attempts should be made to use naturally occurring alumino silicate fibers, or fibers that can be readily made by melt spinning of oxides. These are areas where the developing world can immediately get into the use and manufacture of metal-matrix composites. This learning experience with inexpensive particulate metal-matrix composites will also set the stage for the developing world to get into the area of high performance metal-matrix continuous fiber composites when they become common place in the developed world, and the possibility of using ultrahigh performance materials in the developing world increases, in the next few years.

7. ELEMENTS OF EDUCATION AND TRAINING IN METAL-MATRIX COMPOSITES FOR THE DEVELOPING WORLD

For the developing world to get into the position of manufacturing and using metal-matrix composites, it will be necessary to start teaching and research in design, processing, and use of composites, in selected institutions in developing countries, complimented by a United Nations sponsored International Training Institute. These would generate individuals who would be familiar with global knowledge on metal-matrix composites, and can readily learn to use these new family of materials for there own location specific oblems. In the absence of such indigenous manpower, trained personnel and infrastructure, there is the danger that the developed world imperatives in metal-matrix composites will continue to drive the development of these materials, and the progress will not be of much relevance to the developing world. The per capita availability of materials in developing countries is low and is a major constraint in raising living standards. Composite materials, specially metal-matrix composites, provide an opportunity to increase the supply of required materials at prices affordable in developing countries. However, it is necessary that scientists in developing countries are trained to explore the opportunities in metal-matrix composites for the development of their respective countries.

The science of design of composites involves prediction of properties of composites as a function of chemistry and structure of its constituents and processing. For example by changing the volume percentage and orientation of graphite fibers, magnesium graphite fiber composites with negative, zero or low positive coefficients of expansion can be designed. Subsequent to design of structure of composite component, the processes to manufacture and test the composites have to be designed and simulated. Process design requires considerable data base on manufacture of similar composites. Design of tests requires considerable data base on relationships between structure--properties and performance on the specific composite in question.

In addition to the information generated in the west, the developing country scientists must be trained to use local resources and facilities to design, fabricate and test metal-matrix composite materials for use in their own environments. In certain developing countries, there are large agricultural waste products like paddy husk available; conversion of these resources into high performance whiskers like silicon carbide for reinforcements in metal-matrix composites would be an important imperative for them.

The newly emerging metal-matrix composites are based on most abundant elements (for instance carbon, aluminum, silicon, nitrogen, oxygen, magnesium to make carbon reinforced aluminum, silicon carbide reinforced magnesium, silicon carbide reinforced alumina) which are available in all countries quite equitably. Therefore the development of these composite materials will free several countries from resource constraints in manufacture of advanced materials. This, however, presents a threat to some developing countries whose economies are based on export of certain minerals like copper ores. The scientists in developing countries should be trained to analyze, and react to opportunities and threats from developments in metal-matrix composites.

Once the chemistry, structures, shape, size, volume percentages of constituents is decided by structure property relationships, the next step is to design the process to synthesize the composites. Process design is as important as product design. After the process design, the next element is design of testing and inspection procedures of composites to simulate long term performance in short term testing. The process design for developing countries should be of the type which can be used for manufacture in the low technology environment which often prevails in these countries. Computer simulation of performance of composites and the process to manufacture them, could save scarce resources in developing countries in terms of materials and energy wasted in trials. These aspects of design and simulation should form essential features of training in metal-matrix composites which could be imparted through the following elements.

7.1 Elements of Training Program in Metal-Matrix Composites

1. Lectures by program coordinators and permanent staff of the training center on principles of composite materials science. A possible text used can be Composite Materials by K. K. Chawla, American Elsevier.
2. Lectures by guest faculty working on metal-matrix composites in other institutes in developed countries.
3. Lectures by guest faculty familiar with developing countries. These could be people who are either working in a developing country or are familiar with developing country environment in relation to metal-matrix composite materials.
4. Demonstration of computer applications of design of structure, processing, properties and testing of metal-matrix composite materials. This could be done using the software available through organizations listed in this report which can be operated on personal computers and other stand alone computers available in developing countries.The participants from developing countries should be encouraged to bring material on their resources and infrastructure, and typical applications that have higher priority in their countries. Development of metal-matrix composites to

meet basic human needs using local resources should have high priority. Some examples would be composites made with local resources like mined or manufactured graphite particles, sand, aluminosilicates including clay, mica, and carbonized and pyrolized plant-based resources like natural fibers, rice husk and equisetum which can yield silicon carbide whiskers for reinforcement of composites. The work done on aluminum-graphite and aluminum-shell char composites at Regional Research Laboratories of CSIR (India) at Trivandrum and Bhopal can serve as an illustrative material to stimulate similar thinking on using local resources to make metal-matrix composites.

5. Video courses on composites available from ASM International and other organizations.
6. Laboratory demonstration of basic manufacturing processes including powder processing, vapor phase consolidation, and casting techniques. The training centers could collect samples of components of composites made in different parts of the world and demonstrate their properties and performance.
7. Demonstration of instrumentation for process control and for inspections and testing of composite materials. This could be part of an overall training in the use of modern instrumentation and sensor equipment with feedback circuits and intelligent processing using expert systems, for materials design, selection and processing. Modern instrumentation including electron microscopes, microprobes, chemical analyzes with high resolution and surface analytical techniques like ESCA, AUGER, SSNMR, SIMS, and automated testing equipment should be a part of overall exposure to advanced instrumentation for design, processing and use of metal-matrix composites.

8. A long term and continuing mechanism must be established through which summary of new information base can be supplied to the scientists working on composites in developing countries. The participants should be encouraged to write back and consult with the center on the opportunities and experience on designing, manufacturing and using composites using local resources in their respective countries. This growing body of information base could be shared by all developing countries.

8. SUMMARY

Metal-matrix composites with tailored properties have the potential of becoming one of the fastest growing family of new materials which can have large impacts on developing countries. At this time the best performing and most expensive metal-matrix composites are being considered for high value-added, relatively low-volume military and aerospace applications. However, automotive and other engine and electro mechanical energy applications which require lower cost and higher part volume, are now closer to commercialization, and these are of greatest interest to developing countries. With continued development of composite manufacturing processes and improvements in alloy design, including the possible use of particulate composites, high performance and low cost will draw closer together. The developments in the near future will involve using the casting and powder processes to produce tailored interfaces, new matrix alloys which will yield higher ductility and toughness along with higher strengths in discontinuous reinforcement composites. The science of predicting properties and performance of metal-matrix particulate composites will gain considerable ground. At this time the low cost particulate composites such as cast aluminum-alumina, aluminum-silicon carbide and aluminum-graphite composites appear to be most promising for the developing world. These composites can be readily produced in the developing countries using readily available ingredients and simple techniques, and can be used in energy and materials saving applications. It will be best to begin with simple applications like bearings, pistons, cylinder liners and then move into other high performance components. The developing world should pay special attention to the possible use of metal-matrix composites in energy, housing, and transportation sectors which are of high priority including solar photovoltaics, semiconductor and superconductor industries. Developing countries such as India and China have a good research and industrial base for producing metal-matrix composites, mechanisms should be developed to expand this capability into other developing countries through expansion of education and training in metal-matrix composites and through exchange of information between developing countries themselves. Developing countries should impart suitable training in design, processing, manufacture and use of composites made from local resources using locally available manufacturing infrastructure.

9. INFORMATION RESOURCES ON METAL-MATRIX COMPOSITES

The following journals and publications have a good repository of information on metal-matrix composites:

(1) Journal of Composite Materials

(2) Composites

(3) Proceedings of the "International Conferences on Composite Materials." Six of these have been held and the seventh will be held in China.

(4) Composite Materials Handbook by ASM International

(5) Video courses on Composites from ASM International

(6) Metallurgical Transactions (Journal by ASM-AIME)

(7) Materials Science and Engineering (Journal)

(8) Journal of Materials Science (Journal form the UK)

(9) Proceedings of Composites Conferences Organized by ASM International AIME, SAMPE, American Society for Composites and the Journals brought out by these societies.

(10) Proceedings and lecture notes from a large number of short courses organized in China, Europe, India, Japan and the United States on Composite Materials.

(11) Powder Metallurgy International (Journal)

(12) Metals Abstracts

(13) Engineered Materials Abstracts

(14) Chemical Abstracts

In addition to the above open literature, a large number of reports on commercial prospects of metal-matrix composites have been written by several consulting companies in the United States and are available at a price to subscribing organizations.

Several university centers on composites including the University of Delaware's Center of Composites publishes news letter which lists activities going on in respective centers. In addition, information is available in the United States from NTIC and MMIAC which has government information banks on composites.

APPENDIX I. SELECTED BOOKS ON METAL-MATRIX COMPOSITES

1. Advanced Composites: The Latest Developments. Proceedings of the Second Conference on Advanced Composites, Nov. 18-20, 1986, Dearborn, Michigan, ASM International.

2. Composite Technology. Proceedings of the Annual Conference on Materials Technology, April 14-15, 1988. Edited by Margaret Genisio, Materials Technology Center, Southern Illinois University at Carbondale, Illinois.

3. Testing Technology of Metal-Matrix Composites. Ed. Peter R. Digiovanni and Norman Ray Adsit, ASTM, 1988, Philadelphia, PA 19103.

4. Interfaces in Metal-Matrix Composites. Proceedings of Symposium Held at Annual Tech Meeting of Metallurgical Society in New Orleans, Louisiana, March 2-6, 1986, Ed. A. K. Dhingra and S. G. Fishman, The Metallurgical Society AIME, Warrendale, PA, USA.

5. Mechanical Behavior of Metal-Matrix Composites. Proceedings of a Symposium of ASM held at the 111th AIME Meeting, Dallas, Texas, Feb. 16-18, 1982. E. John E. Mack and Maurice F. Amateau, The Metallurgical Society of AIME.

6 K. K. Chawla, Composite Material Science and Engineering. 1987, Materials Research and Engineering. Ed. B. Ilshner and N. J. Grant. Springer Verlag, New York, Berlin, Heidelberg London, Paris, and Tokyo.

7. Cast Reinforced Metal Composites," Proceedings of the International Symposium on Advances in Cast Reinforced Metal Composites. 1988, World Material Congress, Chicago Illinois, Ed. S. G. Fishman and A. K. Khingra, ASM International, Metals Park, Ohio.

8. Engineered Materials Handbook. Vol. 1, Composites ASM International, 1987, Metals Park, Ohio.

9. Advanced Materials Conference Proceedings. Dec. 2-4, 1985, Dearborn, Michigan, ASM, Metals Park, Ohio.

10. Proceedings of the Fifth International Conference on Composite Materials. ICCMV, July 29-30, Aug. 1, 1985, Ed. W. C. Harrigan Jr., I. Strife, A. K. Dhingra, The Metallurgical Society of AIME. (Also proceedings fo the sixth and seventh ICCM Conferences). The ICCM VIII will also have proceedings.

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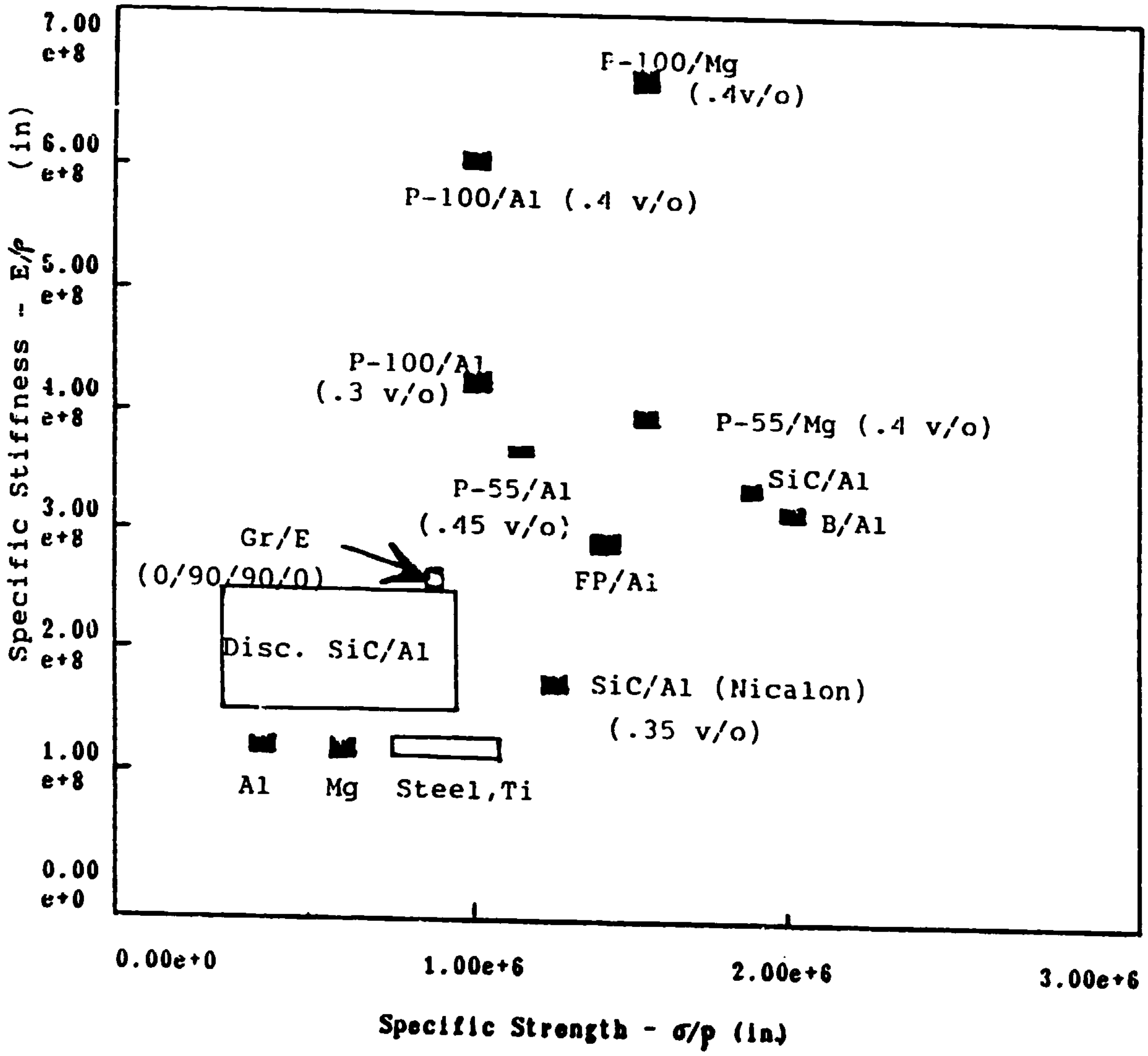

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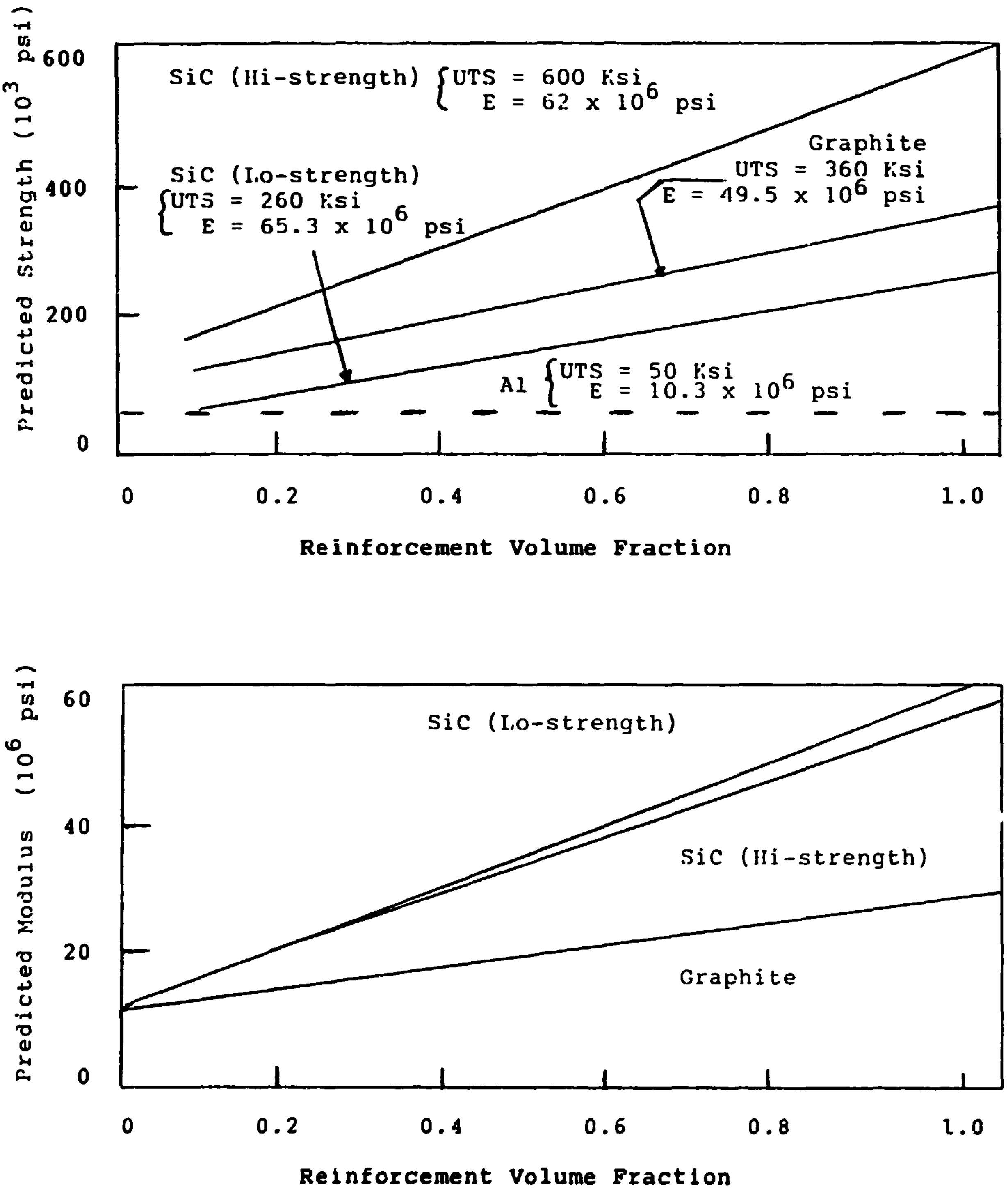

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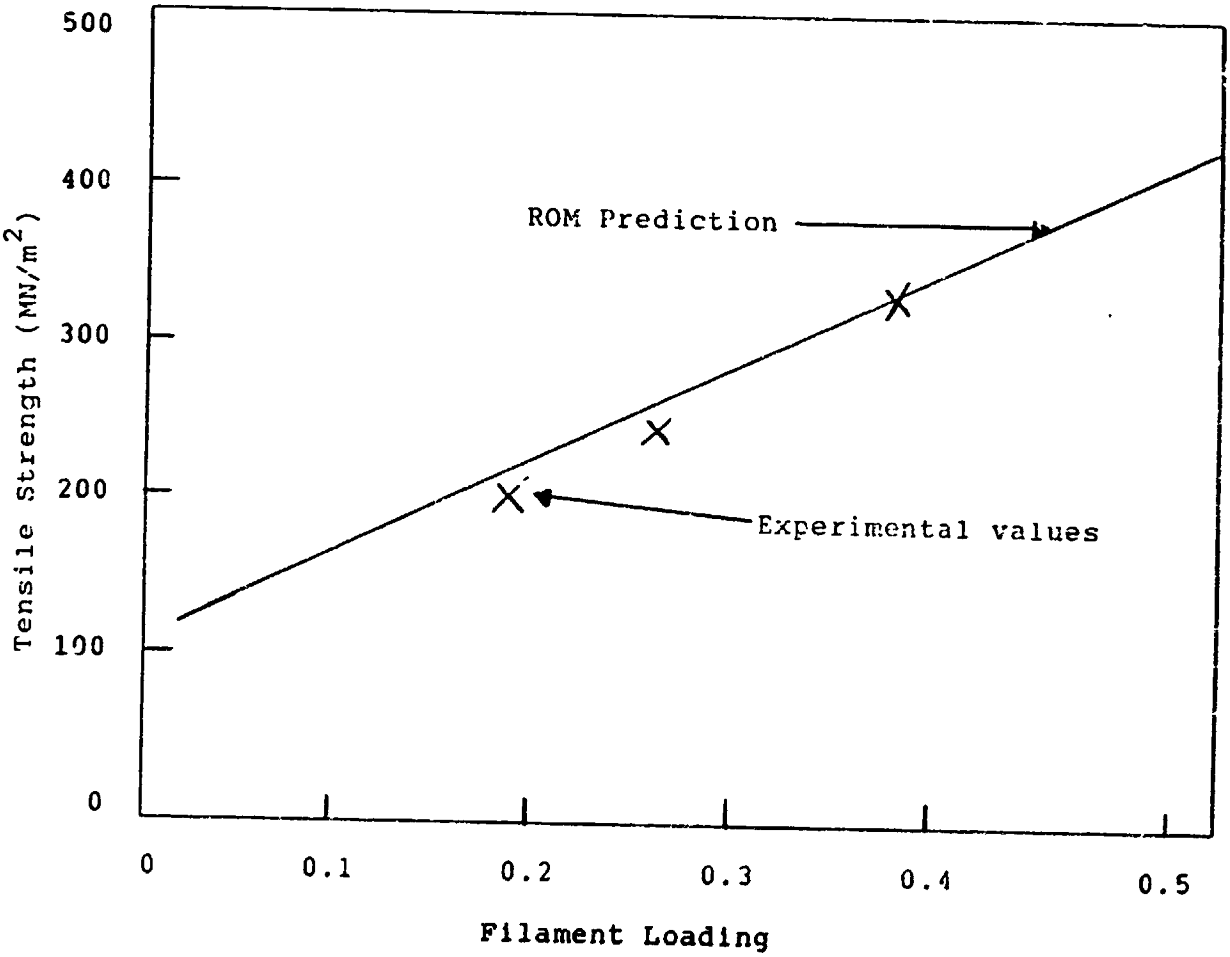

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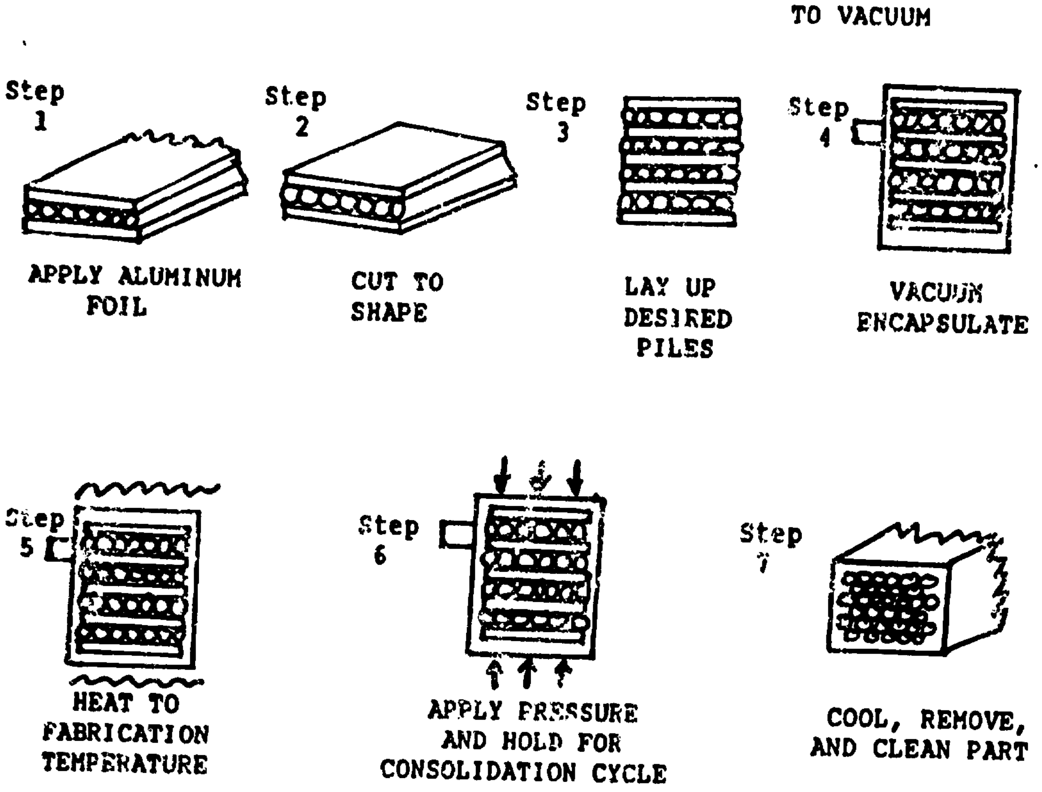

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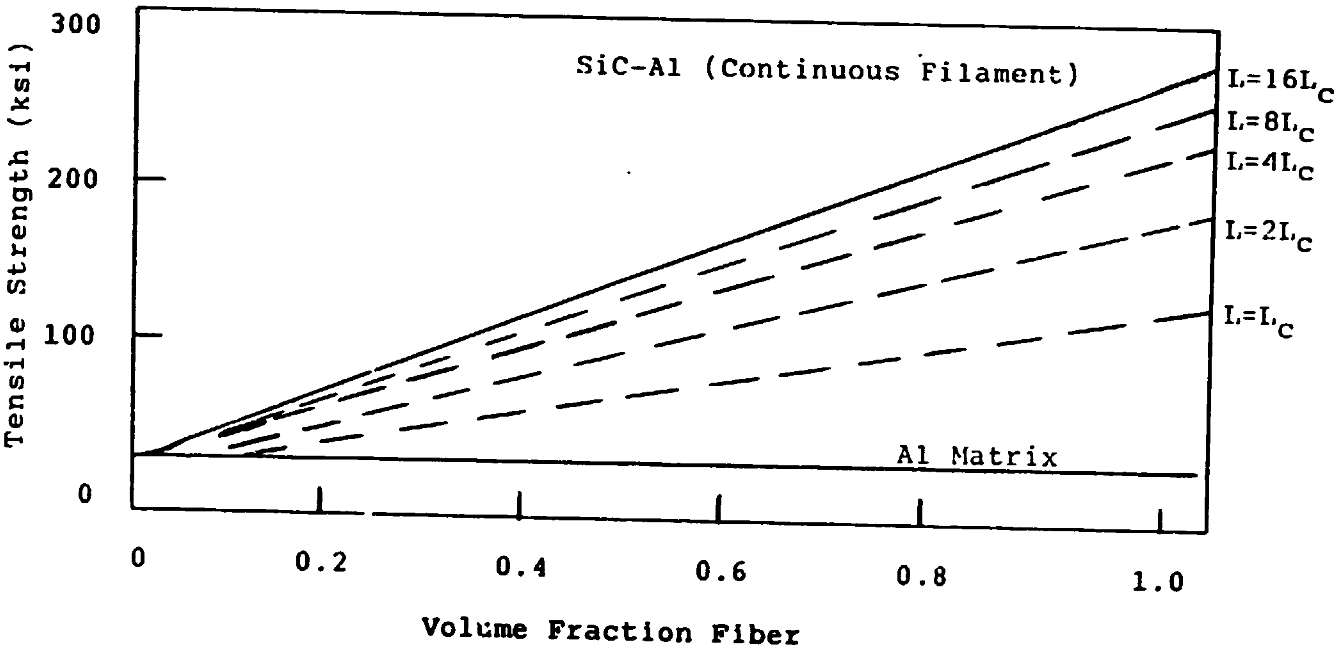

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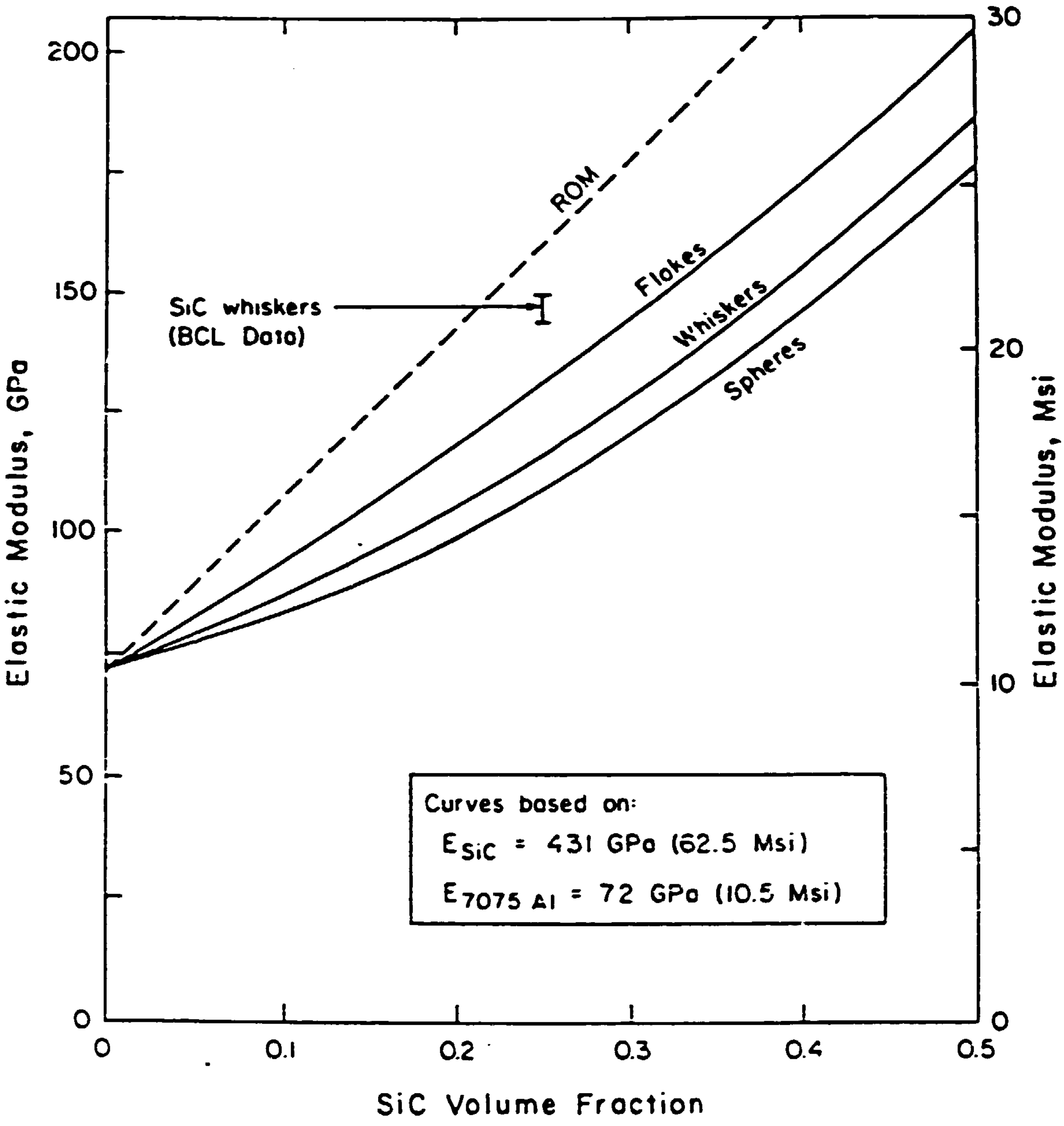

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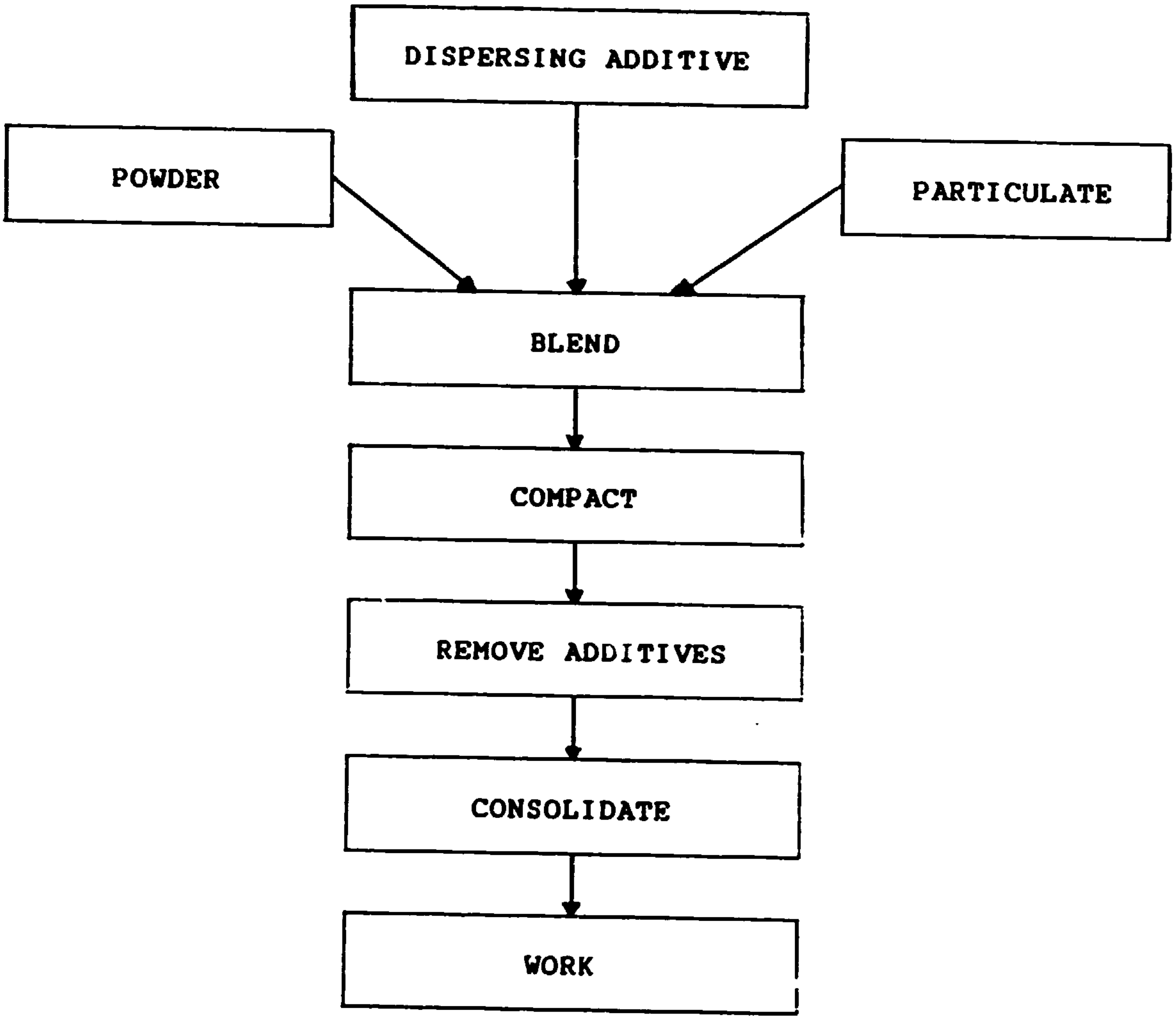

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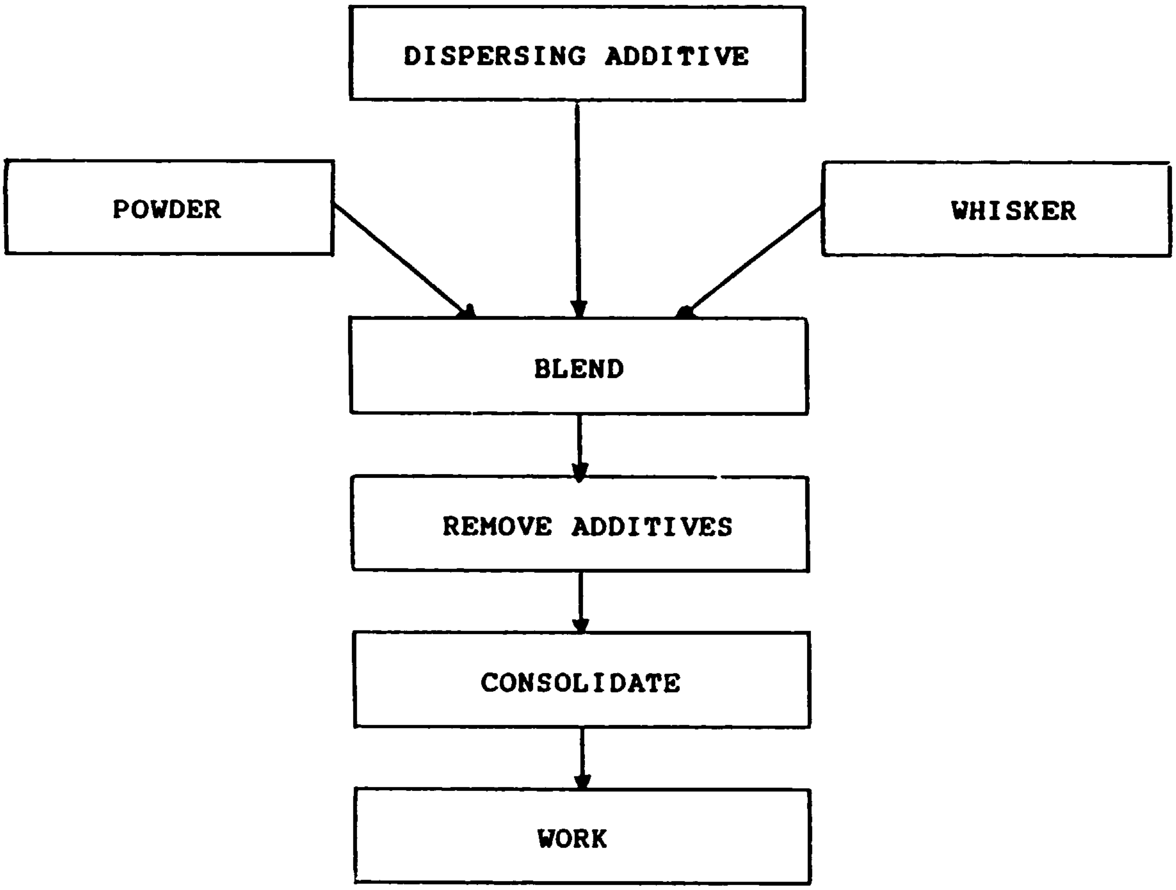

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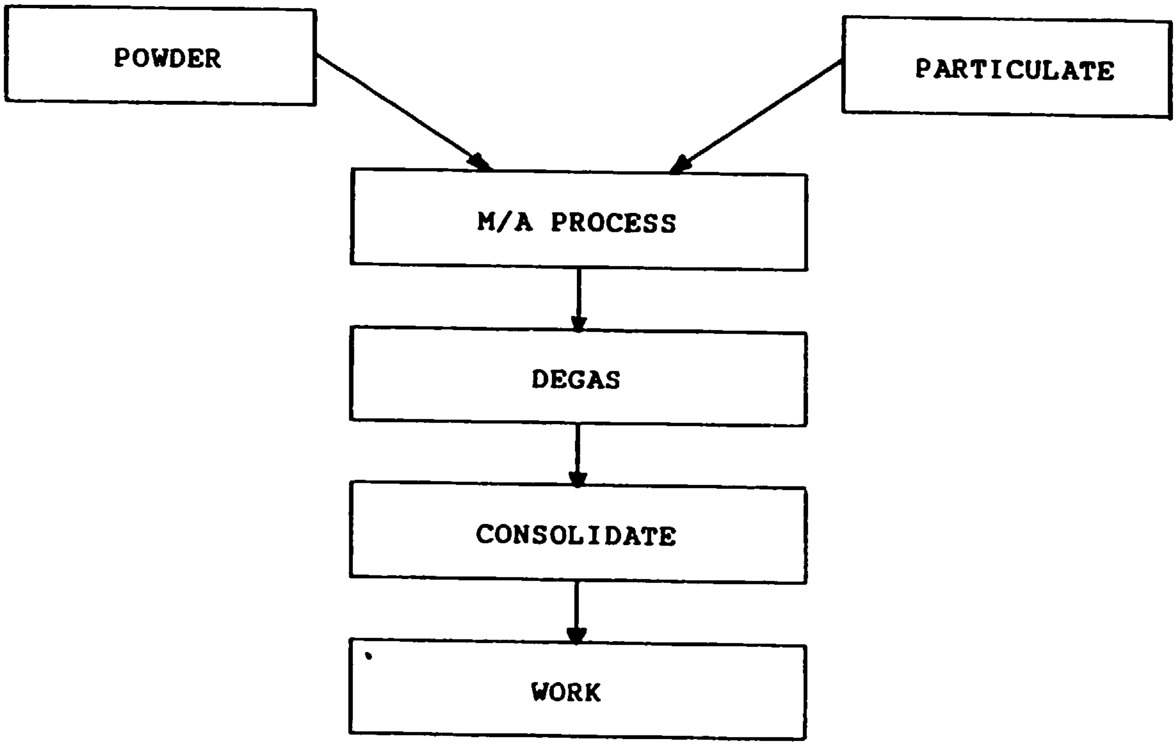

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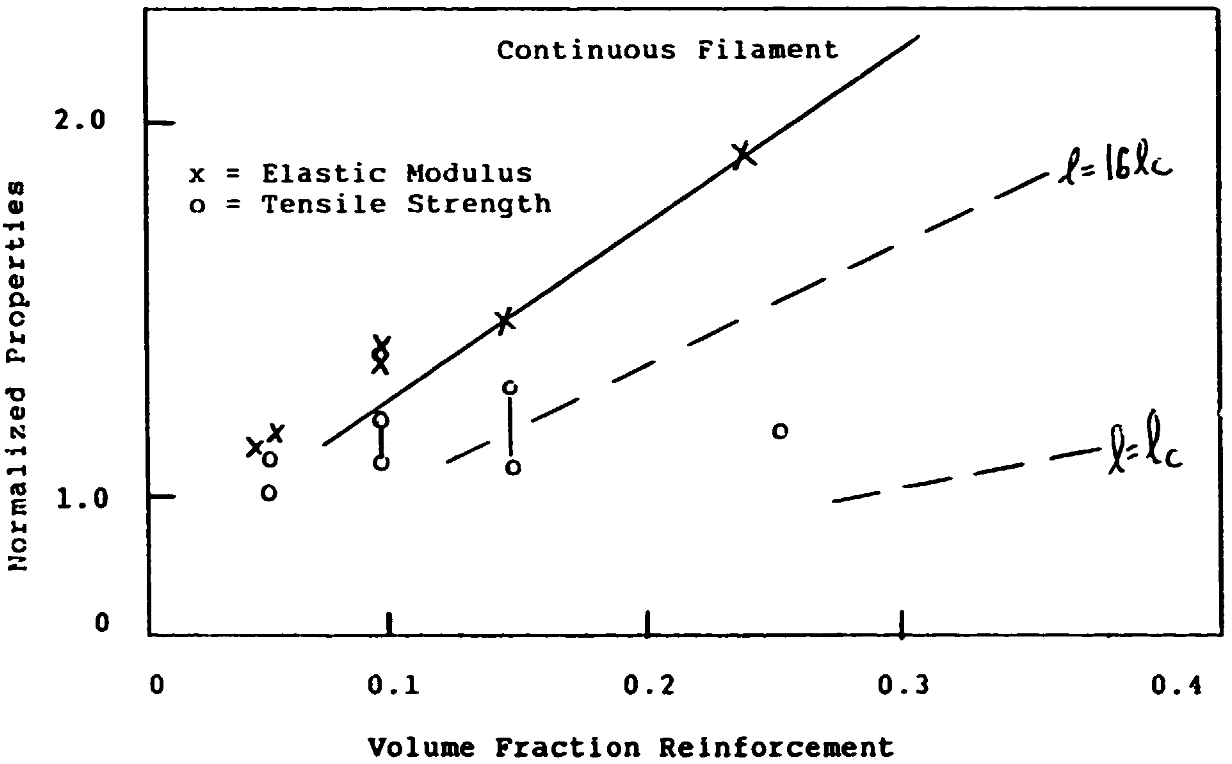

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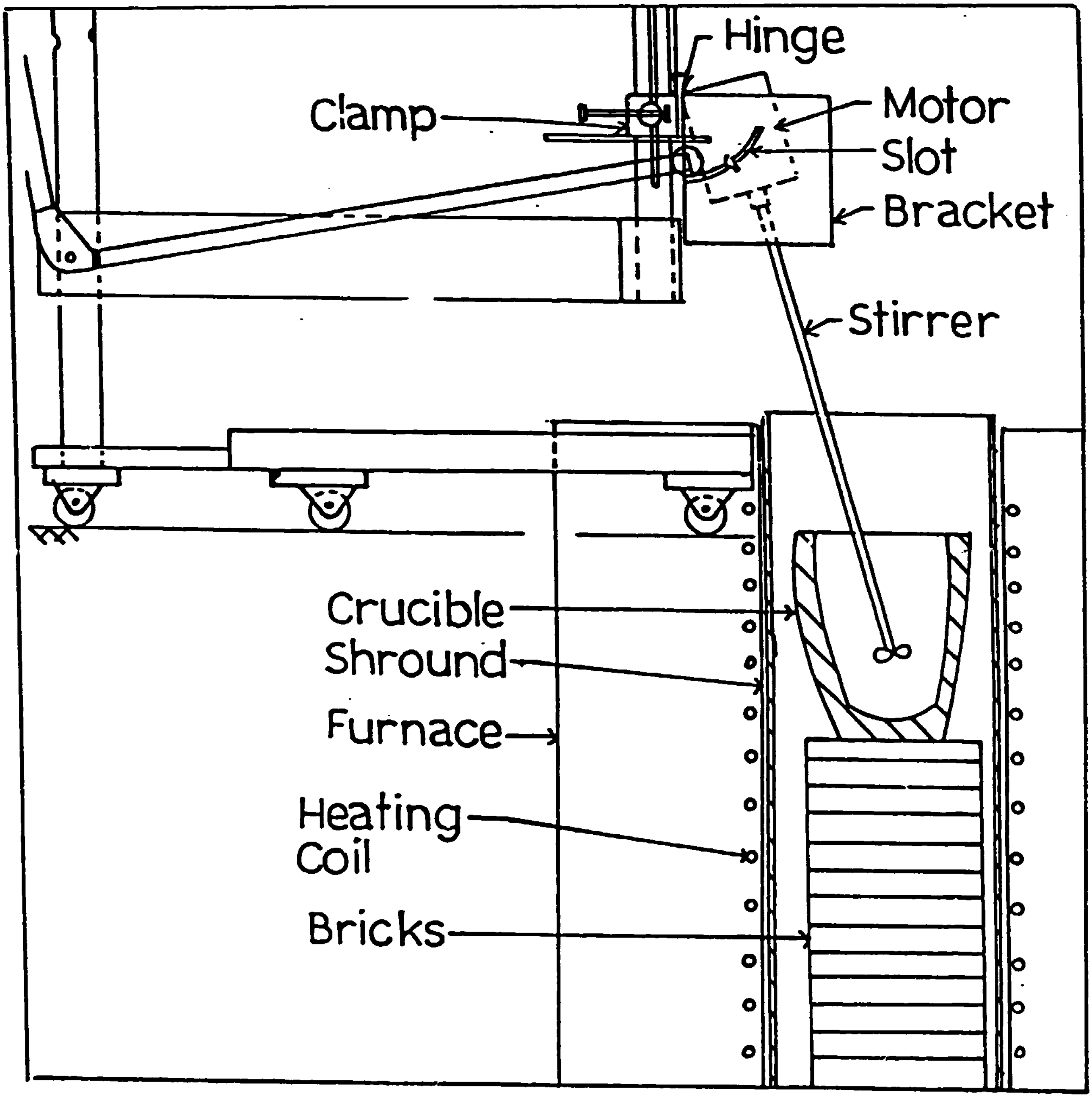

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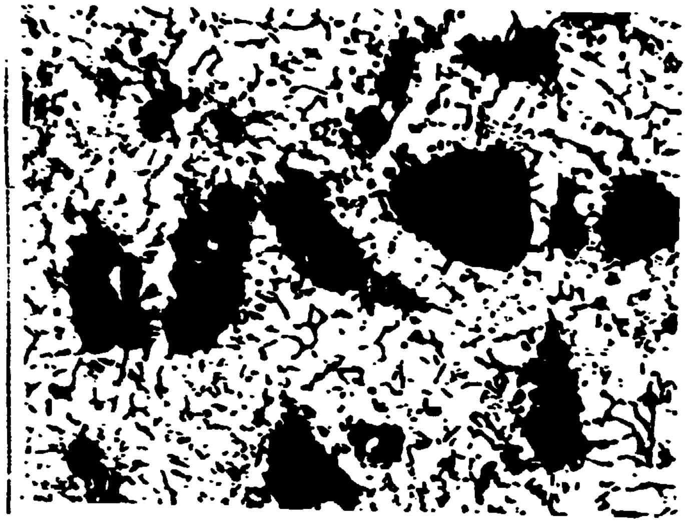

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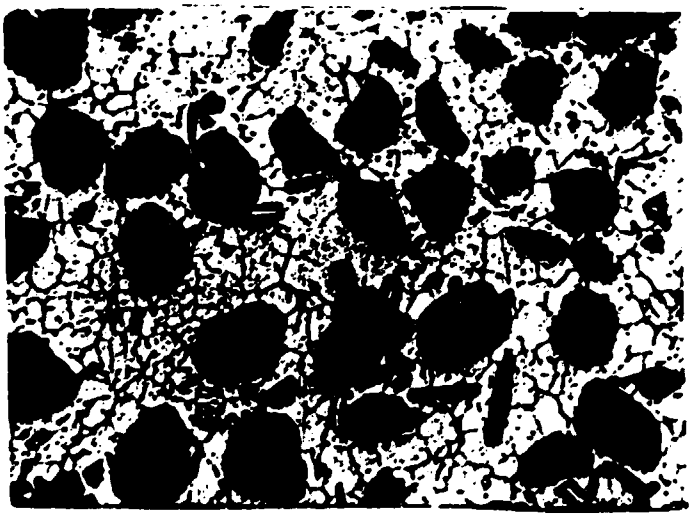

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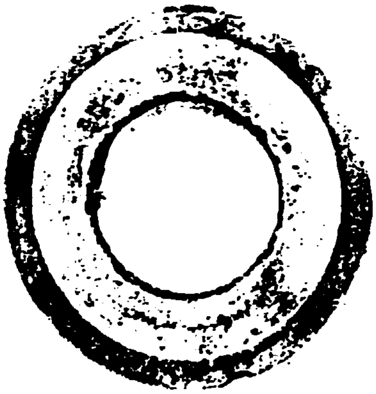

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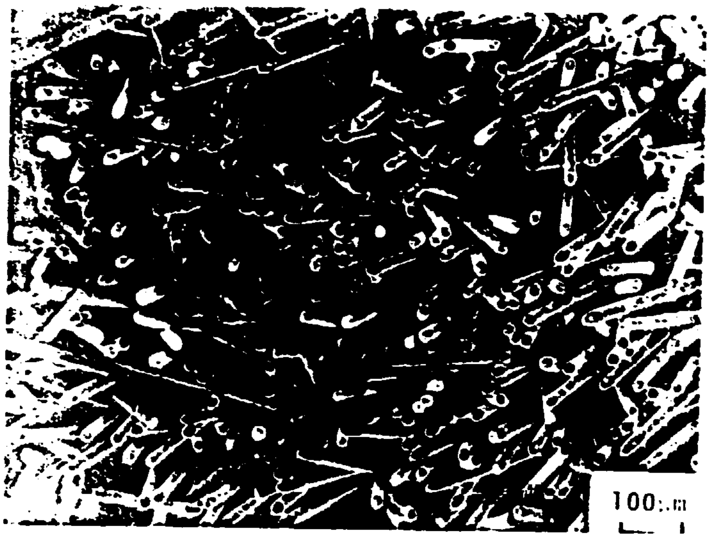

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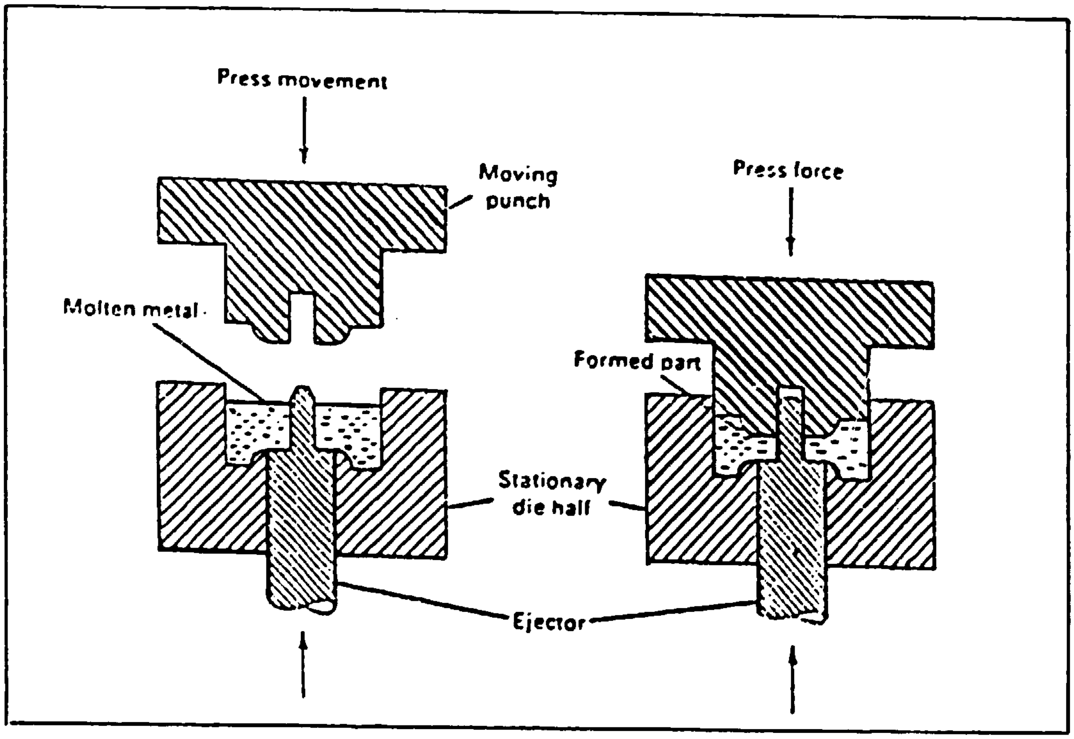

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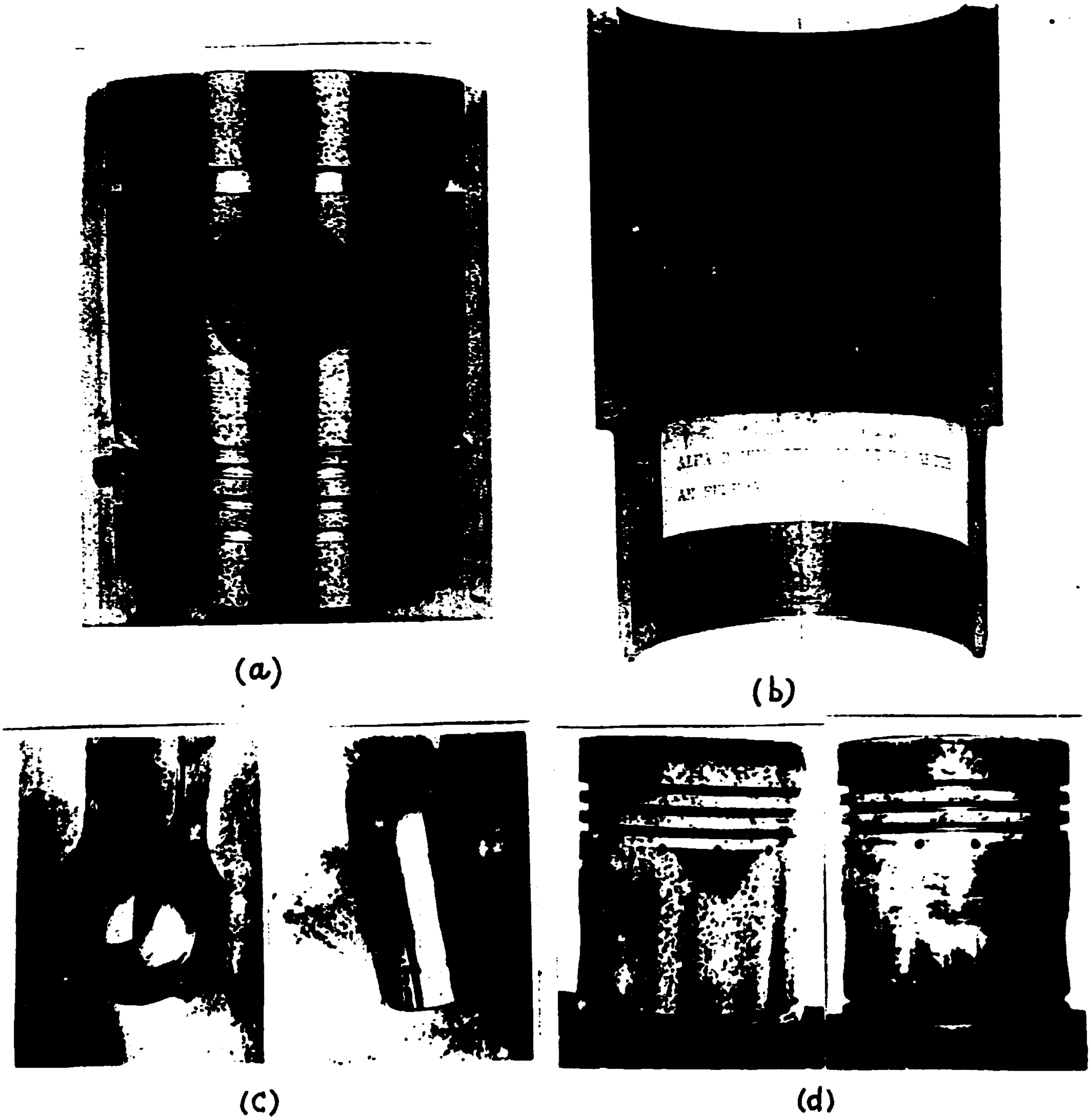

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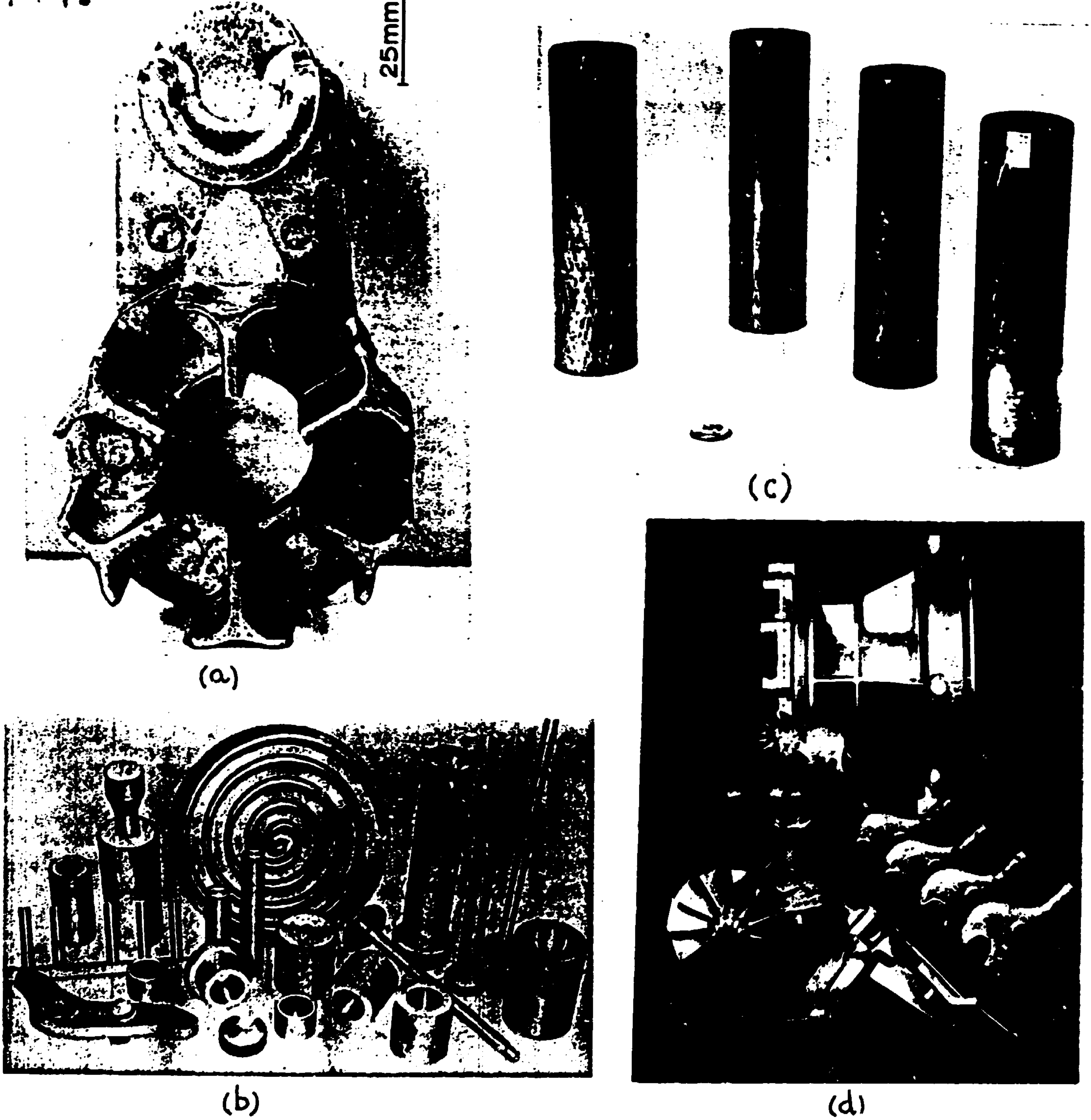

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