METAL MATRIX COMPOSITES: HISTORY, STATUS, FACTORS AND FUTURE

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CHAPTER-I

1. INTRODUCTION

"And we are going forward with research on a new Orient Express that could, by the end of the next decade, take off from Dulles Airport, accelerate up to 25 times the speed of sound, attaining low Earth orbit or flying to Tokyo within 2 hours. And the same technology transforming our lives can solve the greatest problem of the 20th century. A security shield can one day render nuclear weapons obsolete and free mankind from the prison of nuclear terror. America met one historic challenge and went to the Moon. Now America must meet another: to make our strategic defense real for all the citizens of planet Earth."

- Ronald Wilson Reagan, State of the Union Address (February 4, 1986) [1].

These words by Ronald Reagan, the 40th President of the United States of America were a turning point in the evolution of metal matrix composites. He was talking of the National Aerospace Plane (N.A.S.P) project. By uttering these words, he officially acknowledged the existence of N.A.S.P. This incident served as an impetus for the development of metal matrix composites as a branch of study in the field of material science because the nation realized the need for lightweight materials that can withstand high temperatures[2].

The definition of a Metal Matrix Composite according to Farlex Free Dictionary is:

"A material in which a continuous metallic phase (the matrix) is combined with another phase (the reinforcement) to strengthen the metal and increase high-temperature stability." The metal matrix composite can be confused with an alloy. However, accordin to the definition, the second component or the reinforcement should exist as another phase in considerable amounts.

Also, particulate reinforced metals can be confused with dispersion strengthening and precipitation strengthening. The strengthening in a metal matrix composite is by transferring of load from the matrix to the reinforcement .i.e. reinforcements are the primary load-bearing components. But in dispersion strengthening systems, the strengthening occurs due to the mechanism of impeding dislocations.

In many industrialized countries, there is a great interest in evolving metal matrix composite (MMC) materials. Scientists from East and West or N.A.T.O and Warsaw countries tried numerous combinations of matrices and reinforcements since work on MMCs began in the late 1950s. This led to some developments in the aerospace field, but the resultant commercial application was limited. The introduction of ceramic whiskers as a discontinuous reinforcement and the development of 'in-situ' eutectics were studied in the early 1960s for high temperature applications in aircraft engines. It was in the late 1970s and early 1980s that the automobile industries started to take MMCs seriously. In the last 20 years, metal matrix composites have developed from a mere lab interest to a distinct and flourishing class of materials with numerous applications and huge commercial markets. However, MMC technology is still in its embryonic stage of development, and other important systems undoubtedly will emerge.

The whole history of metal matrix composites was analyzed by listing and evaluating the progression of journal articles published on this topic from the time of its origin and tracking its development through different trends to the present and future of this material is predicted. The countries from which these scientific papers were published are studied and the number of papers published and how their nature was affected by the history of that nation is also observed. The data used to make the study has been listed in appendix III and appendix IV.

The factors that influence metal matrix composites has been listed and analyzed. The author is aware that the number of journal articles published and patents filed from a country is not the only index for its technological innovation. However, it is a strong index and the most conventional one.

CHAPTER - II

2. History of Metal Matrix Composites following Generations

According to Tim Palucka and Bernadette Bensaude-Vincent, Caltech, the evolution of composite (includes polymer, ceramic, and metal matrices) materials can be divided into four different generations[3].

(a) First Generation (1940s): Glass Fiber Reinforced Polymers (GFRPs).

(b) Second Generation (1960s): High Performance Composites in the post-Sputnik Era.

(c) Third Generation: The Search for New Markets and for the Synergy of Properties (1970s & 1980s).

(d) Fourth Generation (1990s): Hybrids and Nano-composites.

From the classification itself it is evident that metal matrix was not considerably developed during the first generation of composites development.

2.1. Second Generation (1960s): High Performance Composites in the post-Sputnik Era:

The launch of Soviet satellite Sputnik in 1957 was a major event in the history of MMCs. This prompted the beginning of “Space Race” between the super-powers. The spacecraft had to be built with lighter materials than monolithic metals and stronger than polymer composites to carry payload to space breaking the gravitational grip and also resist the high temperatures up to 1500 °C that develop during reentry of the spacecraft. Cincinnati Developmental Laboratories combined asbestos and phenolic resin for use in a possible re-entry nosecone material. It was during this period that scientists started to look at metal matrix composites for a solution. Prior to this development, little work was done in this field barring an effort to reinforce copper with steel reinforcement wire. The space race inspired scientists and innovators to develop carbon and boron fibers[3].

Carbon and Boron Reinforcements: Graphite (carbon) fibers were developed from rayon and high strength and stiffness boron fibers were developed by Texaco. Carbon fiber was leading the race due to its easier processing capabilities and lower cost. Graphite fibers were used to reinforce polymer matrix composites because of the reactivity of carbon with magnesium and aluminum. However, the development of air-stable coatings prevented the reaction between carbon and the metal that resulted in the development of Graphite-Magnesium and Graphite-Aluminum composites.

Boron's major application was in military systems where the focus was performance and cost less of an issue.But it had three problems.

(i) Boron had to be deposited on a tungsten wire that was used as a substrate

(ii) High cost

(iii) Tight radius could not be bent by the filament.

In 1969, boron-epoxy rudders were installed in F-14 jets made by General Dynamics. Boron reacted with the metal matrix above 600 °C. So a coating had to be developed before boron-reinforced metals became a practical reality[3].

2.2. Third Generation (1970s & 1980s): The Search for New Markets and for the Synergy of Properties

Once the race to the moon was over, scientists started thinking of re-usable space craft the like MIR spacecraft from the U.S.S.R, Skylab, and the Space Shuttle. A re-usable space-craft is subjected to repeated temperature swings. This forced the scientists to look for materials that have the combination of properties like high stiffness and strength, high temperature resistance, and low co-efficient of thermal expansion (C.T.E) so that the material will not contract and expand much during the thermal cycling periods. New fibers were developed in the mid-1970s and coatings for carbon and boron fibers made them possible for metallic matrices[3].

If SiC particles are combined with a metal matrix like Aluminum, this reduces the C.T.E of the mixture. In this way, the C.T.E of the composite can be controlled by altering the volume fraction of the reinforcement. Even zero thermal expansion can be produced by combining matrices and reinforcements that have mutually compensating thermal expansion. This property can be made in applications that require high dimensional stability, for example space applications. Continuous fibers of SiC, boron or carbon increase the modulus of the component dramatically. If one adds 30% continuous carbon fiber to aluminum, the modulus of the metal can double[3].

The main hindrance for metal matrix composites that prevents entry into fast moving consumer markets (FMCG) is cost. An exception that can be cited is the area of sports equipment, where Duralcan (Al reinforced with 10% Al2O3 particulates) and Al reinforced with 20% SiC particulates are used in bicycle frames for low weight and high strength. They are of high cost and used in high performance mountain bikes[4].

2.3 Fourth Generation (1990s): Hybrids and Nano-composites:

Hybrid materials combine organic and inorganic components at the molecular scale. Historically, the study of bio-mineralization garnered the attention of scientists to the possibilities of hybrid structures. This led to a new field of science called biomimetism[3].

Metals like aluminum are combined with nano-particles of SiC resulting in enhanced mechanical properties. Scientists use the concept of bones to inspire this, a clear case of biomimetism[5].

CHAPTER-III

3. History of Metal Matrix Composites (Chronological Analysis)

3.1 Methods

Compendex is the online version of the Engineering Index. Compendex covers the documents from 1969. Engineering Village is the platform from which Compendex is made available by the publisher Elsevier. Compendex is a reliable source. It is recognized for the breadth and depth of its coverage for all disciplines in engineering.

CSA Illumina (formerly Cambridge Scientific Abstracts) is a publisher that provides a number of online databases, some of which are engineering specific. The organization publishes a number of bibliographic databases in different fields of Science and Technology, Arts and Humanities, and Natural and Social Sciences. A sub-division of this, Engineered Materials Abstracts started in 1986, and gives an in-depth coverage of composites, ceramics, and polymers. CSA METADEX is the all-inclusive database that reports comprehensive accounts of metals and alloys. This source is considered to be superior to Engineering Index by the scientific community. However, the university where the author of this report studies does not have a subscription to either METADEX or the CSA.

Materials Research Database with METADEX. So the next best resource at his disposal was Engineering Village.A number of search combinations were used to list the papers on metal matrix composites:

1. Metal matrix composites
2. Metal composites
3. Reinforced metals
4. Reinforcement + metals
5. Fiber reinforced metals
6. Filament reinforced metals
7. Whisker reinforced metal
8. Aluminum matrix composites
9. Titanium matrix composites
10. Silicon Carbide + Aluminum
11. Boron + Aluminum
12. Silicon Carbide + Titanium

The above mentioned search tool was used to find papers comprehensively until 1986. However, upon reaching 1987, the number of papers started to increase exponentially, so we chose 6 journals for composites based on impact factor for practical use of time and resources.

Table 1: List of Journals

Number	Journal	Impact Factor (Year 2010)
1	Composites Science and Technology	2.901
2	Composites Part A- Applied Science	2.410
3	Composite Structures	2.006
4	Composites Part B- Engineering	1.704
5	Applied Composite Materials	0.935
6	Journal of Composite Materials	0.806

The sudden increase in the number of papers is explained in the section 1985-1989. The review is divided into thirteen parts: metal matrix composites before 20th century, developments in the 20th century prior to 1960, 1960-1964, 1965-1969, 1970-1974, 1975-1979, 1980-1984, 1985-1989, 1990-1994, 1995-1999, 2000-2004, 2005-2009 and 2010.

3.2 Metal Matrix Composite before 20th Century

Examples of metal matrix composites stretch back to ancient civilizations. Copper awls form Cayonu (Turkey) date back to about 7000 BC. They were made by repeated laminations and hammering process, which gave rise to high levels of elongated non-metallic inclusions[6]. An iron plate excavated from the Great Pyramid at Gizeh, Egypt dates from the 4th Dynasty, circa 2750 BC. The plate had numerous laminates of wrought iron that was welded together through hammering[6]. “The Illiad of Homer” in 800 BC describes Achilles’ shield as having five layers--two bronze/tin/gold/tin/bronze [6]. The Indonesians of Java and other Malayan Islands made a number of knives known as krisses. The Indonesian krisses usually are forged to have repetitive curves along their length. Krisses were made from about 1379 AD onwards in Indonesia under Hindu influence. The modern kris was made by solid-state welding of a tool-steel to welded layers of wrought iron[6].

3.3 Developments in the 20th Century Prior to 1960

Eric Schmidt from Germany did notable work on dispersion hardened metal systems. In 1924, he filed three patents (Nos. 425451, 425452 and 427370) on consolidated mixtures of aluminum/alumina powders that led to extensive research in 1950s and 1960s. The first patent mentioned above deals with the preparation of the work-piece and the other two discusses the treatment of metals for strengthening[7-9].

Consider dispersion hardening and precipitation hardening. The mechanism of hardening works by impeding the dislocation motion with particles (non-shearable precipitates and fine oxide particles). The primary objective is to minimize the space between the particles. For better ductility performance, low volume fraction is desired.

On the other hand, a volume percent up to 15% is used for high temperature and higher creep resistance applications. For higher creep resistance, the dislocation should climb over dispersoids by diffusive processes. However, the strengthening mechanism in this material is through impeding dislocations. So it should not be termed a MMC as per the definition. These attempts are not categorized as the seminal work that resulted in the evolution of metal matrix composites.

In those days, the term “composites” was used in a different meaning than today. Then, if one material was combined with another material, it was called a composite. In 1946, J.A. Merill published a paper called “Rubber-metal composites” that discussed adhering/bonding of rubbers like Buna Nor Butyl Rubber with different metals like steel or aluminum to create components for a washing machine gyrator, linings for tanks, piping, covering exhaust fans etc.[10].

In 1951, H.L Cox of the National Physical Laboratory, Middlesex published a paper “The Elasticity and Strength of Paper and other Fibrous Materials”. It discussed the response of fibers on the strength and stiffness of paper and fibrous materials. Here the matrix is not metal, but it was one of the first major attempts to study effect of fiber reinforcement on a metal[11].

In 1957, J.D. Eshelby published his work “The Determination of the Elastic Field of an Ellipsoidal Inclusion and Related Problem”. This paper also dealt with the influence of strain inside ellipsoidal particles in a matrix and how it influences the applied stress field in the surrounding matrix[12].

The first paper the writer that discusses metal matrix composites, as per the strictly following the modern definition was by W.E. Stuhrke in 1958, “The Mechanical

Behavior of Aluminum-Boron Composite Material", *Metal Matrix Composites*, ASTM. This paper discusses a diffusion bonded composite made up of five layers of unalloyed aluminum reinforced with 12-15% boron filaments[13].

3.4 1960-1964

D.L. McDanels, R.W. Jech and J.W. Weeton published "Metals Reinforced with Fibers" in 1960 from the USA. This paper discusses a copper matrix reinforced with tungsten fibers [14]. In 1961, J.D Eshelby published "Elastic Inclusions and Inhomogeneities" in the journal *Progress of Solid Mechanics*. This work is in the same as vein as the one mentioned before, that discussed hardening of the material by means of inclusion in the metals[15].

A MMC paper published by N.F Dow in 1963 called "Study of Stresses near Discontinuity in a Filament-Reinforced Composite Metal" was from the Missile and Space Division of the General Electric Corporation. They discussed the discontinuities in filament-reinforced composites and the stresses around the filaments. Calculations made from the formulas derived for local stresses in filament or binder, and for the shear stresses induced between them showed disturbances from the general stress level are primarily local, near the discontinuity. Particularly the shear stress between fiber and binder is apt to rise to a high peak value at the discontinuity. Any attempts to reduce the shear stress, as by permitting yielding of the binder, will also increase the filament length required for effective reinforcement. Boron fibers were developed and marketed during this period [16].

One fact that can be deduced is that the first concerted effort to develop modern MMCs originated in the 1950s and early 1960s. The principal impetus was to improve the structural efficiency of metallic materials while and maintaining their advantages, including high shear strength, maintaining good properties at high temperatures.

3.5 1965-1969

Researchers around the world like the U.S.A, Germany, and the U.S.S.R discussed metal matrix composites in general over the time. There were papers where researchers tried to experiment by combining metals and reinforcements, but metal matrix composites were not developed as a branch of material science with significance. Researchers tried different types of matrices (iron, chromium, nickel, zirconium, aluminum) and reinforcements (Tungsten fibers, Aluminum Oxide fibers and whiskers, Silicon Carbide fibers and particulates, Glass fibers, and Zirconium Hydride Platelets). They even tried different combinations. One paper discussed environmental factors in the design of composites. Some investigated the discontinuous reinforced metal matrix, may be inspired by experience gained form dispersion strengthening and precipitation strengthening of metals. Some papers dealt with the opportunities and applications of this versatile material. Even at that stage, research was done on the production issues of whisker reinforced composites.

From the given data, we can see that the U.S.A was in the forefront of metal matrix composite research. The researchers of this country delved into almost all issues concerning metal matrix composites, including production issues, fiber strengthening, mechanical properties, and applications of MMCs.

The total number of papers published was 29, an 89.7% increase over the previous period discussed above. The number of papers published by the U.S.A was 8

(27.6%), Germany 4 (13.8%), U.K 3 (10.3%), France 2 (6.89%), Australia 2 (6.89%), Japan 2 (6.89%), U.S.S.R 2(6.89%), and Chile 1(3.4%).

Here the author was not able to find the source of 5 papers. They are represented as ‘unassigned’ (17.24%).

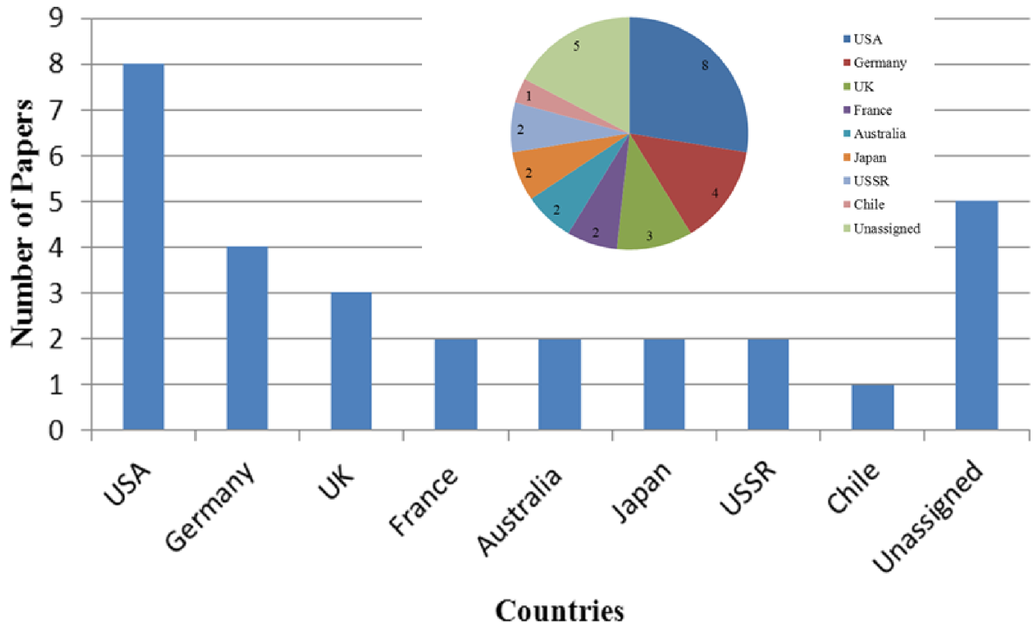


Figure 1: Number of MMC Papers published from 1965-1969 divided by country

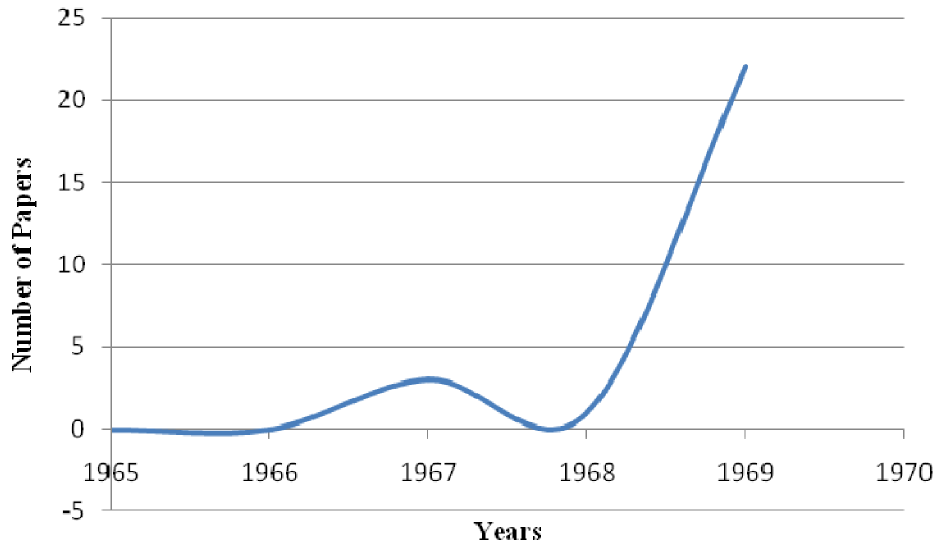


Figure 2: Total Number of Papers published from 1965-1969

3.6 1970-1974

Metal matrix composites were a relatively immature technology when the early 1970s recession occurred. The 1973-1975 recession in the U.S.A and around the world was a period of stagflation that resulted in the termination of the post WW-II economic boom. The reason for the recession was connected with the 1970s oil crisis that began in October of 1973[2].

The Yom Kippur War between Israel, Egypt and Syria started on 6th October, 1973. The Arab nations supported Egypt and Syria financially, logistically, politically and some even supported them militarily. On the other hand, the United States supported Israel[17].

As a visible sign of their political support, OPEC stopped oil exports to the U.S.A and other Western nations as a pressure tactic to end their support of Israel. This resulted in a dramatic quadrupling of the gasoline prices from just 25 cents to one dollar in a few months, the so called “oil shock”[17].

This problem coupled with increased government spending due to the ongoing Vietnam War accompanied by a stock market drop resulted in serious stagflation in the United States. Other reasons for the recession was the collapse of the Bretton Woods system,and competition in the metal industry from the emergence of newly industrialized countries resulting in a steel crisis. The recession lasted till March 1975, even though its effect lasted for almost 20 more years[18].

This recession resulted in curtailing funds for research and development that lead to the end of this early phase of metal matrix composites' initial discovery and development [2]. The oil embargo that the West faced led them to evaluate many things about energy such as cost and supply. This crisis made evident that prices of products like oil play an important role in the economy of a society, that the world needed so much oil to run on a day-to-day basis, and will literally pay a heavy price if a bottleneck occurs as a result of politics, natural disasters or a gradual exhaustion of non-renewable energy sources. In short, until this event, no one worried about "energy security"[2].

This line of thought made everyone realize the necessity for energy-efficient materials like composites. This motivated the policy makers to invest more funds for the development light materials like organic and metal matrix composites [2]. So the implications of early 1970s recession was two: (1) the curtailing of research funds that resulted in ending the initial phase of MMCs discovery and development and (2) served as impetus for the future development of structurally efficient systems [2].

The research of metal matrix composites as we know today started in full throttle during this period. The focus was mainly on Aluminum matrix composites, most of them reinforced with boron and carbon fibers.

It was during this period that Aveston and Kelly published “Theory of multiple fractures of fibrous composites” as a conference proceeding in *National Physical Laboratory*, UK. This paper discussed composites in general. It explained the stress-strain behavior of a composite considering the mechanism at the fiber-matrix interface. This paper eventually became a landmark paper in the evolution of metal matrix composites[19].

Researchers mainly focused on continuous reinforcements. Research on discontinuous reinforcement did not take off during that time; studies in this field were conducted primarily from Europe, mainly NATO countries. Another important point to be stressed when discussing this period was the focus of research on fabrication issues such as the forming, brazing, welding, soldering, machining, and tooling for specific parts like gas turbine blades, heat exchangers, missile and spacecraft components.

Beryllium reinforcement was used for the first time by W. Taylor and J.A. Hawk Jr. from USA in 1970. Tungsten reinforced aluminum matrix composites and sapphire reinforced aluminum composites were also studied during this period.

Analytical methods like Scanning Electron Microscopy and Radiography were used to understand the surface topography, composition and electrical conductivity of MMCs. Copper matrix composites were investigated for electrical applications; a significant contribution was made from Japan. Tungsten wires used were tested in nickel based super alloys for high temperature applications like gas turbine applications.

The focus was shifted from general material properties to mechanical properties like compressive and tensile strength, fracture modes, cracking and yield strength. Creep and other thermo-mechanical characteristics were also discussed in some papers.

This period saw the emergence of hybrid composites. A paper published by J L Christian, "Material and Fabrication Development and Applications Studies of Aluminum-Boron- Stainless Steel Composites" from 1970 from the USA discussed aluminum-steel matrix composites reinforced with boron.

Researchers even delved into the interface properties and chemical compatibility of different MMCs.

High strength monofilaments like silicon carbide (SiC) and boron allowed considerable efforts on continuously reinforced metal matrix composites through-out the 1960s and early 1970s. The total number of papers on metal matrix composites published during this period was 125, a 76.8% increase when compared to the previous period. The number of papers published from the U.S.A was 70 (56%), U.K 14 (11.2%), U.S.S.R 11(8.8%), Germany 11(8.8%), Japan 6 (4.8%), France 4 (3.2%), Ukraine 3 (2.4%), Poland 3(2.4%), Canada 2 (1.6%), Egypt 1 (0.8%), Denmark 1(0.8%), India 1(0.8%), Australia 1(0.8%), Israel 1(0.8%), and Portugal 1(0.8%). We see that the U.S.A published more papers than the rest of the world combined in this field. This exhibits their research prowess in that period. The significant part of the research was for defense applications like jet engines, missile, and space missions.

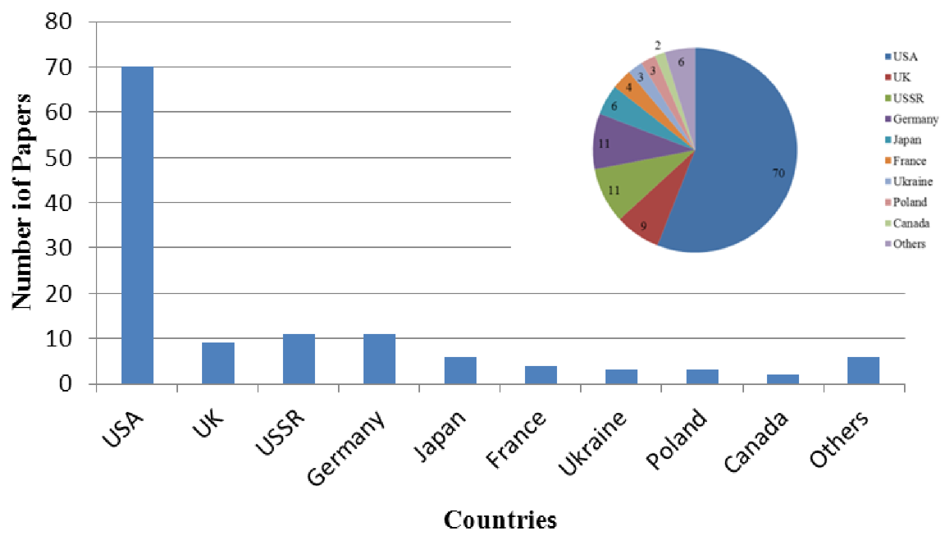


Figure 3: Number of MMC Papers published from 1970-1974 divided by country

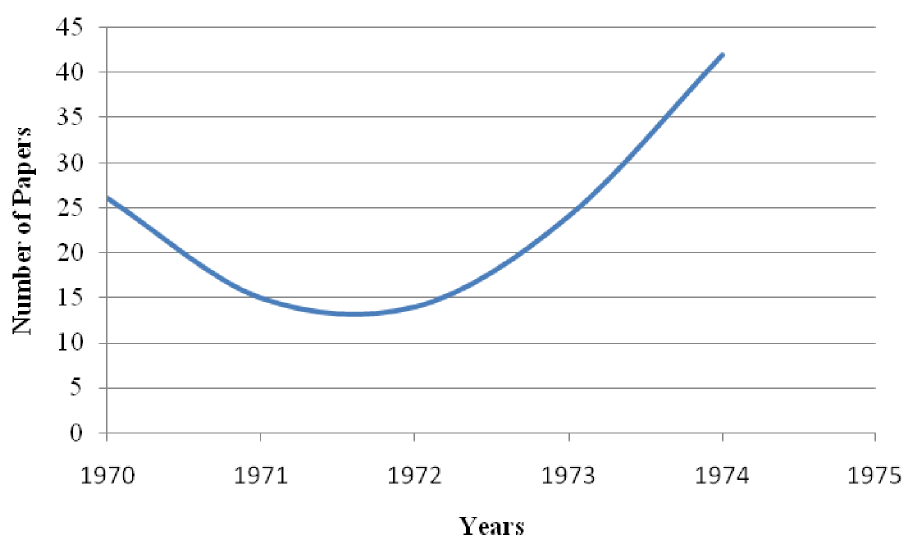


Figure 4: Total Number of Papers published from 1970-1974

In the above figure, we have combined all the countries that published one paper each and categorized them as “Others”. This includes Egypt, Denmark, India, Australia, Israel, and Portugal. Most of the publications that came from the U.S.S.R were for high temperature applications intended for space and defense applications, a clear indication of the attitude of that nation in those times.

3.7 1975-1979

By the late 1970s, the model of materials development and commercialization began to change dramatically. Emphasis was given for affordability and sensitivity to risk, even for military systems, which made it difficult for high performance applications to be incorporated in real world systems [20].

By the end of the 1960s, the United States made two successful manned moon landings. The policy makers felt that the country had achieved President Kennedy's goal of reaching the moon and coming back by the end of 1960s, there was no need for further missions. There was also a growing feeling that the significant fraction of funds dedicated for the space programs should be diverted to other uses. The near mishap of the Apollo 13 astronauts in April 1970 bolstered anti-NASA feelings; feelings that resulted in cancelling of missions 15 up to Apollo 20. The rest of the remaining Apollo and Saturn hardware was diverted to the Skylab space station in 1973-1974 and an Apollo-Soyuz Test Project which occurred in July 1975. Many budgetary cut-backs resulted in cancelling ambitious projects NASA planned for the 1970s. Instead, NASA devoted most of the decade for the development of the space shuttle[21].

On top of this, the magnitude of military acquisitions decreased drastically as countries shifted their focus from massive new deployments to sustanining active military campaigns. The fear of Soviet attack in the aftermath of the Cuban missile crisis in the early '60s died out. That resulted in a fiscally constrained strategy of extending the life of existing systems[21].

Considering all these challenges, the development and infusion of emerging high performance materials such as metal matrix composites faced strong barriers. This can be proved by the number of papers published explained at the end of this section. This period saw the most varied experimentation with regard to the kind of matrix metals. Copper and Magnesium were the most widely used matrices. Also, researchers experimented with Cobalt, Silver, Niobium, Lead, Zinc, Nickel, and super alloys for turbine blades. Cast iron and steel matrices were also widely used. Also, steel fiber reinforcements were commonly used for aluminum matrices.

Another notable development of this period was the experimentation with a number of metal matrix and metal reinforcement combinations (for example, Cu-W, Ti-Nb). A number of articles discussing the mechanical and thermal properties of MMCs were published during this time. They discussed fracture mechanisms, impact strength, fracture toughness, fatigue behavior, creep behavior, and thermo-mechanical behavior.

This period saw the first use of finite element analysis for metal matrix composite research.

Non Destructive Testing methods like X-Ray diffraction techniques, electron microscopy, ultrasonic radiography and acoustic emission were widely used to study metal matrix composites during this period. Scientists and engineers also studied the influence of corrosion on the matrices of MMCs.

Fiber reinforced metal matrix composites were researched for aircraft propulsion applications. Hybrid composites were also widely studied during this period.

An important application of metal matrix composites cited quite often in literature is its use in Graphite reinforced Aluminum high gain antenna boom of NASA's Hubble Space Scope and Sip/Al composites and Grp/Al composites for electronic packaging for communication satellites and Global Positioning Satellites. A paper published by Ellison and Wade "Application of Metal-Matrix Composites to Spaceborne Parabolic Antennas" at Lockheed Missiles and Space Co., Sunnyvale, can be considered as one of the seminal works that discussed this application in 1979.

Attempts to renew the development of discontinuously reinforced MMC using SiC whisker reinforcements occurred in the late 1970s. The practical difficulty of evading whisker damage during fabrication and the high cost of whiskers led the researchers to particulate reinforcements. They developed materials that have nearly equal strength and stiffness, but easier fabrication and lower cost.

The total number of papers on metal matrix composites published during this period was 163, a 23.3% increase. This percentage increase is less when compared to the increase in the number of papers seen in the previous periods. The reason for the shortage of papers can be attributed to the recession that hit the Western World in the early 1970s. The result of the recession was more visible in the period 1975-1979, because effect of reduction in funding for research was felt in the later part of the 1970s.

The total number of papers published was 163. The number of papers published from the U.S.A was 46 (28.2%), U.S.S.R 29(17.8%), Japan 12(7.7%), Germany 9(5.5%), France 6 (3.7%), U.K 4 (2.4%), Brazil 2 (1.2%), India 1(0.6%), Denmark 1(0.6%), Australia 1(0.6%), Romania 1(0.6%), Canada 1(0.6%), Italy 1(0.6%) and Iran 1(0.6%). Here we see that the number of papers from the U.S.A, Germany and the U.K has reduced from the period 1970-1974. The number of papers from the U.S.S.R and Japan increased. The Western nations mentioned above were struggling from recession, but Japan was not affected. Its economy was growing and prospered during the decade as a result of increasing exports.

The U.S.S.R had its own oil producing states, so the economic downturn did not hit them as hard. Also the 1970s was the peak of Soviet space research. The number of papers from France had a nominal increase by 2.

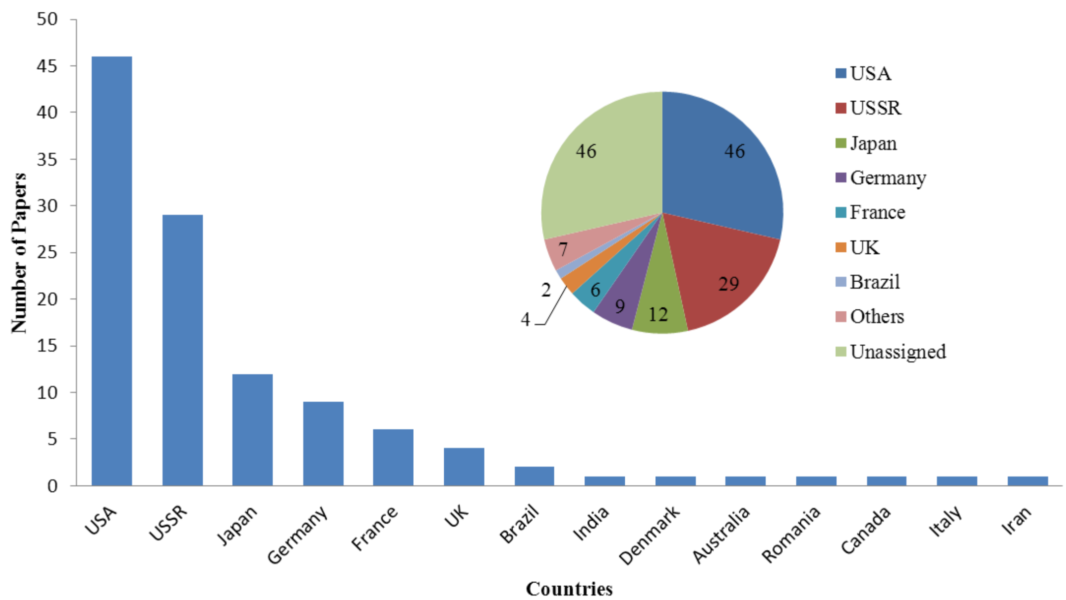


Figure 5: Number of MMC Papers published from 1975-1979 divided by country

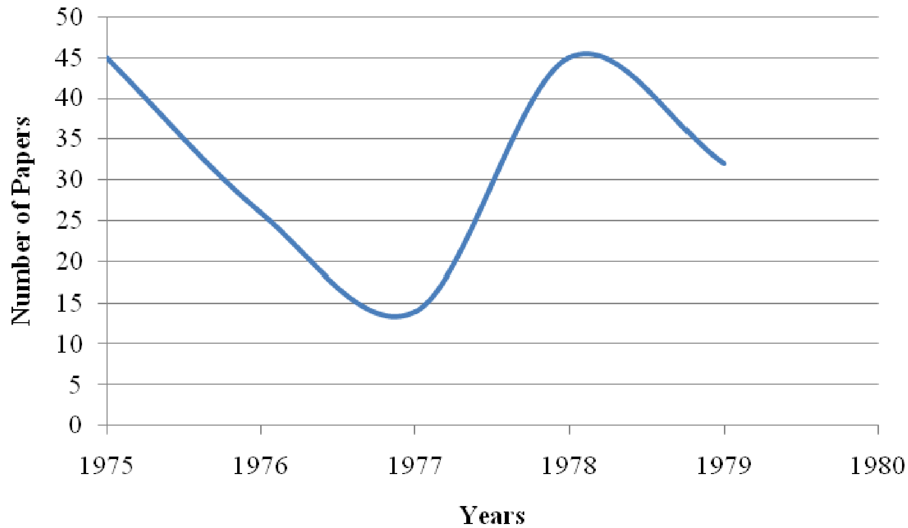


Figure 6: Total Number of papers published from 1975-1979

3.8 1980-1984

This period witnessed the maturing of this area. The research focused mainly on Aluminum and Titanium matrix composites. This period saw a shift from continuous reinforcement composites to discontinuous reinforcement composites. Also, the micro-structural properties of MMCs were more closely studied.

The interest in MMCs was reinvigorated in the 1980s. This change was spurred by research efforts directed on discontinuously reinforced metal matrix composites, which expanded the potential applications of MMC systems. Even though the performance gain for discontinuous composites is limited when compared to continuous reinforcements, these developments provided the conduit for improved affordability and processability. Industry took note of this material due to its decreasing cost and better properties compared to monolithic metals. Substantial effort was made by small businesses and commercial laboratories. The former’s effort focused on attaining a balance of affordability, performance and risk acceptable to them. Early work was done on Aluminum powder as a precursor to discontinuously reinforced MMCs.

In 1981, Fukuda and Chou published “An Advanced Shear-Lag Model Applicable to Discontinuous Fiber Composites” from the University of Delaware.

One important property of metal matrix composites, the residual stresses developed during its production and operation was addressed during this period by researchers from the University of Texas, Austin as indicated in the article “Residual Stresses Measurement in Metal Matrix Composites”.

The interface between the matrix and the reinforcement was widely studied during this period. Interface coating, interface reactions, its effect on fracture toughness and their effect on thermal cycling was investigated by researchers all over the world.

Thermal properties like expansion measurements, thermal degradation and creep were thoroughly researched during this period. Aluminum composites reinforced with silicon carbide were widely investigated by scientists from the U.S.A, especially the formability and fiber alignment aspects. Also their fatigue, fatigue cracking and corrosion fatigue were given importance.

Powder metallurgy and sintering is a major production process for metal matrix composites, especially titanium matrix composites. These processes gained popularity during this period. Research on the fabrication of MMCs using squeeze casting was also done during this period. Pressure casting was commercially performed since the early 1980s[15].

In the late 1970s and the early 1980s, scientists worked on continuous fiber matrix composites and determined that the strength of the composite is influenced strongly if the matrix contained second phases (such as Si or Al_2Cu in aluminum) in contact with the fiber and if there is considerable chemical reaction between matrix and reinforcement (such as the reaction between aluminum and carbon fiber that forms the compound Al4C3). The research of this nature came mainly from Japan.

Plasma technology was used for the fabrication of metal matrix composites for the first time during this period. Dusan Matejka from Bratislava published "Some Physical Properties of Type Al-Steel-Al Composite Prepared with the Aid of Plasma Technology". It was followed by "Low-Cycle Fatigue of an Al-Stainless Steel Fiber Composite produced by Plasma State Deposition of the Matrix" by Pedro Tamayo Meza and Pedro Mario Cano.

The concept of helical fibers were introduced during this period. They were usually used to improve transfer of stress from the matrix to the fiber over straight fibers. Their properties, deformation behavior, tensile loading and fracture toughness were researched in detail. This originated mainly from Japan. Tensor analysis was also done on MMCs during this period. Another important development during this period was the studies on the corrosion and pitting of aluminum matrix composites.

Other aspects that were widely researched were wettability, influence of intermetallic compounds, and the wear behavior of MMCs.

The total number of papers published was 237; a percentage increase of 31.2%. The number of papers published from the U.S.A was 110 (46.4%), Japan 37(15.6%), the U.S.S.R 26(10.97%), India 10(4.2%), Germany 6(2.53%), Sweden 4(1.68%), and the

United Kingdom 4(1.68%), Bratislava, Canada, Qatar, France, Ukraine, and Belgium each had 2 (0.8%). Turkey, Romania, Mexico, Holland, Israel, Denmark, and Brazil each had 1 paper (0.3%).

Here also we can see that the number of papers from the U.S.A was more than all the papers published around the world combined. In that period, the United States had sponsored number of research projects that required high-end materials like metal matrix composites. The U.S manned space flights resumed with Space Shuttle Columbia in 1981. A number of components of this space-craft were made in MMCs, for example, boron fiber reinforced aluminum composites were used for the tubular struts for the rib and frame components in the mid-fuselage section and landing gear drag link [22]. In 1981, the U.S Air Force was working on the requirement for a new air-superiority fighter, christened the Advanced Tactical Fighter (ATF) to replace the existing F-15s. It was developed as a demonstration and validation program for the USAF that incorporates emerging technologies like advanced fly-by-wire flight control systems, super-cruise, efficient propulsion systems, stealth technology, advanced alloys and composite materials. The Advanced Tactical Fighter (ATF) developed into today's Lockheed Martin F-22 Raptor[23]. All these contributed to the higher number of journals articles on metal matrix composites.

The number of journal articles from the U.S.S.R did not change much when compared to the prior period. Their space program was progressing well during this period. The U.S.S.R started developing their version of a space shuttle "Buran" in the early 1970s, but their construction began in 1980 and in 1984, the full scale body of the space-craft rolled out. They had a number of parts made of MMCs, especially its engine components[24].

Japanese automotive companies started to take note of metal matrix composites during this period. Most of the research efforts in this field were funded by their private sector, contrary to the government funding for defense research as in the case of countries like the U.S.A, and U.S.S.R. Shin'ichi Towata of Toyota published a paper, “Interaction between SiC Fibers and Aluminum Alloys” in 1983 from Japan. It was in the same year that Toyota Motor Manufacturing used a selectively reinforced piston head for diesel engines. This was produced by selective squeeze casting which is a low cost and high production process. The component consists of selective reinforcement of the aluminum alloy by a discontinuous fiber preform in the ring groove area of the piston. These give thermal fatigue resistances, improved wear resistance, and lowered thermal conductivity. Lower thermal conductivity results in a greater part of the heat developed by combustion gases used for producing work. Also reinforced aluminum has a lowered co-efficient of thermal expansion, so higher tolerance limits can be achieved which results in higher pressure and better performance. In addition to this, from 1990 onwards Honda Prelude 2.3L engines used squeeze cast piston liners[25]. The research efforts during this period resulted in many more innovations in the coming years. This explains the unusual increase of papers from Japan.

Here we can see that India contributed 10 papers. During the previous period, their contribution was just 1. It was during this period that their Defense Research Development Laboratories (D.R.D.L) revived the Integrated Guided Missile Development Program (I.G.M.D.P). Also they launched the Light Combat Aircraft

(L.C.A) program in 1983 to replace the ageing Soviet Mig-21 aircraft which was the mainstay of their air-force. The L.C.A became the smallest and lightest multi-role jet fighter plane in the world, thanks to the extensive usage of composites (45% of the weight[26].

In the figure below, we combined all the countries that published one paper each and categorized them as “Others 1” and all the countries that published two papers as “Others 2”. The countries that published one paper are Turkey, Romania, Mexico, Holland, Israel, Denmark, and Brazil. The countries that published two papers are Bratislava, Canada, Qatar, France, Ukraine, and Belgium. Also, the author was not able to confirm the origin of 21 (8.86%) papers.

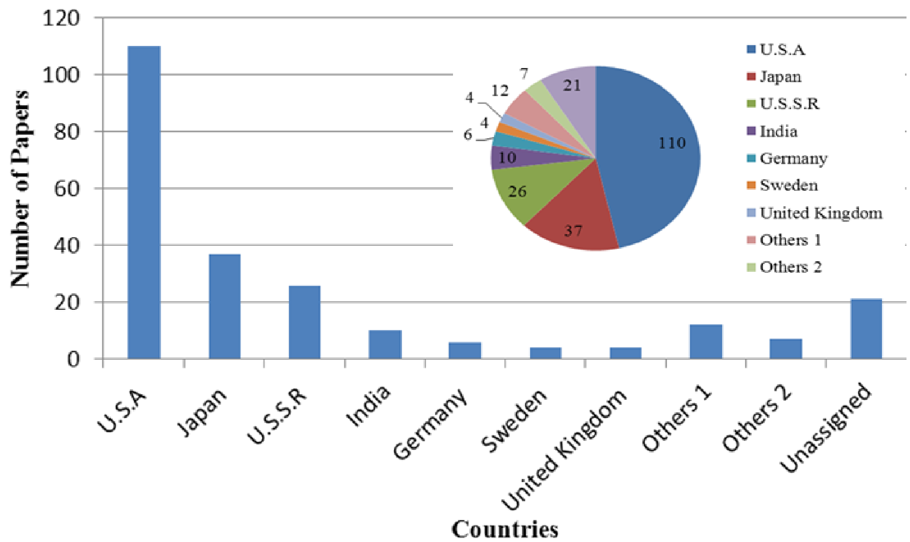


Figure 7: Number of MMC Papers published from 1980-1984 divided by country

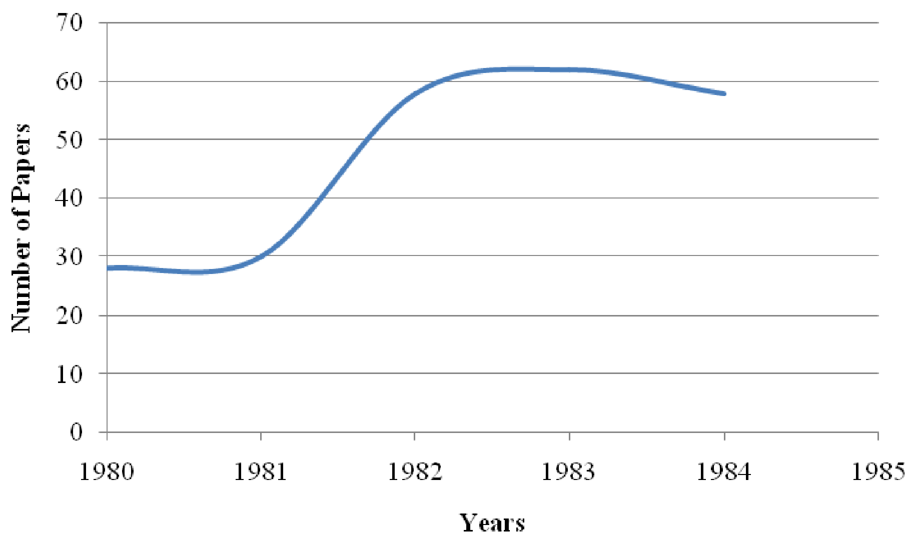


Figure 8: Total Number of Papers published from 1980-1984

3.9 1985-1989

The most influential event in the evolution of metal matrix composites after the 1970s recession happened in 1986. U.S President Ronald Reagan in his State of the Union Address acknowledged the presence of the National Aerospace Plane (N.A.S.P) program. This event resulted in a huge influx of funds for research on MMCs because such a vehicle required materials strong and light but that handles high temperatures. Monolithic metals were too heavy for this application and organic matrix composites could not handle the high temperatures developed on the skin of the aircraft. In this context, the focus was on performance and the cost associated with it was overlooked. This initiated great interest in continuously reinforced metal matrix composites. The end result was an exponential increase in research projects on both discontinuously-reinforced and continuously-reinforced MMCs in the academic community throughout the time period.

If we observe this period closely, we find that it is a natural the continuation of work that was done in 1970s and 1980s. This period saw the emergence of G. Dvorak, who did pioneering work in the development of micro-mechanics and plasticity models of metal matrix models. Interface mechanisms received attention during this period also. A number of papers discussed the anisotropy and orthotropic properties of discontinuously reinforced metal matrix composites. The notch fatigue behavior of aluminum composites were examined during this period.

Significant institutional contributions towards the research of metal matrix composites were from the University of Texas, Austin and the University of Delaware. The research at the University of Texas, Austin focused on interface properties of aluminum matrix composites reinforced with graphite. Another entity that made significant contributions towards development of MMCs was the Naval Surface Warfare Center's Maryland facility.

As described earlier, in this section, the author has collected the papers comprehensively from 1985 to 1986 for analysis. As the number of papers increased exponentially from there, we chose 6 journals (see Table I) for composites based on the impact factors for practical reasons. As we do not have the number of papers for a whole period, one must make inferences on the number of papers published and its percentage increase. From 1985 to 1986, the number of papers published is 65. Based on the 6 journals with the highest impact factor mentioned above, the number of papers published from 1987-1989 was 25.

From 1985 to 1986, the U.S.A published 36 papers (55.4%), France 6 (9.2%), U.S.S.R 3(4.6%), Germany 3 (4.6%), Japan 3(4.6%), and the U.K 3(4.6%). Switzerland, Australia , Poland, Israel, Italy, India, and Denmark published 1 paper each (4.3%).

Considering the period from 1987 to 1989, the total number of papers published from selected number of journals is 23. U.S.A published 13 papers (56.5%), France 3 (13.04%), China 1 (4.3%), Germany 1 (4.3%), Sweden 1 (4.3%), Japan 1 (4.3%), Canada 1 (4.3%), India 1 (4.3%), and Italy 1 (4.3%). If we closely look at the two sets of data, despite the huge increase in papers around the world, we can see that the percentage contribution from the U.S.S.R has reduced drastically (8.33% and 0%) when compared to the previous periods.

The period from 1985 to 1991 was a transition period for that country. Mikhail Gorbachev was elected General Secretary of the Politburo of the U.S.S.R on 11 March 1985. The country was facing extreme economic difficulties during that period. Their economy was almost facing a collapse due to bureaucracy, corruption, and inefficient manufacturing under Socialist rule. The War in Afghanistan was causing a great strain on their economy. In addition, the U.S.A influenced the Saudi Arabian oil companies to increase their oil production. This resulted in a 3x fall in oil prices. This affected the Soviet economy adversely because, oil exports were an important source of their income. From CIA estimates, the size of the Soviet economy was approximately half of the U.S economy during this period[27]. This forced policy makers to curtail funding for space and defense research which reduced volume of work that came from that country[27].

Another notable feature of this period was the entry of China. China, a country with the largest population, contributes only 8% of the world's G.D.P. Still it had not contributed a single paper till now. The reasons for this can be analyzed. As mentioned above, a major interest in reinforced metals originated only by late 1960s[28].

The People's Republic of China was established in 1949. The policy makers restructured the science establishment following the Soviet model, which was characterized by bureaucracy rather than professionalism and meritocracy. Under this model, the leadership of scientific organizations was entrusted to non-scientists. This adversely affected the scientific output of China because the government officials or party cadres with limited exposure to the scientific world controlled recruitment, promotions, fund allotment and even determined the research topics. Information was under state control and could only flow through official channels, research institutions ended up impotent and ineffective. This resulted in tension between professional scientists and the communist rulers of China[28].

The single biggest blow to scientific research and innovation in China occurred during the Cultural Revolution (1966-1976), initiated by Mao Zedong, the chairman of the Communist Party of China. The scientists and researchers who demanded more autonomy were punished by labeling them as "rightists" and "counter-revolutionaries" and removed from academic positions. Most scientific research stopped and in some cases, certain scientists were sent to the country side to work with the peasants to learn political virtues. Research work was done only in the field of nuclear weapons and its delivery vehicles. Universities had to shut down from 1966 to 1970. When they opened for undergraduate courses, the focus of academic programs was on political training and manual labor. The students were selected on the basis of political inclination and nepotism rather than academic performance. All scientific journals had to stop publication in 1966 and subscriptions for foreign journals lapsed during this period[28].

The Cultural Revolution ended with the death of Mao. By 1978, efforts were made to restore scientific research of the country. The 1978 National Science Conference discussed an increase of scientists and volume of research work in order to catch up for the lost time and reach international levels by the mid of 1980s. It also discussed work in fields like manned space flight, laser science and high-energy physics. Extensive debates and experimentation resulted in a March 1985 decision by the Party Central committee for restructuring of China's science system. This granted autonomy and funds for research on futuristic projects. This explains why the first paper on MMCs from China was published during this period [28].

In the figure below, we combined all the countries that published one paper each and categorized them as "Others". The countries that published one paper were Switzerland, Australia, Poland, Israel, Italy, India, and Denmark. Also, the author was not able to confirm the origin of 4 (6.15%) papers.

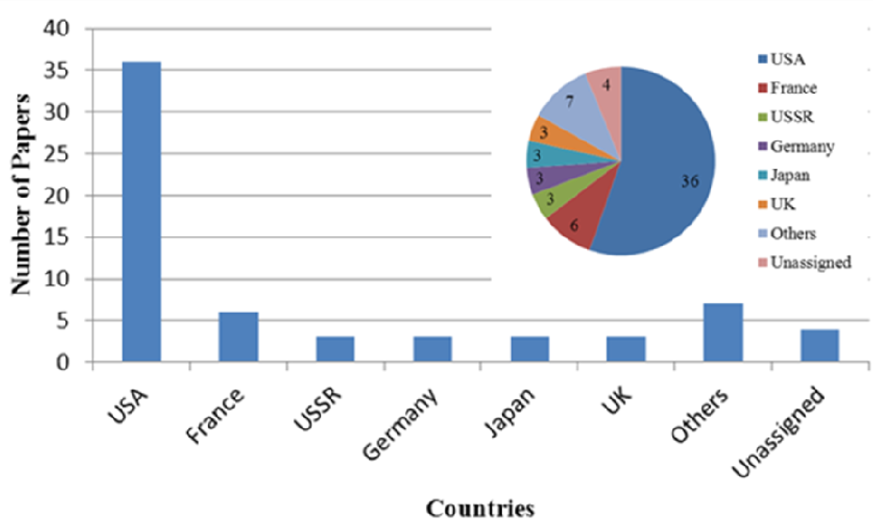


Figure 9: Number of MMC papers published from 1985-1986 divided by country

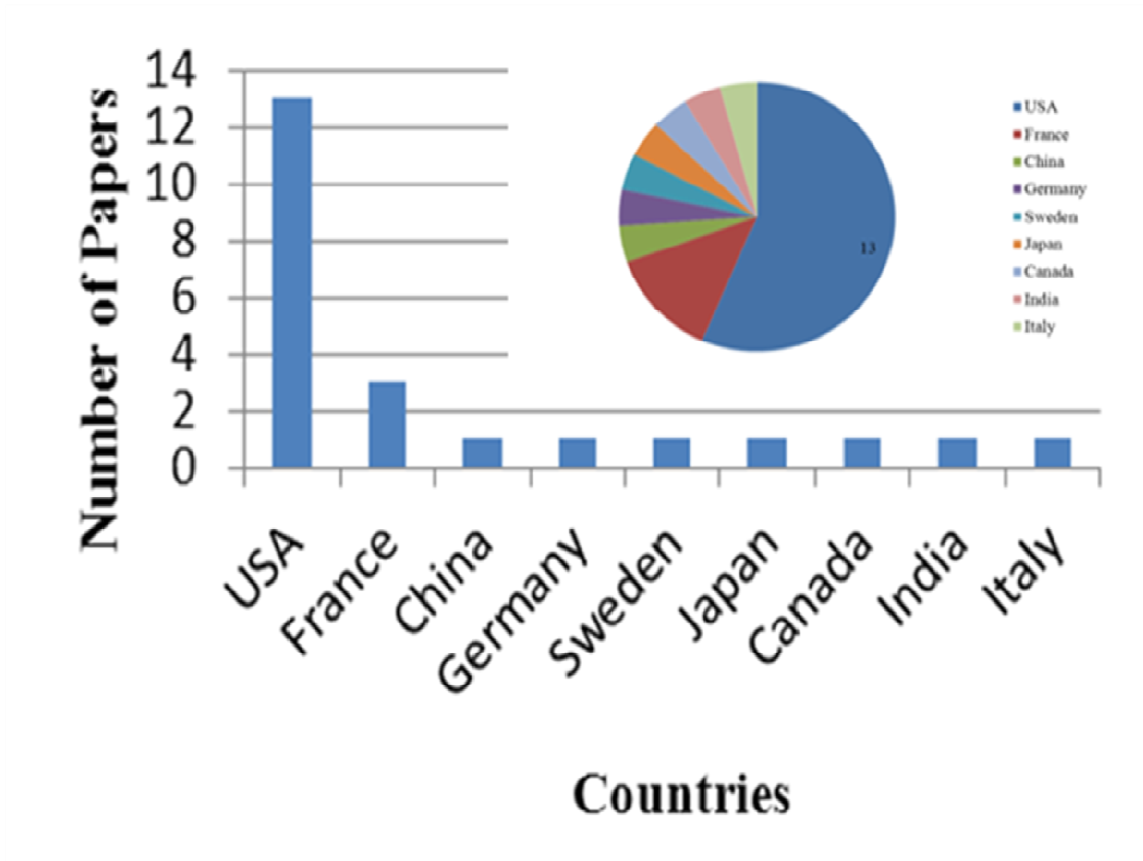


Figure 10: Number of MMC Papers published from 1987-1989 divided by country

3.10 1990-1994

In the early 1990s, the U.S. Air Force Title III program created considerable funds to create an MMC technology foundation for the aerospace industry in the U.S.A. This resulted in the development of many applications for discontinuously reinforced aluminum (DRA) that served as milestones in the future [20].

It was during this period when scientists and engineers around the world focused mainly on aluminum matrix composites. Titanium matrix composites were also researched, but less than the former. It was rare to find a paper that discussed anything other than these two materials. Continuous and discontinuous reinforcements received almost equal attention. High temperature applications of these materials were the focus.

High volume fraction powder reinforced MMCs were developed during this period for thermal management in electronic packaging. They are produced when molten metal is infiltrated on powder preforms. High concentrations of reinforcement are required here because the thermal conductivity of the matrix has to be compensated by reinforcements like Si or alumina. The demand for particulate reinforced MMCs has been increasing steadily during the period from 1981 to 1990.

The researchers of this period focused on the mechanical behavior of aluminum matrix composites. Mechanical characterization and mechanical properties in general, like stress-strain behavior, non-linear response, fracture toughness, and crack growth were thoroughly examined.

High temperature applications of aluminum matrix composites were investigated during this period, especially the creep of SiC reinforced composites. Elevated temperature response on ageing, fatigue, and ultimate strength of composites also came under review.

As mentioned above, Titanium matrix composites were also investigated during this period, primarily Ti-SiC composites. As Titanium can be considered a high temperature material, its mechanical properties and fatigue at higher temperatures was investigated.

Residual stress is an important issue for most composite materials. This issue for metal matrix composite was investigated in greater detail during this period. The investigators of that period mainly investigated the residual stresses in continuous fiber matrix composites.

Casting, especially squeeze casting is an important fabrication method for the discontinuously reinforced composites. The research that consolidated the present situation was the result of efforts during this period. Scientists and engineers studied the castability, fluidity, extrusion and defects of this process.

A number of researchers studied bi-axial mechanics of metal matrix composites during this period. The method of finding interfacial shear and matrix plasticity by fiber fragmentation was put forward by Koss, Petrich, Kallas, and Hellmann in their work "Interfacial Shear and Matrix Plasticity during Fiber Push-Out in a Metal Matrix Composite".

A study about the environmental degradation of aluminum matrix composites was also done during this period. From the data collected from the above mentioned 6 journals, the total number of papers published was 99. The number of papers published from the U.S.A was 59 (59.59%), China 10 (10.10%), U.K 8(8.08%), and Japan 4 (4.04%); Israel, Russia, France, India, and South Korea 3 (3.03%); Germany, Canada, and Taiwan 2 (2.02%); Greece, Jordan, Iran, Denmark, and Turkey 1(1.01%).

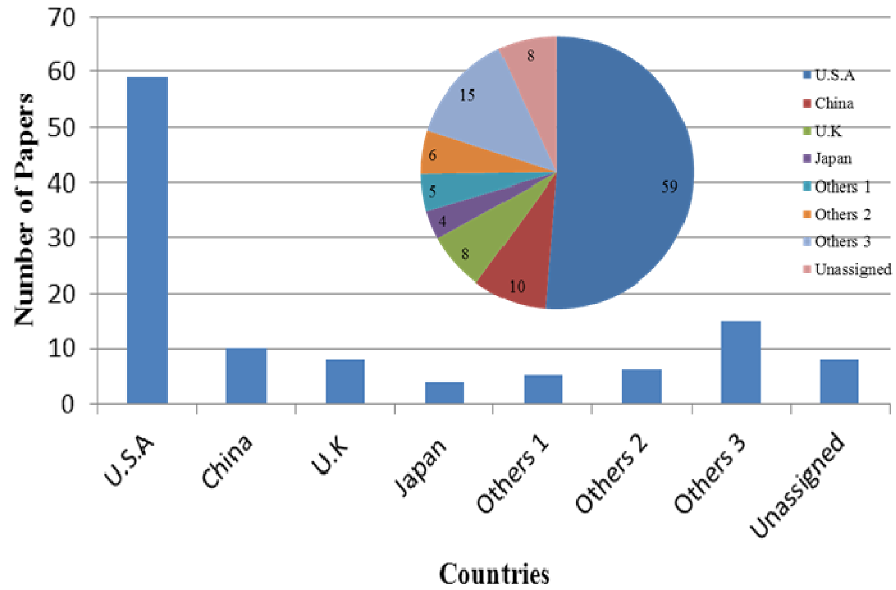


Figure 11: Number of MMC Papers published from 1990-1994 divided by country

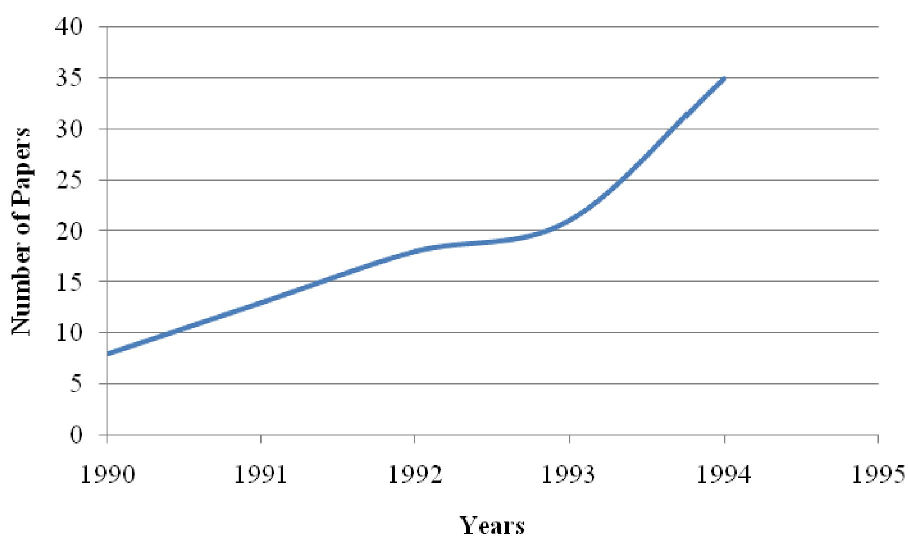


Figure 12: Total Number of Papers published from 1990-1994

In the figure below, we combined all the countries that published one paper each and categorized them as “Others 1”, the countries that published two papers as “Others 2”, and countries that published three papers are “Others 3”. The countries that published one paper are Greece, Jordan, Iran, Turkey, and Denmark. The countries that published two papers were Germany, Canada, and Taiwan. The countries that published three papers were Israel, Russia, France, India, and South Korea. Also, the author was not able to find the origin of 8 (7.47%) papers.

One notable aspect of this period, the number of journal articles coming from the U.S.S.R ceased by 1992. The reason was that country ceased to exist in 1991. The economy of Russia after the collapse of Soviet Union was in crisis. The funding for research even in key areas like defense and space froze and the country had to face massive defection of researchers. Many futuristic projects like Sukhoi-47 and Buran stalled or cancelled. This situation continued till the economic boom of the 2000s[27].

The number of journal articles from China increased from 1 to 10 within a span of 5 years. After the death of Mao Zedong, Deng Xiaoping made his way up to China's leadership.Even though he was never the paramount leader of the country, his policies led the country on the road of economic reform and openness. This had effects in Chinese science and technology. Innovation and research were recognized the driving force for economic development[29].

3.11 1995-1999

Aluminum matrix composites were the main focus of this period; however Titanium matrix composites got ample attention. By the mid 1990s, a number of MMCs were used in space applications like SiC reinforced aluminum for wings and blades, SiC-reinforced copper for rocket nozzles and Al2O3 reinforced aluminum for fuselage.

Researchers experimented with the mechanical properties, interfacial properties like imperfect bonding, stress distribution, F.E.M modeling and damage evolution of Titanium composites reinforced with SiC fiber. The origin of most work was from the U.S.A, but Western Europe's contribution was also considerably high. Titanium matrix composites reinforced with other reinforcements like carbon fibers and TiB single crystals were also subjected to investigation like their fatigue life, interface chemistry and residual stresses developed inside the composite.

A notable development of this period was the importance given by researchers to the interface properties in metal matrix composites. They thoroughly investigated the effect of heat treatment, and residual stresses. The advent of computer brought the advantage of numerical simulation for research pertaining to microstructure and stress predictions.

Researchers investigated the effects, reduction, and modification of residual stresses on metal matrix composites with great interest. Research was done on the influence of residual stresses on the interface of reinforcement and matrices.

The influence of reinforcement orientation particle orientation and size and fiber angles was investigated. The ageing of metal matrix composites received attention during this period.

Magnesium matrix composites received unusual attention, especially those reinforced by SiC particles. Their potential applications are in the ground transportation industry, like gears, gear box bearings, shift forks and disk rotors[30].

A number of papers discussed fiber-push out tests of MMCs. A major development during this period was that the publications discussing hybrid matrix composites increased. Aluminum matrix composites were combined with materials like steel or carbon and employed as matrices.

Based on the 6 journals listed above, the total number of papers published was 229 an the increase of 56.8%. This considerable increase can be attributed to the increase in the number of papers from China as well as other countries like France and Israel, who did not contribute significantly in the past. The number of papers from the U.S.A was 66 (28.2%), China 35 (15.3%), France 16 (6.9%), Israel 13 (5.68%), U.K 13(5.68%), Japan 12 (5.2%), Australia 9(3.9%), South Korea 8(3.5%), Hong Kong 7(3.05%), India 7(3.05%); Singapore, Italy, Germany, Singapore, and Slovenia 4 (1.75%) each (indicated as Others 4 in the figure below); Canad and Turkey published 3 (1.3%) each , Russia, Taiwan, Denmark, Iran, and Spain 2 (0.8%); and Austria , Ireland, New Zealand, Belgium, Switzerland, Finland, and Ukraine 1(0.8%)(indicated as Others 1 in the figure below).

The surge of papers from China has been explained before. The absolute absence of Russia was due to the economic collapse that happened in country that resulted in hyperinflation. The GDP of that country shrunk to 40% between 1991 and 1998[27]. The sovereignty of Hong Kong was transferred from United Kingdom to the People's Republic of China in 1997, however till date the journal articles are published with the Hong Kong address.

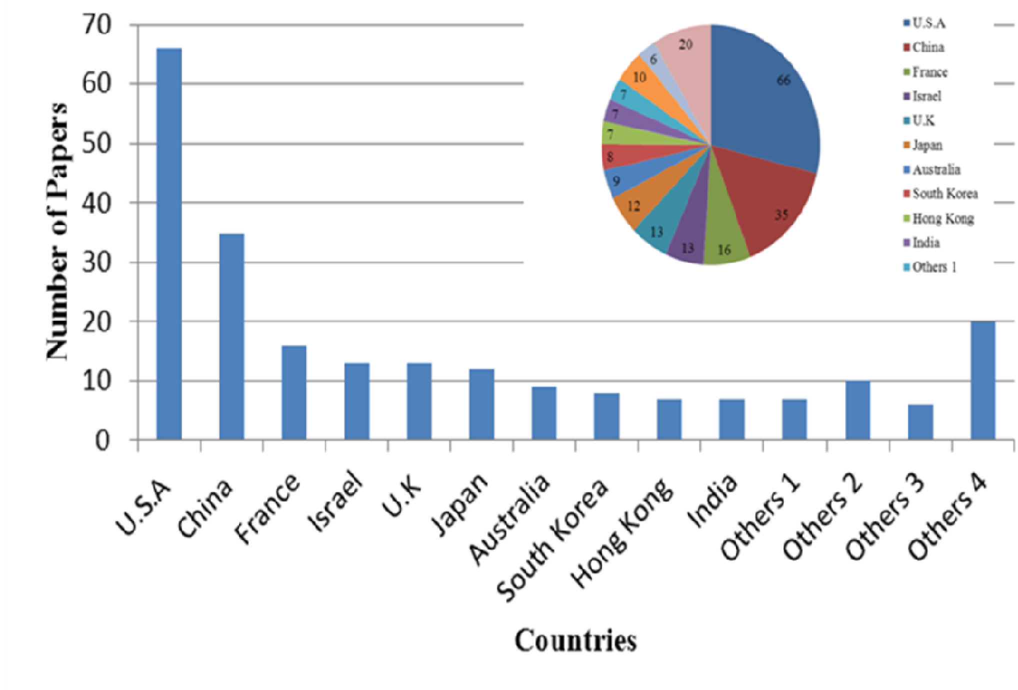


Figure 13: Number of MMC Papers published from 1995-1999 divided by country

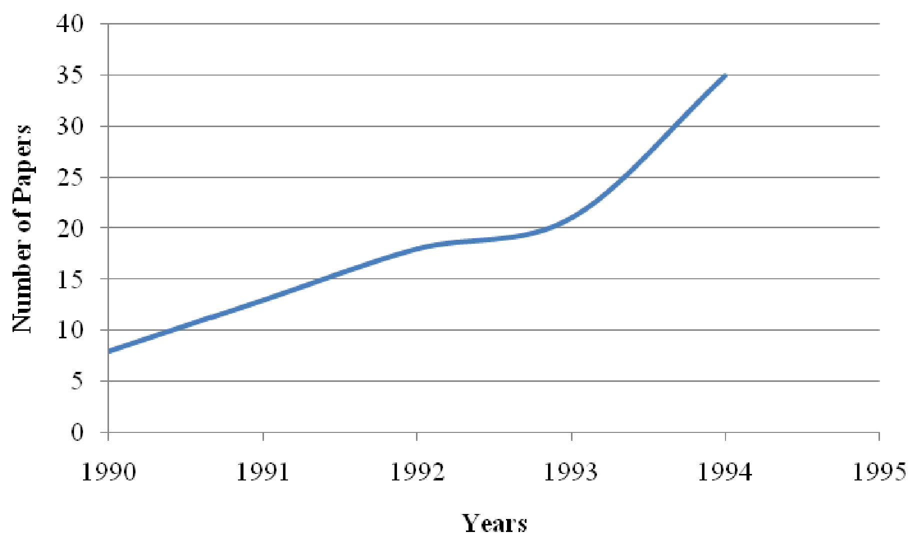


Figure 14: Total Number of Papers published from 1995-1999

3.12 2000-2004

The researchers of this period focused mainly on the fabrication issues of metal matrix composites. Welding aluminum and titanium matrix composites were examined during this period. Friction stir welding in particular garnered attention from researchers. Experts researched spark plasma sintering of titanium matrix composites reinforced with TiB. Sintering as a process was also examined. Scientists from Turkey studied the drilling of Al matrix composites reinforced with SiC particles. Milling of magnesium alloys were explored during this time. Squeeze casting of aluminum matrix composites were investigated by scientists and engineers. The origin of papers that discussed this subject was mainly from China and Turkey. Researchers from Turkey initially concentrated on the design aspects of MMCs, but slowly they diversified their focus to other key issues of this material.

Wear, friction behavior and dry sliding characteristics were studied during this period by investigators mainly from Asian countries like China, Japan and India. They mainly discussed aluminum and stainless steel matrices, TiNi matrices and Ni-Mo matrices.

During this period also, magnesium and copper matrix composites got ample attention. Magnesium was alloyed with aluminum and titanium for structural strength for use as matrices for MMCs. The origin of most of these journal articles are China, India and Singapore. Scientists mainly focused on the thermal properties of copper matrix composites. A notable development of this period was the increase of papers that dealt with nano-composites. Magnesium was the most common matrix used and the source of most of the papers was from China. Use of cellular materials in metal matrix composites was used in MMCs during this period.

Another notable development of this period was the papers that discussed stress analysis of metal matrix composites. Onur Sayman, a researcher from Dokul Eylul Univeristy (Turkey), did pioneering work in elasto-plasto stress analysis of metal matrix composites reinforced with continuous fibers made significant contributions by varying temperature linearly and parabolic ally. Some papers also discussed the stress analysis of discontinuously reinforced metal matrix composites, both aluminum and titanium.

From the six journals reviwed, the total number of papers published was 213, a nominal decrease of 7.5%. The number of papers from China was 34 (15.9%), the U.S.A 20 (9.4%), Turkey 22 (10.32%), South Korea 20 (9.4%), Germany 17 (7.98%), the U.K 15 (7.04%), France 15 (7.04%), India 14 (6.57%), Japan 11(5.16%), Singapore 9 (4.22%), Italy 9 (4.22%), Hong Kong 6 (2.8%), Canada 6 (2.8%), Russia 5 (2.3%), Australia 5 (2.3%), Spain 5 (2.3%), Switzerland 4 (1.87%), Egypt 4 (1.87%), Taiwan 3(1.4%), Jordan 3 (1.4%); Netherlands, Mexico, Slovenia, Austria, Iran, Canada, Malaysia, Iran, and Brazil is 2(0.9%); and Chile, South Africa, Finland, Ireland, and Portugal is 1(0.5%).

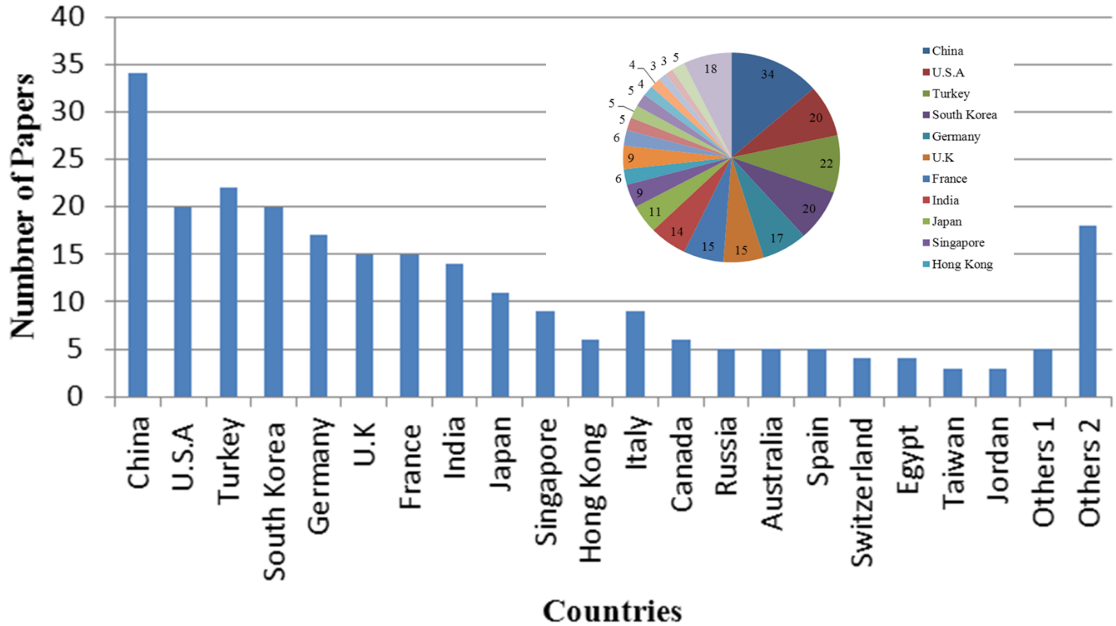


Figure 15: Number of MMC Papers published from 2000-2004 divided by country

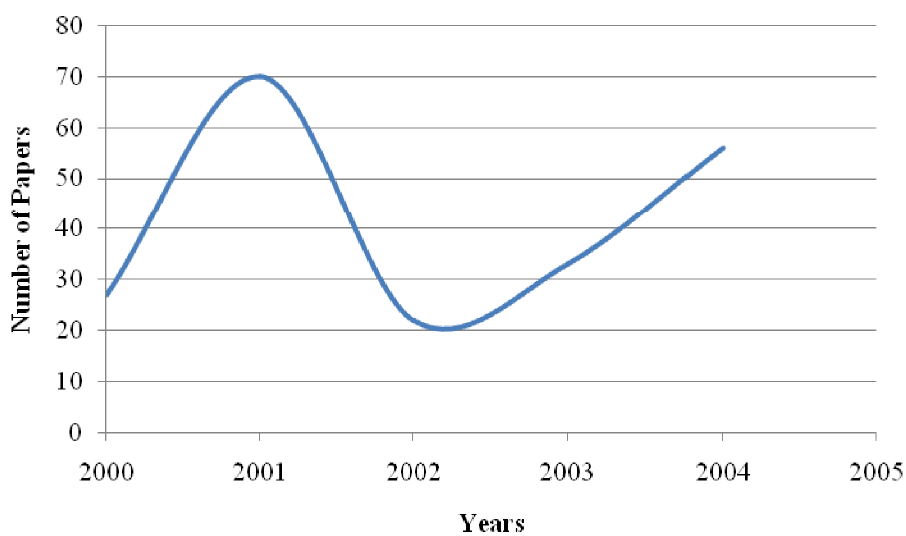


Figure 16: Total Number of Papers published from 2000-2004

the first time in history that the People's Republic of China overtook the U.S.A in the number of papers published. The fraction of papers published from the U.S.A decreased considerably from periods 1970-1974 and 1980-1984, but the fraction of papers published from China increased considerably over the time.

Boeing launched their 787 Dreamliner project in January 2003. This event was a turning point in the evolution of polymer matrix composites. Approximately 80% by volume and 50% of its weight of the whole aircraft is made with composites. Each aircraft contains approximately 35 tons of carbon fiber reinforced polymer[31]. Also, the "V-22 Osprey" tilt-rotor program of Boeing used 50% of its weight as polymer matrix composites[32]. However, both these programs having focused on polymer matrix composites did not significantly improve the development of metal matrix composites. From the period from 1990-1994 onwards, the number of countries contributing to the research of MMC is increased sharply. A number of new players started to emerge around the world, and the number of papers form major players in the past started to diminish. This is a tendency of the 'world getting flatter'.

If we observe closely the countries of origin of the published articles, we see that a considerable contribution happened from Asian countries like China, South Korea, India, Japan, Singapore, Hong Kong, Taiwan, Jordan and Iran. We see almost the same pattern during the previous period also, even though this aspect is not that visible.

The reason for the increase of papers from China has already been discussed. South Korea has emerged as the one of the most technologically advanced and digitally connected countries. Its political and commercial capital is known as the "tech capital of the world" [13]. The economic liberalization in India occurred in 1991. Since then that country has achieved 6-8% growth for quite a long period of time and its economy has improved very well [15]. The MMC research in Japan is mainly driven by the automotive industry.

Another point to be noted here is Russian Federation published 5 papers. By the end of 1990s, the Russian economy stabilized and by early 2000s they re-launched their discontinued development projects like Mig 1.44/1.42 and Sukhoi-47/PAK FA, latter uses composite parts extensively on its airframe [3].

3.13 2005-2009

The most notable aspect of this period was the sudden increase in the number of papers that apply nanotechnology in the MMC research. Most of the articles discuss nano-particles reinforced MMCs and some discuss carbon nano-tube reinforced metal composites. A couple of papers discussed nano-fiber reinforced composites. Most of them studied how to improve the mechanical properties, like compressive response, ductility and fatigue. The production and heat treatment aspects of nano-composites were also discussed. That nanotechnology was used widely in metal matrix composites does not mean researchers only investigated reinforcement particles and fibers used to strengthen matrices. Characterization techniques like nano-indentation and nano-coatings were discussed by many. Some studied nano hybrid composites. Magnesium alloy matrices were the most commonly used matrices.

Another point that worth mentioning is the country of origins of the papers that researched nanotechnology in MMCs. The highest contributor in this case was Singapore. The Department of Mechanical Engineering at the National University of Singapore made valuable contributions in this particular area of study.

Hybrid technology was also widely used during this period. Most of them discussed mechanical properties and characterization issues. An interesting point to be noted is that the origin of most of the papers are from Asian countries like South Korea, China and India contrary to the usual domination of Western countries. Though fiber metal laminates cannot be strictly considered as metal matrix composites, a considerable number of papers were published during this period. Researchers of Delft Institute of Technology, Netherlands made significant contributions in this field.

A considerable number of papers discussed the use of metal matrix composites for ballistic protection. The response of high velocity impact on different MMCs was examined during this period. They studied the macroscopic response/damage of metal matrix composites after high velocity impact. Also, some investigated the low velocity impact response of composite sandwich panels with foam core.

Metallic foams and sandwich panels were subjected to detailed investigation. Ceramic foams were used to reinforce Al matrix composites. Also sandwich panels were reinforced with Aluminum foam cores. L.Z. Zao *et.al*. published “Thermal Expansion of a Novel Hybrid SiC foam–SiC particles–Al composites” that discusses hybrid reinforcement (SiC particles and SiC foams) for Al matrix composites. A. Daoud *et.al.* published “Fabrication, microstructure and compressive behavior of ZC63 Mg–microballoon foam composites”. Fly ash micro-balloon foam was used as reinforcement in Magnesium alloys. The effect of fabrication factors like pouring temperature, dimensions and types of stirrer, melt temperature and mold type on distribution of the fly ash balloons were discussed.

During this period, we saw a general increase in the use of Magnesium matrix composites reinforced with SiC particles. The reasons for the high demand of Mg matrix composites are low density, high specific stiffness, high wear resistance and good creep strength. Magnesium matrix composites are mainly used in lightweight automotive brake systems and aerospace applications like engine parts, gears-boxes, transmissions and compressors.

In 2005, D.B Miracle published his work “Metal Matrix Composites – From Science to Technological Significance”, which traced the path of MMCs from its origin to the present and attempted to predict its future.

The number of papers published during this period was 217. Here also, there is a nominal increase of 1.8% in the number of papers. The number of papers published by China was 57 (26.26%), the U.S.A 35 (16.12%), U.K 22 (10.03%), Turkey 25 (11.5%), Italy 19 (8.75%), France 18 (8.29%), Singapore 18 (8.29%), Spain 16 (8.3%), India 15 (6.9%), Germany 14 (6.5%), Hong Kong 12 (5.5%), South Korea 11(5.07%), Japan 9 (4.14%), Iran 9 (4.14%), Australia 7(3.2%), Canada 5(2.3%), Austria 5(2.3%), Czech Republic 5(2.3%), Slovak Republic 4(1.8%), Sweden 4 (1.8%); South Africa, Mexico, Switzerland, Netherlands, Russia is 3 (1.38%); Taiwan, Brazil, Ukraine is 2 (0.9%); and Slovenia, Portugal, Jordan, Poland, Brazil, Poland, Belgium, Egypt, Finland, Vietnam, and Venezuela is 1(0.4%).

During this period, the list of countries that has contributed has increased tremendously.

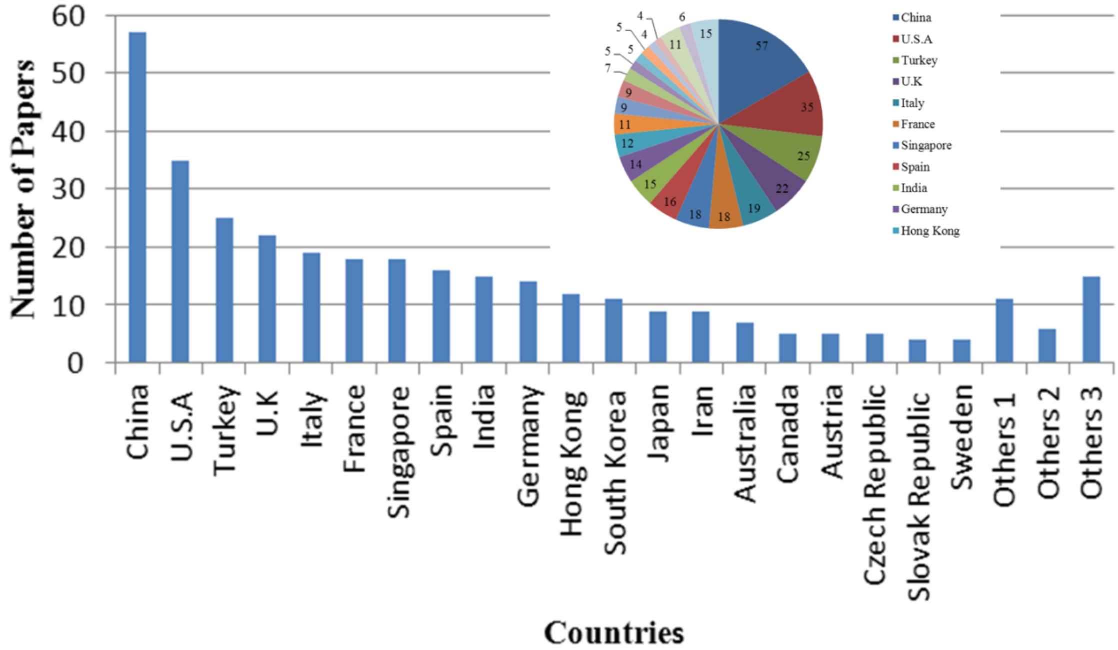


Figure 17: Number of MMC papers published from 2005-2009 divided by country

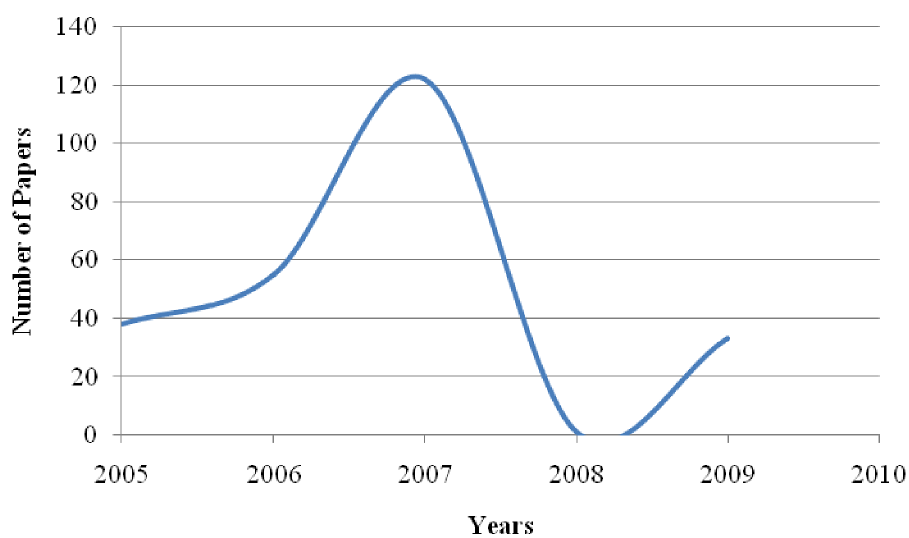


Figure 18: Total Number of Papers published from 2005-2009

3.14 2010

The period that has to be discussed next is 2010-2014. However, this report is being prepared in the later part of 2010. By observing the developments this year, the author observes reasonable similarity in the nature of journal articles published to the previous. Single and multi-wall nanotube reinforced metal matrix composites were used to reinforced copper and aluminum matrix composites. Some papers discussed nano-rods and nano-fiber composites. Nano-particles of Al2O3 were used to improve the mechanical properties of magnesium matrix composites. Aluminum foam sandwich panels also displayed their presence this year.

As mentioned before, magnesium matrix composites continue to show importance this year, it is on par with titanium matrix composites. Researchers clearly see potential and room for research for in magnesium matrix composites. Another area to be noted, a number of metal matrix composites reinforced with oxides of the matrix, for example AZ91D magnesium alloy reinforced with Mg2B2O5 whiskers, tungsten matrix reinforced with tungsten wire (with ZrOx coatings), and aluminum-alumina composites.

A total of papers published are 42. China published 8 (19.04%), India 6 (14.28%), Singapore 4 (9.5%), South Korea 3 (7.14%), Germany 3(7.14%), Austria 3 (7.14%); U.S.A, Spain, and Japan is 2 (4.76%); and France, Netherlands, Egypt, Switzerland, Australia, Czech Republic, Iran, and Saudi Arabia is 1(2.4%).

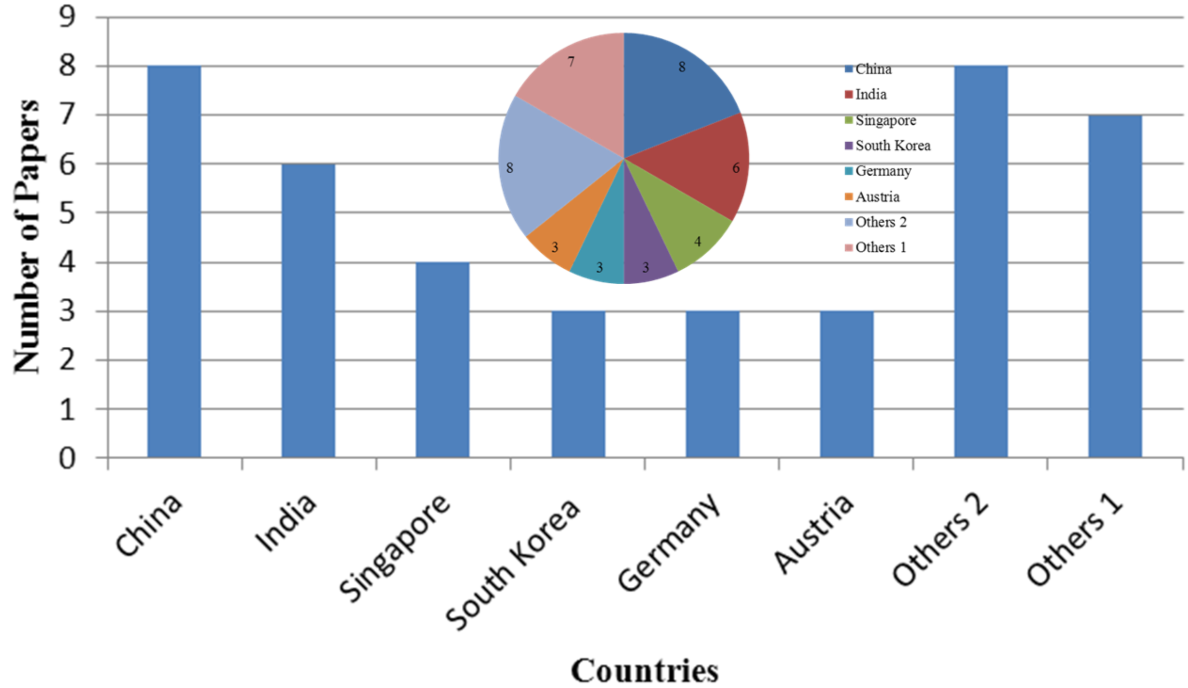


Figure 19: Number of MMC Papers published in 2010 divided by country

3.15 Influence of 2008-2009 recession

The Western World, particularly the U.S.A was hit by a recession in 2008-2009. It may adversely affect the volume of work from the U.S.A and the Western hemisphere in general. On the other hand, due to recession quite a large number of students may return to graduate school. This may increase the research volume in the near future. The newly elected Democratic government headed by President Barack Hussein Obama enacted the American Recovery and Reinvestment Act of 2009, abbreviated ARRA or widely known as the Stimulus Plan. According to this, National Science Foundation (N.S.F) received $3 billion, NASA received a $1 billion and United States Department of Energy received $2 billion [33]. The funds may rejuvenate the research efforts from this country. However, the research projects funded by the private sector may suffer. The

U.S.A's annual defense budget has been growing around 10% in recent years, but it is unlikely to rise after 2011.

The recession of 2008-2009 adversely affected European countries like Iceland, Greece, Ireland, and may affect Spain and Belgium. During the time of writing, Germany has almost survived the recession. The new Conservative government in of the United Kingdom has decided to cut down the military spending by 8% over the next four years [16]. Germany also plans to do so. The U.K and France even plan to share its aircraft carriers [19]. All these developments may negatively affect the research on MMCs in the near future. The Russian economy steadily grew from 1999 to 2008, thanks to the economic policies of the Russian President (Prime Minister during writing) Vladimir Putin. But in October 2008, Russia was one the worst hit economies of the global financial crisis. However, during the time of writing, the economy has bounced back to the pre-crisis levels. Some of the cutting edge defense projects have been launched by the Russian government[34].

The major applications of metal matric composites are in the defense sector. As mentioned above, the defense budgets of the U.S.A, the U.K and Germany may shrink in the near future. The unified Europe is looking at the U.S.A and the N.A.T.O's defense umbrella. So we cannot expect great research volumes from that part of the world. The global financial crisis did not affect the India very much, because the exports only contributed 15% of its GDP. It is one of the fastest growing countries in the world at a rate of 7.2% [15]. Consecutive governments have been investing heavily in research and development especially in strategic sectors like defense, space and power generation.

Metal matrix composites have applications in all these sectors, so we expect considerable research efforts from this country.

A few countries that was least affected by the recession was Japan and China. During the time of writing, China is the second largest and Japan the third largest economy in the world. China has growth rate of 10%. Their defense budget has steadily increased from 1999 onwards. The People's Liberation Army has elaborate plans for modernization that includes many cutting edge projects like J-14 and J-15 fighter planes[35]. They have an advanced space program that has already put human beings on space. The U.S.A and the U.S.S.R/Russia are only two countries that have attained that achievement. Author had noticed that some universities like Harbin Institute of technology, Tsinghua University, Shanghai Jiao Tong University, Tohoku University and above all Chinese Academy of Sciences have been contributing heavily to the research efforts of metal matrix composites. Considering all these factors, we predict the research efforts from countries like China and India will be greater when compared to the efforts from the Western World.

CHAPTER-IV

4. Patterns in the Evolution of Metal Matrix Composites

The total number of journal articles published over different periods has been plotted below. One plot describes the evolution from 1950 to 1986. Another plot describes the evolution based on the publication of 6 top journals listed above.

4.1 1950-1986

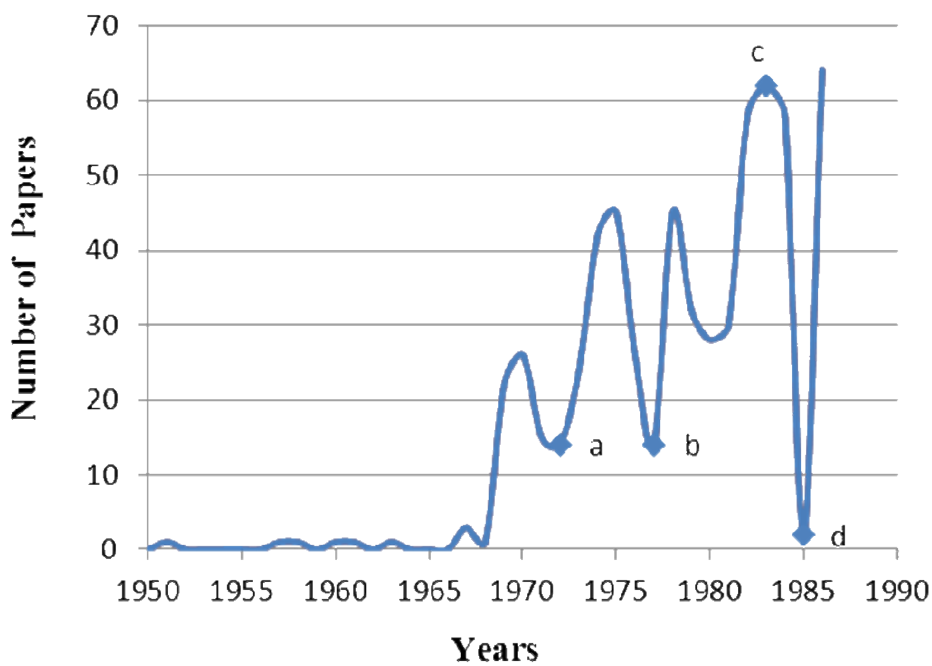


Figure 20: Total Number of Papers published in the period 1950-1986

Here we see that the development of metal matrix composites occurred during the second part of 1960s. The U.S.S.R launched the "Sputnik" in 1957. This served as the opening shots of the “Space Race” between the super powers. The need for light-materials that can handle temperatures up to 1500 °C was felt during this period. The first lunar landing occurred in 1969 (Apollo 13) and the last was in 1972 (Apollo 17) [1]. By the late 1960s, the scientific community in the U.S.A started to loose interest in the space program. The target of landing a man on the moon had been achieved. Also, the public started to forget the dangers of Nuclear War as the panic of the Cuban Missile Crisis that occurred in October 1962 started to weaken from the public memory. This resutled in reduced funding for research of high temperature materials used in space rockets and ballistic missiles. This resulted in the slump of papers from USA during the early parts of 1970s (see a).

Scientists started to think of re-usable space-crafts by the end of 1960s. This required light-weight materials that have a combination of properties like high strength and stiffness, high temperature resistance and low co-efficient of thermal expansion and high thermal fatigue. This reason can be cited for the steep increase in papers from 1969 to 1976, despite small fluctuations. The explosion in journal articles started from 1969. The first moon landing happened in that year. However, the author does not see any causality between these two event.

We see a slump in the number of papers in 1976 and 1977 (see b). This can be explained as the after-effect of 1973-1975 recession that happened in the Western World. However, the drop was not that drastic because countries like Japan and U.S.S.R. were not affected. The high number of journal articles from those countries compensated for the reduction in papers from U.S.A. Still, the recession affected the research for MMCs because in those days U.S.A contributed approximately 40% of the world GDP. The world recovered from that recession by the end of 1970s, the number of journal articles increased steadily (see c). By the beginning of 1980s, private sector especially from Japan started to take note of this material. Their automotive industry, mainly Honda and Toyota started incorporating MMCs in their auto-motives [30].

A recession hit U.S.A. in the early 1980s (July 1981 to November 1982). This might have contributed to the slump in the number of papers in 1982 (this claim has not been supported by any other source, see d).

4.2 1987-2010

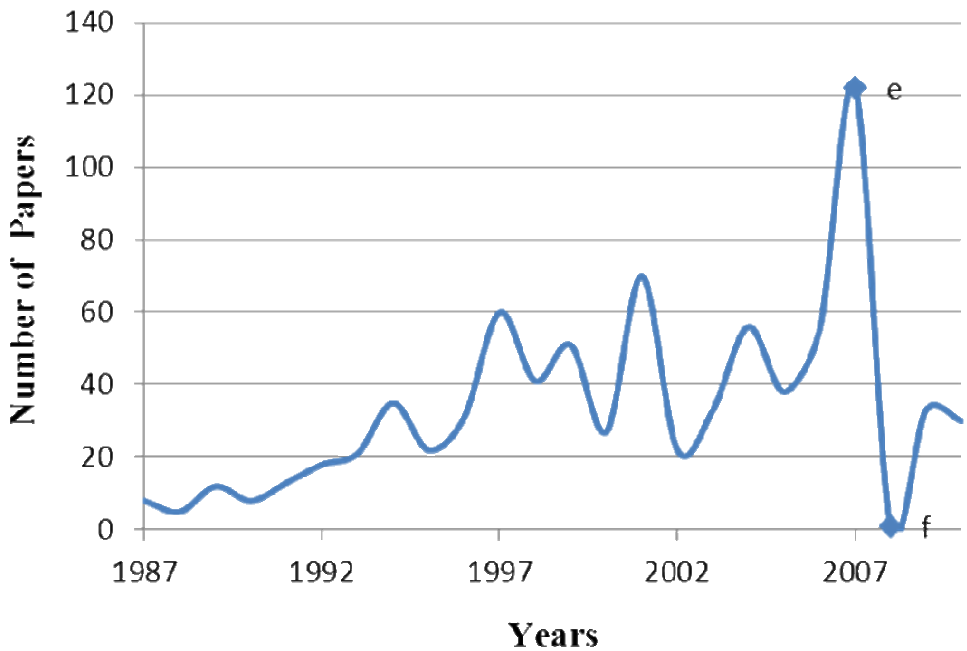


Figure 21: Total Number of Papers Published in the period 1987-2010

As mentioned above, from 1987 onwards the author has listed papers from 6 journals. Here we see that, despite small fluctuations, the number of papers increased almost steadily till 2000. As mentioned in detail before, China started to contribute during the end of 1980s. Slowly and steadily, they became major players in determining the direction and future of metal matrix composites research. Large number of papers from China increased the total volume during mid-2000s (see d).

By this time, the center of gravity of metal matrix composites research shifted from the West to the East. The future of metal matrix composites can only be predicted by analyzing their future meticulously. By the second part of 2000s, we see a dip in 2008 (see f). It may be due to the ongoing recession that started in 2008.

If we analyze the evolution of metal matrix composites, the major contributors to this research effort are the U.S.A., the U.K., Russia/U.S.S.R., Japan, and China. The contribution of these nations is shown in the form of a bar diagram.

From 1950-1986

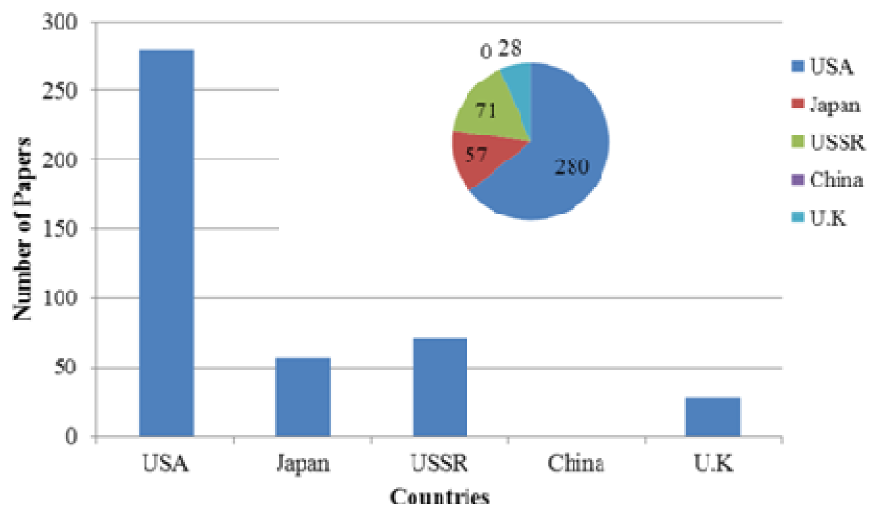


Figure 22: Major Contributors from 1950-1986

From 1987-2010

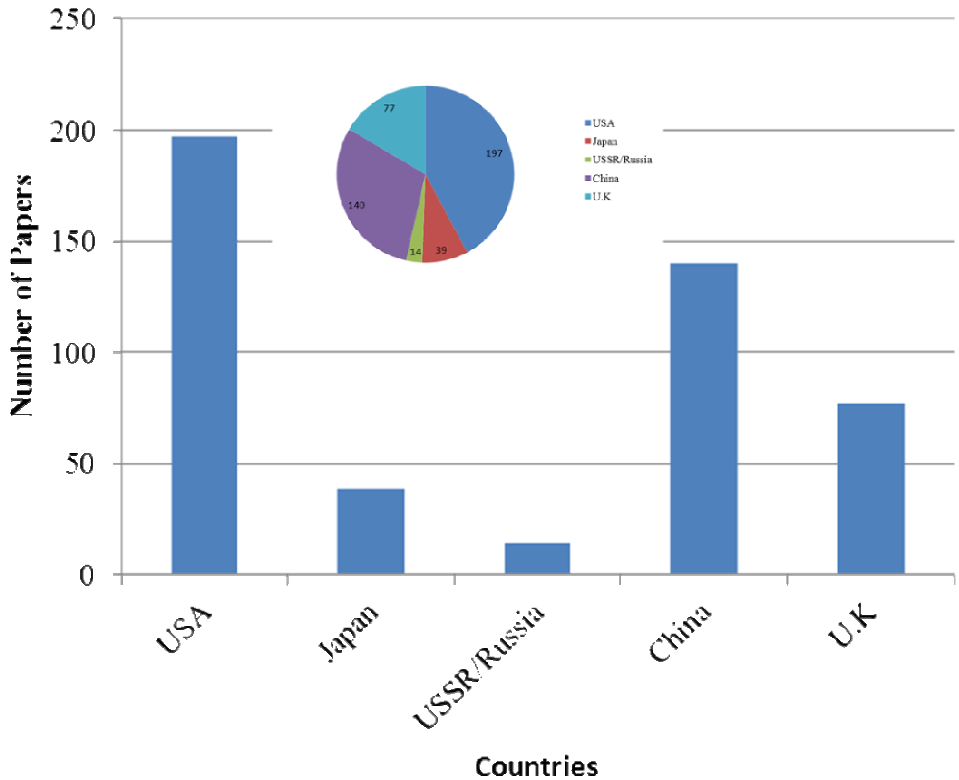


Figure 23: Major Contributors from 1986-2010

Here we see that even during the Cold War, U.S.A was the undisputable leader in MMC research. However, in the post-Cold War era, China is catching up U.S.A.

Here we evaluate the pattern of their individual contribution over time.

4.3 USA

From 1965-1986

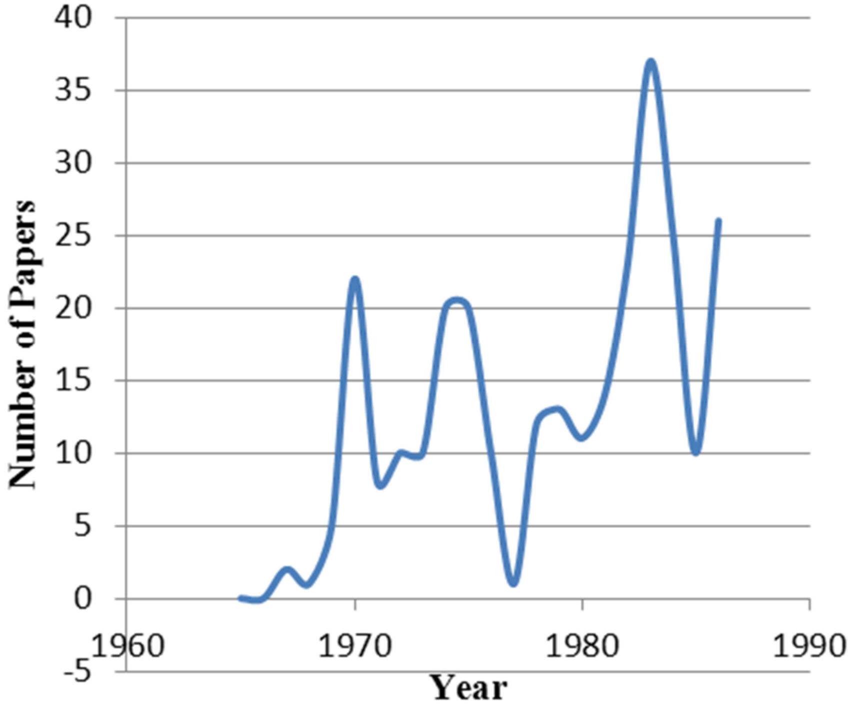


Figure 24: Number of Papers published from USA in the period 1965-1986

The research on metal matrix composites was primarily commenced in the U.S.A. The total number of papers that was published from the U.S.A. from 1965 to 1986 is 287. The reason for the surge of papers in 1970 can attributed to the plans to build reusable space-craft after the Apollo missions. The fall in the number of papers by the mid-1970s can attributed to the early 1970s recession. The country got back to the pre-recession levels by around 1978. The fall in numbers in 1984 may be because of the recession that happened in the U.S during the early 1980s[36].

From 1987-2010

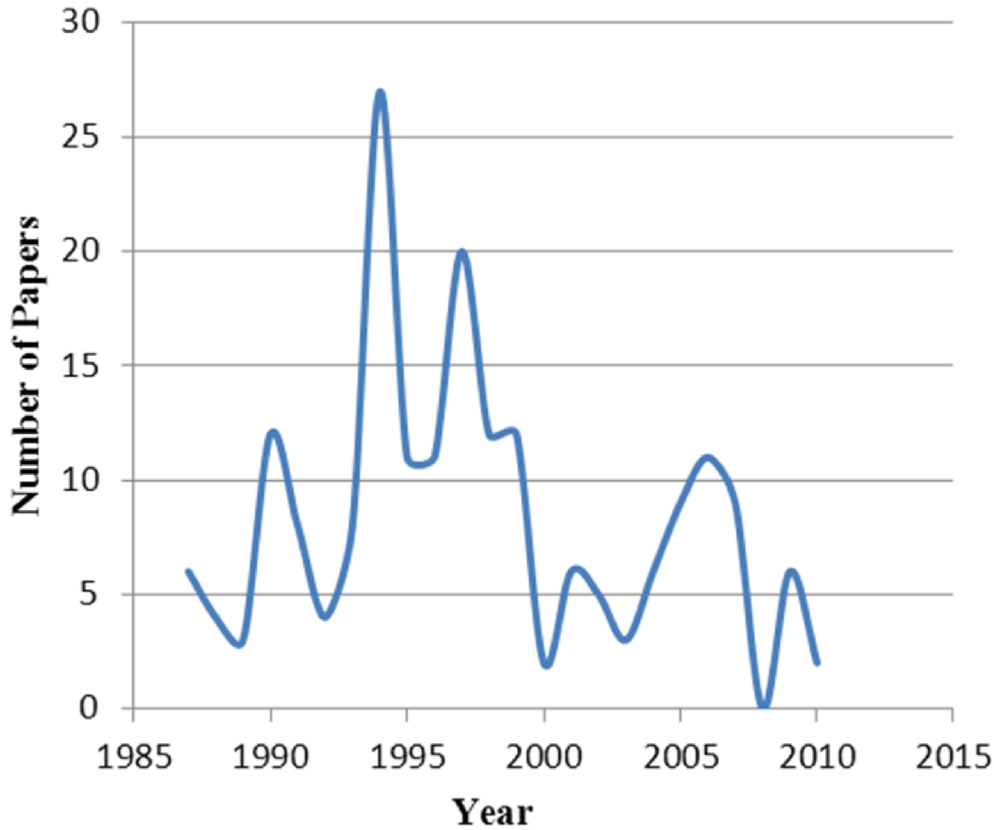


Figure 25: Number of Papers published from USA in the period 1987-2010

The analysis from 1987 to 2010 was performed after studying 197 papers published in 6 journals. The number of papers was in the upward swing till the end of 1990s. The U.S Air Force was developing the YF-22 (later became F-22 Raptor) and Joint Strike Fighter (later became F-35 Lightning II) during the latter part of 1980s and early part of 1990s. Both these aircrafts use considerable amount of composites on their airframe. This might have been the motivation for the research on MMCs during the period [23].

But from 2000 onwards, we see a decline. It can be due to two reasons (1) no challenging air-force projects that require heavy use of MMCs has been announced yet.

As of now, U.S.A. is the only air force that possess 5th generation aircrafts. Other countries like China (J-13 and J-15), Russia (Mig 1.44/1.42 and Sukhoi PAK FA), India (Medium Combat Aircraft/Sukhoi/HAL FGFA), and Japan (ATD-X) are still trying to develop aircraft of this class. The future of NASA projects like Ares and Orion are still facing uncertainty[37]. So the scientific community of this country lacks ample motivation or funds to work on high-temperature, high thermal fatigue resistant materials like this.

However, after the global financial crisis in the later part of 2000s may play a crucial role in the future of the MMC research from this country.

4.4 United Kingdom

From 1965-1986

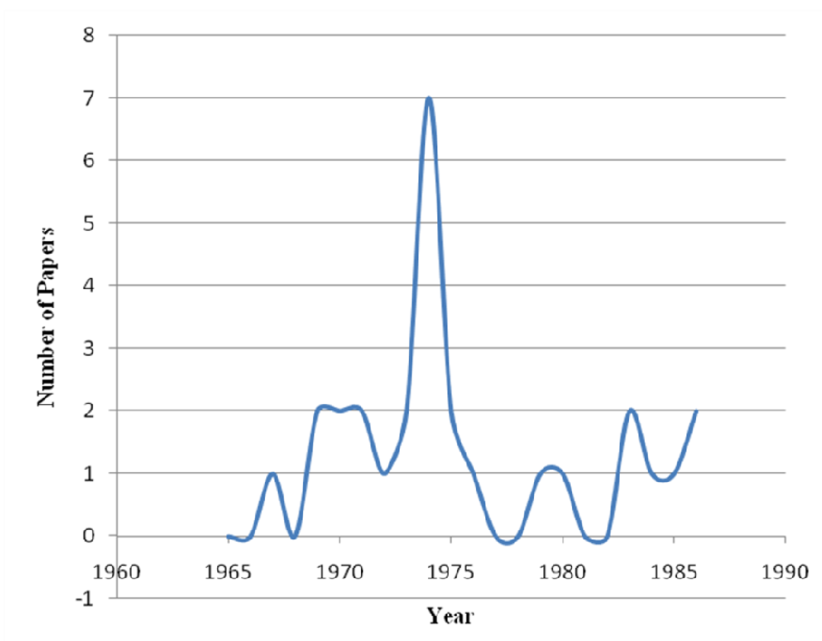


Figure 26: Number of Papers published from USA in the period 1965-1986

As in 1965-1986, the research from UK was largely influenced by the work done in the U.S.A. The research done in United Kingdom was mainly coupled with the research done in United States. The largest share of papers on metal matrix composites occurred during 1970-1974. The Eurofighter Typhoon project was also launched during this period. This could have been a motivation for the development of high temperature materials [24]. From 1960 to 1986, the share of journal articles published from UK is less when compared to countries like the U.S.A, the U.S.S.R and Japan. However, they always made their presence felt.

From 1987-2010

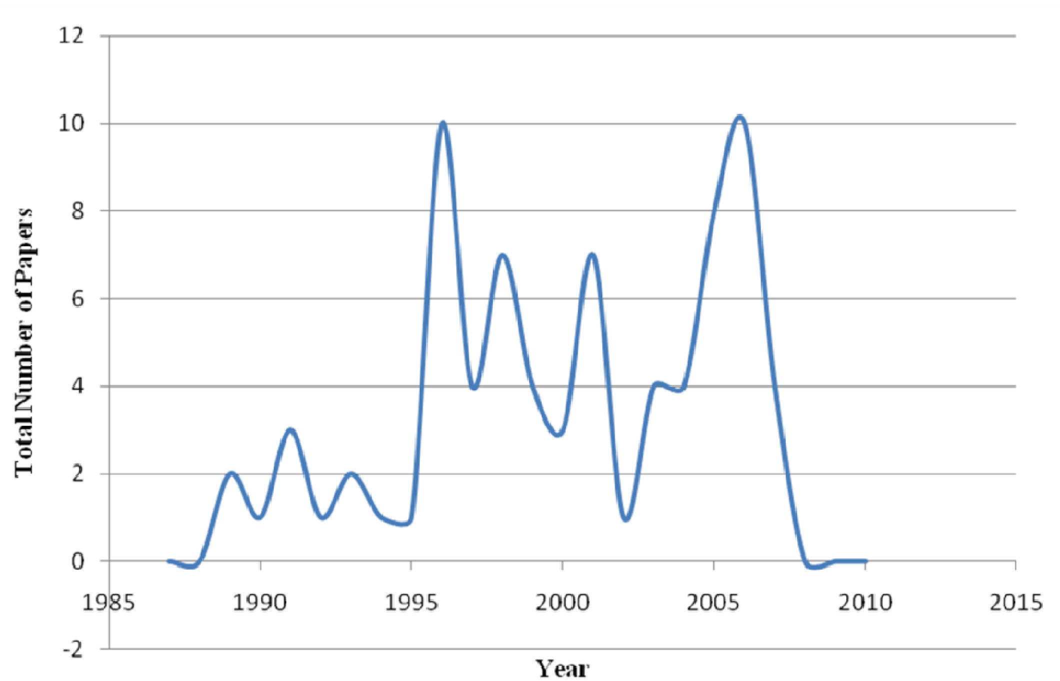


Figure 27: Number of Papers published from USA in the period 1987-2010

The two major surges we see occurred during the period 1995-1999 and 2005-2009. The U.K was a key contributor in the Joint Strike Fighter development program during late 1990s. This could have been the reason for the surge in the number of papers during that period [18]. The economic boom that occurred in the mid-2000s resulted in large research volumes during the middle part of 21st century. BAE Systems launched a number of futuristic projects like Taranis (UAV project) [21].

The Skylon project was launched by Reaction Engines Limited for an air-breathing single-stage to orbit, unpiloted, combined cycle jet engine based space plane. By the mid-2000s, British Government's British National Space Centre and European Space Agency started supporting the program [32]. This creates a need for high temperature materials like ceramic matrix composites and metal matrix composites. This may be the reason for the surge in the number of papers during 2005-2009. However, the recession that affected the Western World resulted in the drastic drop of research work during 2008 and 2009.

4.5 U.S.S.R

From 1965-1986

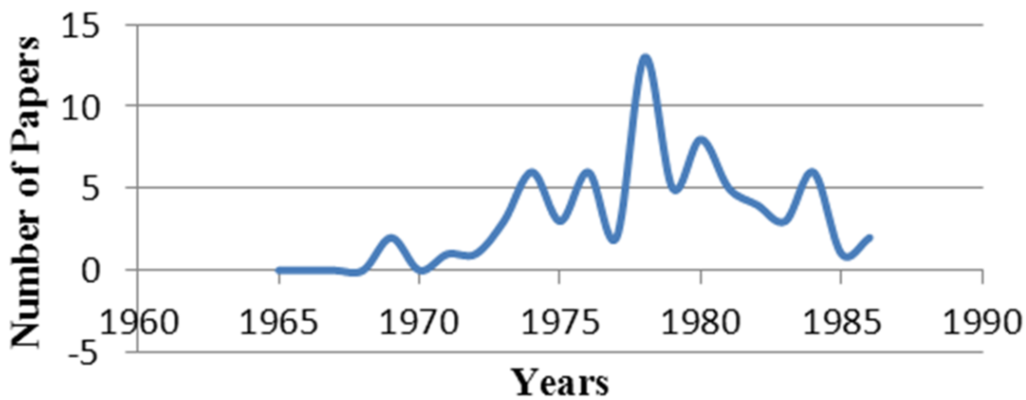


Figure 28: Number of Papers published from U.S.S.R in the period 1965-1986.

The Soviet defense and space program was the prime driver in the research of metal matrix composites. The launch of first satellite 'Sputnik' and the first intercontinental ballistic missile R-7 “Semyorka” ignited the “Space Race” between the super powers [4]. The details of these programs were kept state secrets. However, from the nature of the papers that was published to the common public, it can be deduced that most of the papers discussed high temperature applications.

From 1987-2010

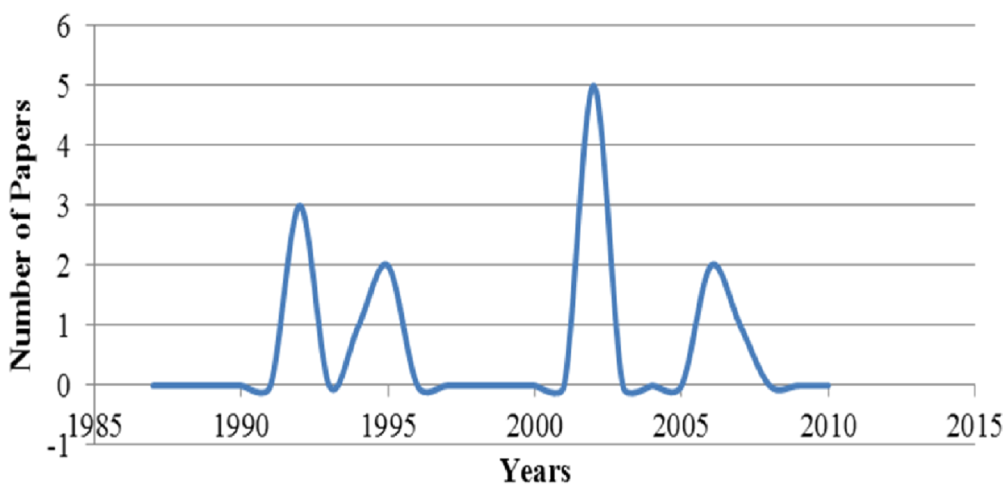


Figure 29: Number of Papers published from U.S.S.R in the period 1987-2010.

The contribution of papers from Russia fell steeply after the fall of U.S.S.R. Their contribution to the research efforts was minimal until early 2000s. The Russian economy was struggling from the early 1990s to the late 1990s. It got stabilized only in the early 2000s. This history has been discussed in detail in the section “2000-2004”

4.6 Japan

From 1965-1986

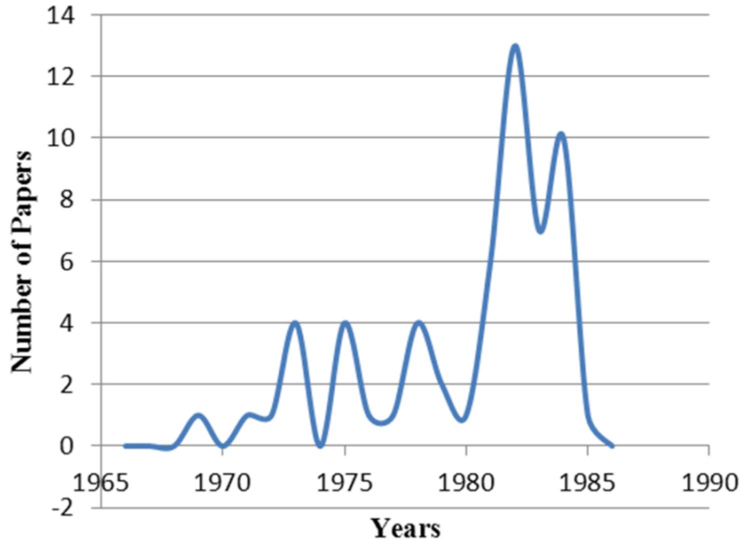


Figure 30: Number of Papers published from Japan from 1965-1986.

In Japan, the research for metal matrix composites is mainly driven by the demand from automotive industry. Discontinuously reinforced aluminum matrix composites are mainly used in the automotive sector. Most of the papers that come from Japan discuss this material.

The contribution from Japan has been kept constant; however we see two spikes in 1982 and 1984. It was in 1983 that Toyota Motor Manufacturing incorporated discontinuously reinforced aluminum composites in their diesel engines. After this a number of companies like Honda and Subaru started funding research for MMCs [25].

From 1987-2010

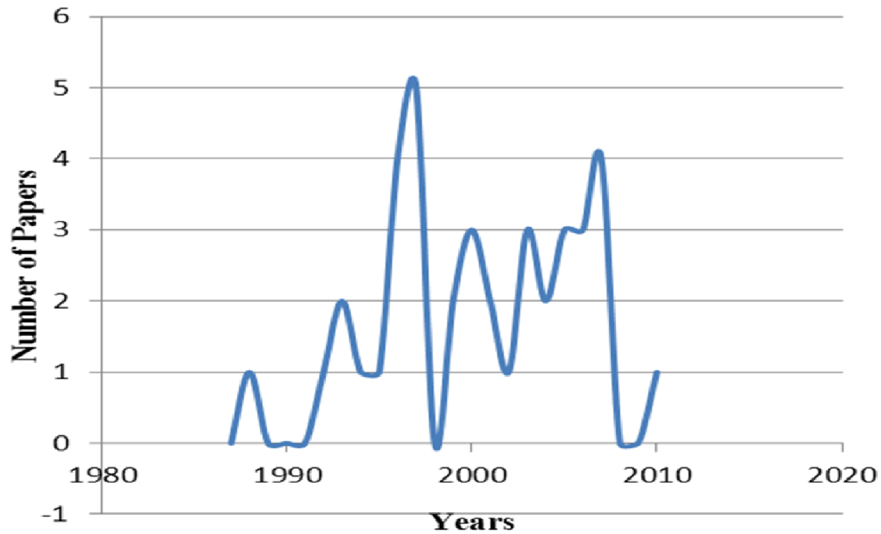


Figure 31: Number of Papers published from Japan from 1980-2010

The number of papers from Japan has been increasing at a steady rate during this period. The increase for demand for Japanese cars in the Western World coupled with the decline of demand for American cars can only increase the research efforts from this country.

4.7 China

From 1965-1986

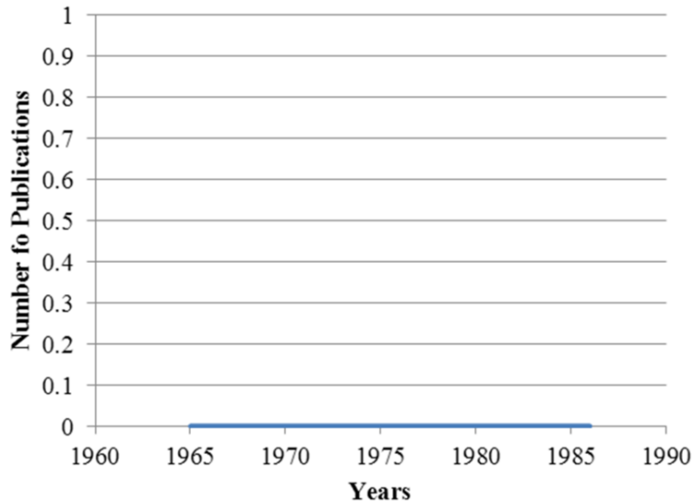


Figure 32: Number of Papers published from China from 1965-1986

The absolute absence of papers from China till 1988 has been discussed in detail in the section 1987-1989.

From 1987-2010

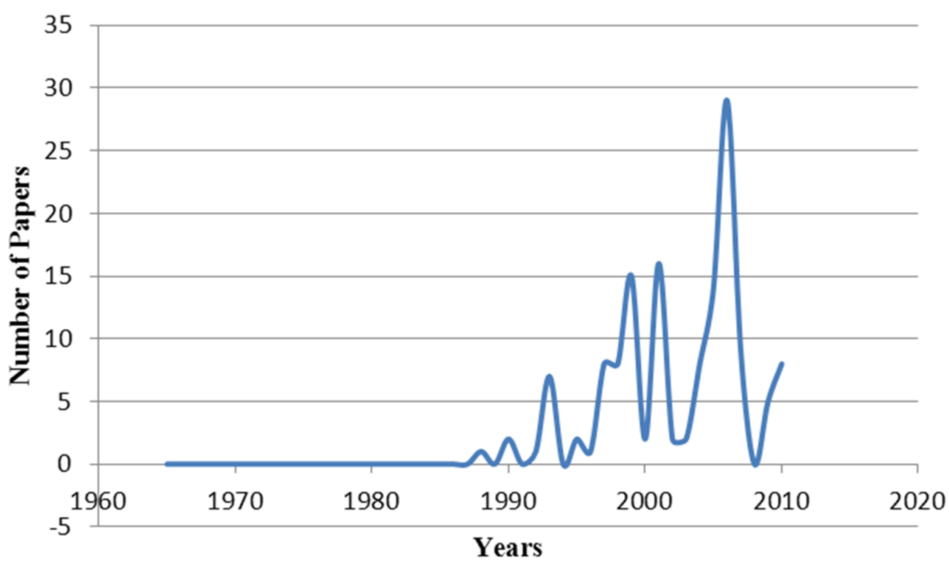


Figure 33 Number of Papers published from China from the period 1987-2010

China is the only country in the world that can maintain a 9% growth rate for the last 25 years. The after effect of this growth rate in the economy is evident from the research volumes of metal matrix composites. They have elaborate plans for defense modernization and have an ambitious space program[35]. A reduction in the number of papers occurred only during the latter part of 2000s, this may be because of the effect of global financial crisis. However, a great volume of research can be expected from this country in the near future.

For all other countries, the period from 1965-1986 and 1987-2010 has been displayed and discussed separately. However, in this case the number of papers from China till 1986 is nil. So the evolution of metal matrix composites from this country can be displayed in one plot.

CHAPTER-V

5. Comparative Study of the 6 Journals Considered

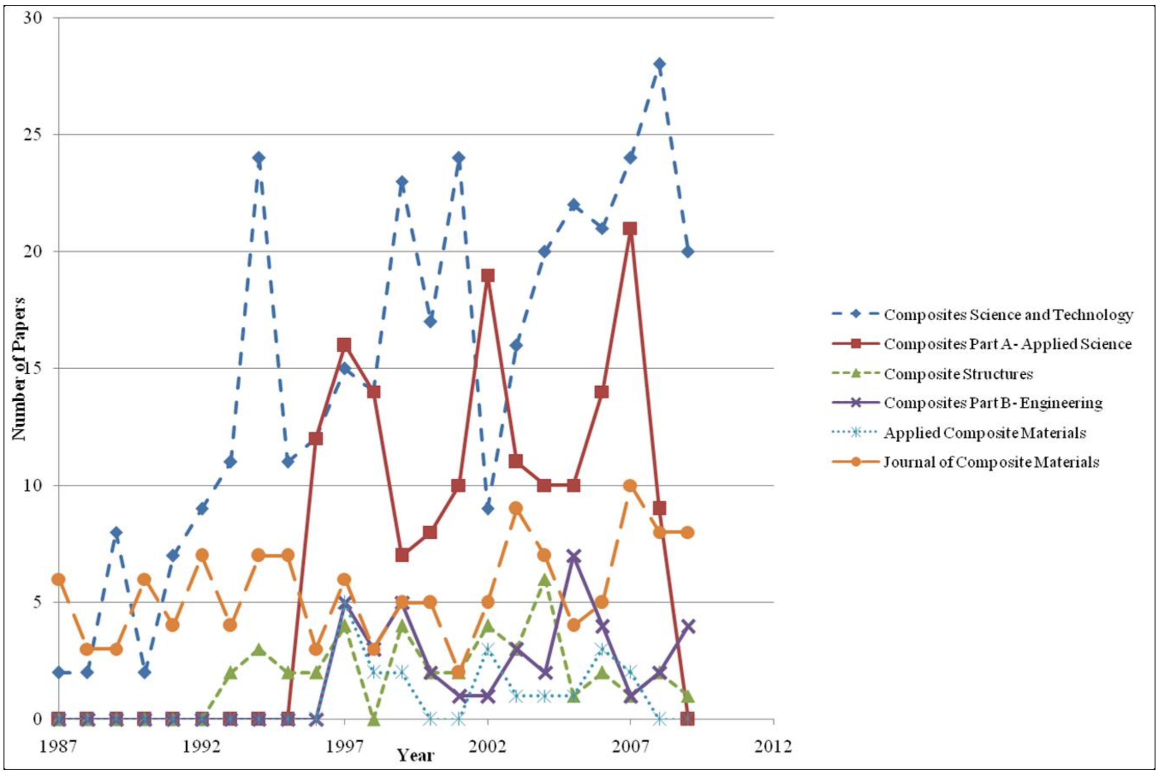


Figure 34. Comparative Study of the 6 Journals Considered

From the given figure, we see that the two major journals "Composites Science and Technology" and "Composites Part A – Applied Science" dominate the group. These two form 66.48% of the total number of papers published from the period 1987-2010. However, the "Journal of Composite Materials" has contributed 139 papers (19.09%) during this period.

If we study the graph, we see that some of the peaks and valleys are common for a majority of the groups, especially the first two journals. This proves that the trends and evolution of MMCs can be easily evaluated by observing the nature and number of papers published in “Composites Science and Technology” and “Composites Part A – Applied Science”. Also, “Journal of Composite Materials” may lag in numbers to the previously mentioned two journals, but the contribution has been pretty steady.

CHAPTER VI

6. Future Opportunities and Challenges

If we observe the direction of scientific research (in general) going on in the beginning of the 21st century, we see attention is given to clean or ’green’ technologies like fuel efficient auto-motives, electric cars, bio-fuels, renewable energy sources inlcuding more efficient solar panels, geo-thermal energy, natural gas, and peak energy demand maintenance etc. The societal pressures often enforced by legislation resulted in creating an atmosphere that requires materials like metal matrix composites. Many governments have passed bills that force companies to improve the average fuel consumption for automobiles and even aircraft. This requires lighter and mechanically efficient materials to be incorporated. Corporations are concerned about the impact of their products on the environment and the cost and availability of conventional energy sources like petroleum and coal. A result is the development of hybrid and electric vehicles requiring materials like MMCs. The factors mentioned above are reason behind the developments like overhead power transmission cables using continuously reinforced aluminum, nuclear waste containment using Al MMC reinforced with B_4C particulates and automotive tire studs manufactured using 6061 reinforced with Al_2O_3 wire intended for use in Nordic regions [2].

The most prevalently used metal matrix composites are discontinuously reinforced composites (DRA). However, difficulty in fabrication hinders its wide spread commercialization. The primary processing issues and factors that influence microstructural integrity of DRA has to be properly researched. The damage tolerance of these materials, especially the fracture toughness and ductility of aluminum matrix composites should be studied in detail. Aluminum matrix composites (AMCs) based on non-standard aluminum alloys should be developed and low-cost, high quality reinforcements should be produced from industrial wastes and by-products [38].

Applications from the automobile industry that can be commercialized in the next 15 years include connecting rods, rocker arms, brake components and automotive pistons. Robot components, propeller shafts, prosthetics, electronic packaging, computer equipment, and even sporting goods can be fabricated using MMCs. However, the ongoing research efforts are not enough to bring about the commercialization of these applications except for the diesel engine piston. Their high cost may act as a hindrance to the extensive application on land and sea based systems. Howwever, they can be used in specific mechanical components like bearings, pumps, transmission housings, gears, suspensions, springs and propeller shafts [4].

The growth in ground transportation industry is mainly due to light weight, reliability and fuel economy. Increased MMC applications in thermal management and electronic packaging may result in new wireless and networking installations[2]. High conductivity coupled with low thermal expansion is the reason why MMCs are used for thermal management and electronic packaging applications [20].

An achievement worth mentioning is the development of continuously reinforced aluminum matrix composites used for overhead power transmission conductors. It is a low cost application developed by 3M, can be used as high tension wires. This application has the potential to increase the demand for aluminum matrix composites dramatically[2].

Titanium alloys are usually used in applications where the temperatures are higher for aluminum alloys, more than 150°C. However, Titanium is heavier, difficult to machine and more expensive, but it has high temperature properties. Discontinuously reinforced Titanium (DRTi) is known for its structural properties and it is used in automotive valves for cars like Lexus ISF and Toyota Altezza. Studies show that DRTi has the capacity to exceed the structural efficiency of all metallic materials and even cross-plied graphite/epoxy [30]. More research and funding in this field pose a bright future for MMCs as a whole.

Selective reinforcement is a feasible approach for uniaxial applications like tubes, struts and hoop components. Built up structures can be produced from wire or tape preforms. A unique process is developed to produce cryogen tanks for rocket propulsion using the tape perform [20].

Many other promising applications are in flywheel containment, high-performance automobile components and high speed electric motors [2].

Magnetic metals and shape memory alloys can be used as matrices for MMCs. Multi-purpose materials can be used for combining structural applications as well as sensing and actuations functions [20].

Research on bimodal reinforcement sizes that control different strengthening mechanism and deformation and different length scales has been launched, however they have not got enough attention. Different reinforcements can be combined to achieve synergistic effects that include intentional combinations of particulates, platelets, whiskers, fibers and/or laminates and even particulates. Some studies already done, shows considerable improvement in fracture properties, especially in grain sizes that has nano-crystalline metals. The influence of fracture properties on varying reinforcement size and distribution and even their grain size can be a subject of serious research [2].

Foam structures can be used for fabricating hybrid materials and structures. Reinforced metal cells that span many foam cells resist foam deformation mechanism and failure. They have additional applications beyond structural, includes blast and crash protection, sound isolation, fire protection and heat transfer properties that can be used in thermal insulators and heat exchangers [2].

Metallic glasses possess high strength that any other material possesses, but they have no macroscopic ductility in the bulk form. However, using crystalline metal reinforcements helps to retain most of the features in metallic glasses and improving the fracture properties dramatically [2].

The opportunities offered by nano-structured composites are immense. They offer high strength and microstructural stability at very high temperatures, contrary to the comparable materials that does not possess a second phase to resist grain growth [20]. We may not able to call these materials metal matrix composites as per the conventional definition, the properties and associated opportunities they offer remain

CHAPTER VII

7. Global Business Trends in MMC markets

The major market for metal matrix composites in the Western world especially in U.S.A are in the aerospace and defense sectors. Department of Defense was funding over 90% of research efforts in U.S.A from 1979 to 1986. The American and European industries are almost same, small, start-up firms supplying the fabricated MMC parts. The matrix is supplied by the large Aluminum companies like Alcoa; however they are planning of forward integration into finished composite parts. Many experts welcome this move because these firms have the capital and R&D facilities to produce reliable metal matrix composites in large volumes for commercial applications at affordable costs. Another barrier that exists in United States for the commercialization of MMCs is the restriction of data flow and information sharing about MMCs for national security reasons. Metal matrix composites are often considered to be classified technology, so availability and exchange of technical data is highly controlled [39, 40].

The metal matrix composite industry in Japan is very different from that of the U.S.A. and Western Europe. Large materials companies produce matrix materials and integrate them with reinforcements and deliver finished MMC parts. Also, the major applications of metal matrix composites are in automobile industry, electronics, and aircraft industry. So they have more potential for growth [40]. Any industry requires commercialization for its growth in breadth and reach.

CHAPTER VIII

8. Factors that Affects Metal Matrix Composites

In addition to the above review and in part due to its comprehensive nature some engineering insights are also evident. These are covered here for completeness. The challenges involved in conceptualizing, designing, fabricating and usage of metal matrix composites are discussed below. 20 factors have become evident:

Weight Percent

Volume Percent

Particle Size

Aspect Ratio

Reinforcement Orientation

Differences in the matrix, such as heat treatment

Heat treatment of the matrix/Microstructure of the Matrix

Reinforcement Shape and Nature

Raw material for reinforcement/Different reinforcements made by different manufacturers and different grades/Heat treatment of the reinforcement Fiber diameter

Mode of Manufacture of Composite

Reinforcement Distribution

Porosity

Fiber Spacing

Interfacial Bonds

Reinforcement Coatings

Alloys used for matrix and reinforcement

Shape of the specimen (like Bar, Plate or Forging)

Thickness of the specimen

Design of experiments

Evolution of materials

8.1 Weight Percent

The weight percent of a metal matrix composite can vary for different application. However, this can be normalized with scaling laws. In most cases, the volume percent is specified and given more importance than weight percent.

8.2 Volume Percent

Volume fraction of a metal matrix composite can vary for different application. However, this can be normalized with scaling laws. The increase of volume fraction improves the tensile strength, elastic modulus and macroscopic yield of an MMC. Increasing volume fraction means more load is taken over by the reinforcement, this improves the ultimate strength. Also work hardening rate improves with higher volume fraction. The creep resistance is also improved[41].

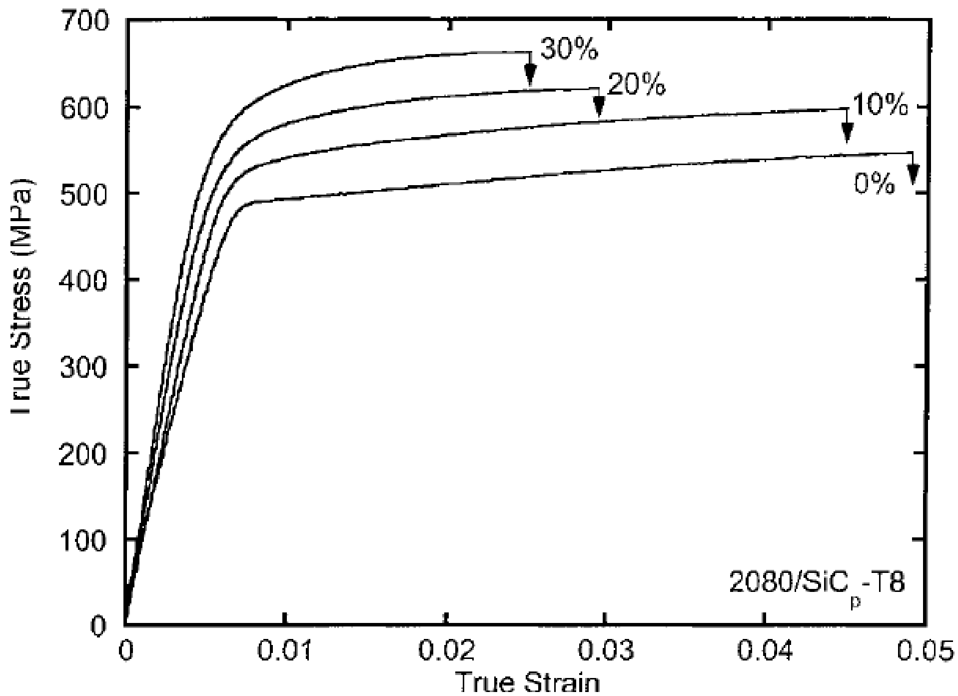


Figure 35: Tensile Behavior for Varying Volume Percent

The fatigue resistance of an MMC can also be improved by increasing the volume fraction and decreasing the particulate size with high stiffness particulate reinforcements. The fatigue resistance of metal matrix composite depends on different factors like matrix microstructure, presence of inclusions or defects that occur from processing, particle size, and testing environment. In the case of a composite, most of the load is tolerated by the high strength, high stiffness reinforcement. So if a reinforced metal and unreinforced metal is under comparison, the unreinforced metal undergoes higher strain. These changes can be clearly seen in high cycle, lower stresses fatigue regimes. But at higher stresses, the difference between a composite and monolithic metal is not obvious. This may be due to the "ductility-exhaustion" of the composite at low cycle fatigue cases[41].

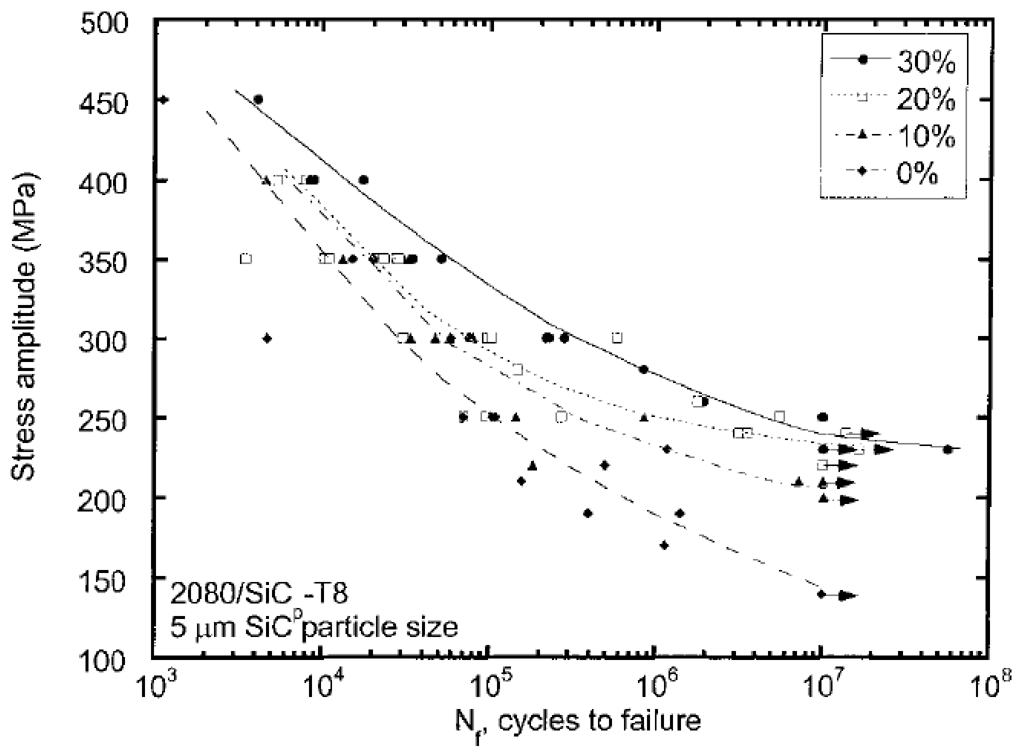


Figure 36: Effect of Volume Percent on Fatigue Life

However, higher volume fraction results in lower ductility for metal matrix composites. This happens due to the early encounter of void nucleation with high volume fraction[41].

8.3 Particle Size

The smaller particle size improves the ductility of a metal matrix composite. This may be because the probability of strength limiting flaw that can exist in a larger particle is higher than in a smaller particle. This improves the particle strength. Also, in larger particles, e.g. above 20 μm, a considerable amount of cracking in particles occur during processing before testing. These cracked particles cannot carry any load and effectively act as voids. This ends up in lowering the strength than that of monolithic metals[42].

Decreasing particle size also results in higher work hardening rate due to the creation of dislocation tangles encompassing the particles. This is due to the plastic discordance between the matrix and the reinforcement and the creation of a dislocation cell arrangement with the inter-particle spacing inversely proportional to the cell size[42]. Lower particle size increases the fatigue strength. If the particle size is decreased keeping the volume percent constant, the inter-particle spacing between the reinforcement also decreases. This results in increased number of barriers for the reversible slip motion that occurs at the place during fatigue. This is a reduction in strain localization by cyclic slip refinement. Above a critical reinforcement size, reinforcement fracture may become dominant and results in reduced fatigue life. Reducing the reinforcement size range distribution results in increasing the fatigue life, because the larger particles are avoided that are prone to cracking [42].

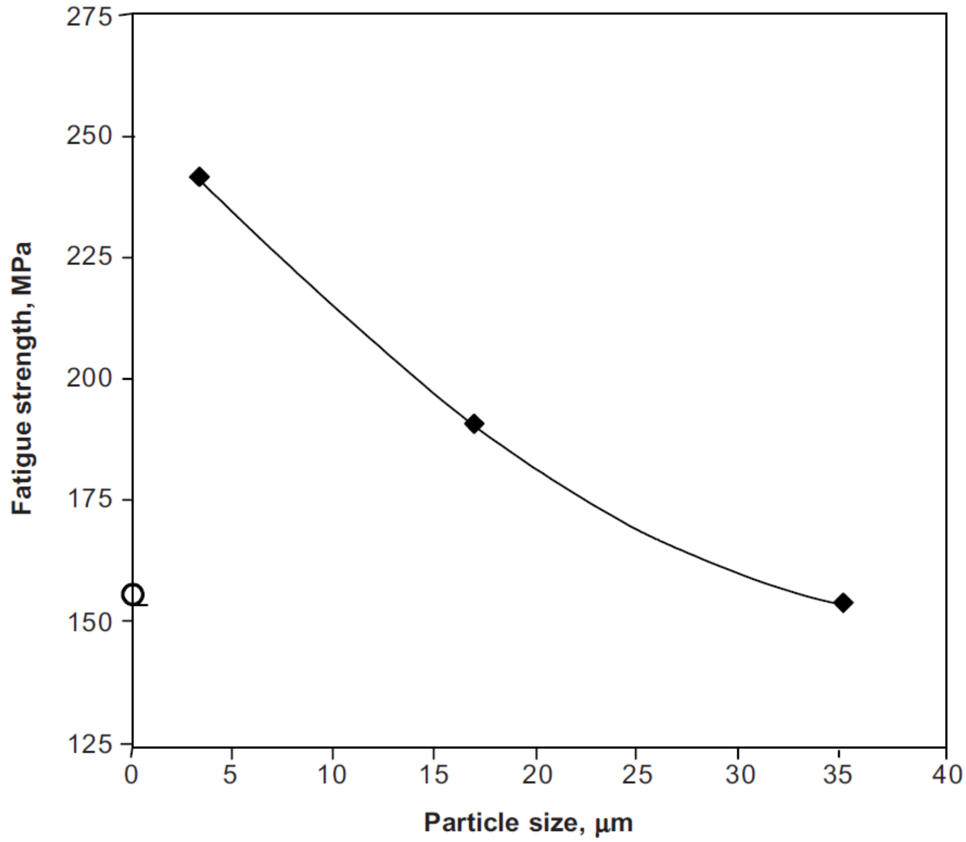


Figure 37: Effect of Particle Strength on Fatigue Strength [43].

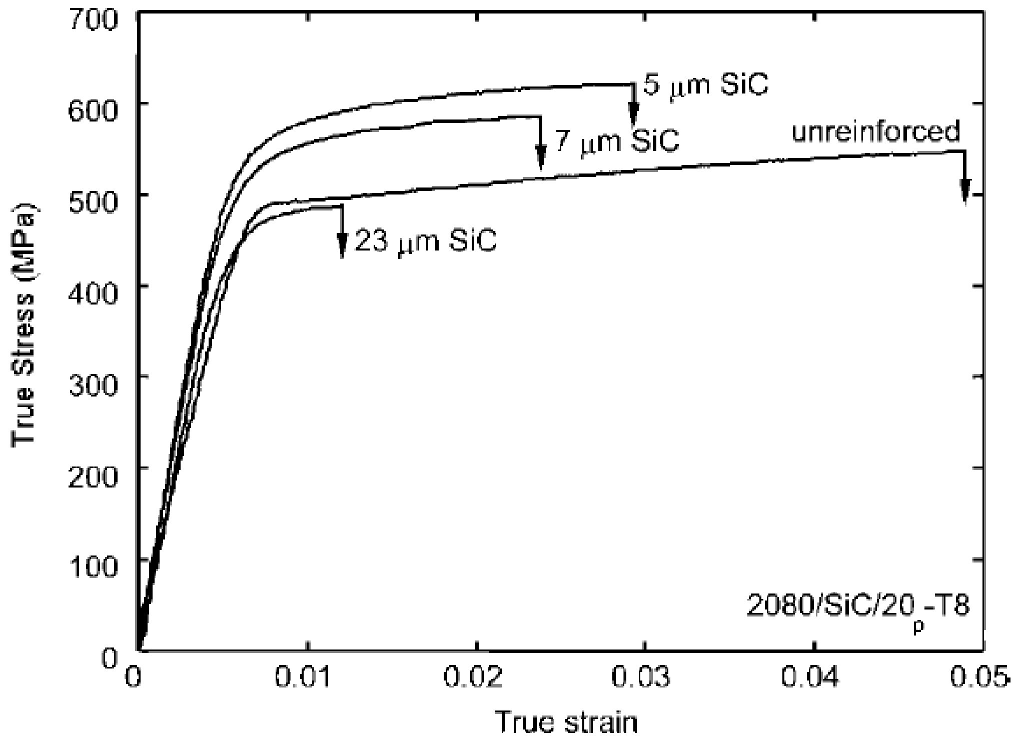


Figure 38: Tensile Behavior for Varying Particle Size [42].

Results show that larger reinforcement particles improve fracture toughness because fractured particles results in cracks with the same size as the particles. They develop at very small plastic strains and the cracks get linked up or connected that leads to the failure of the material [42].

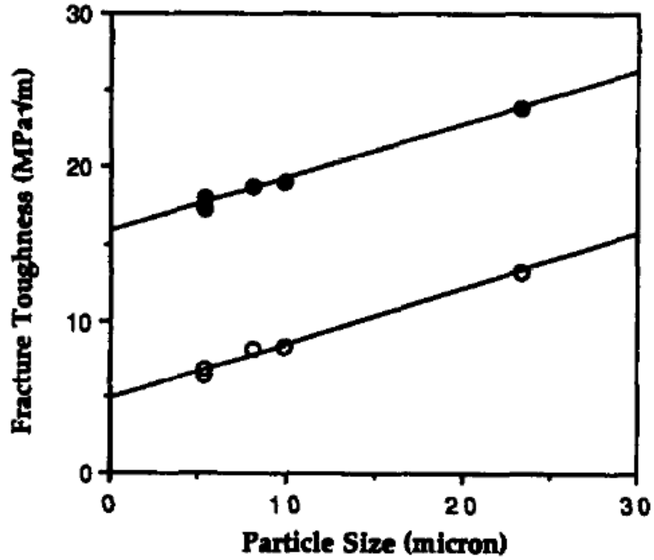


Figure 39: Influence of Particle Size on Fracture Toughness [42].

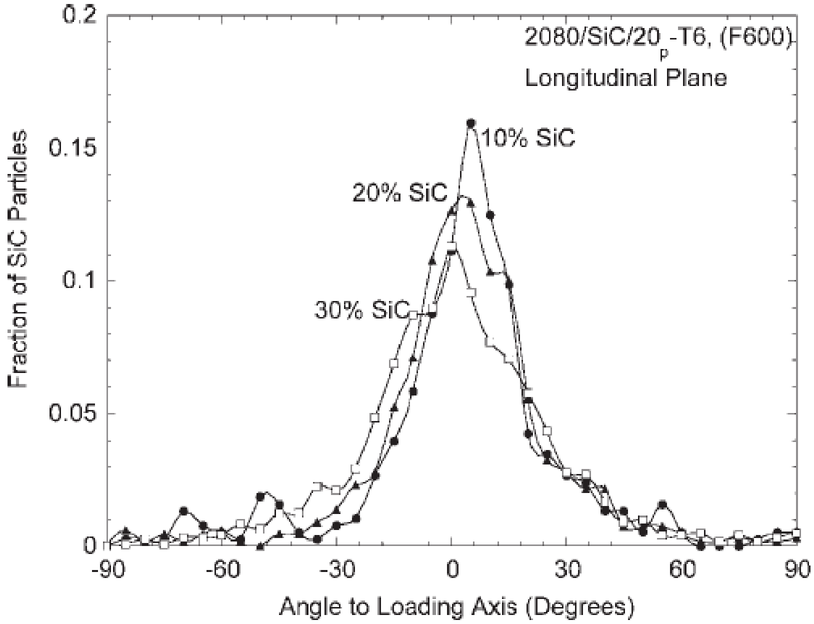
8.4 Aspect Ratio

The stiffness of a composite is improved if the aspect ratio is high, provided the reinforcement is not broken. However, if the reinforcements are damaged, this contribution from the aspect ratio will disappear. Microstructural studies show that single fracture is the reason for the vast majority of particle damage during plastic deformation[41]. The creep resistance also increases with increase in aspect ratio. High aspect ratio whiskers reinforced MMC carry higher loads than particle reinforced metals, because effective load transfer occurs from the matrix to the high stiffness reinforcement. At intermediate temperatures (500 ± 720 K) the whiskers control the strength of the composite. The load is transferred from matrix to the reinforcement that has higher aspect ratio and stiffness. But strength becomes matrix-controlled at high-temperatures (720 ± 900K) because lesser efficiency in load transfer and lesser interfacial shear strength[41].

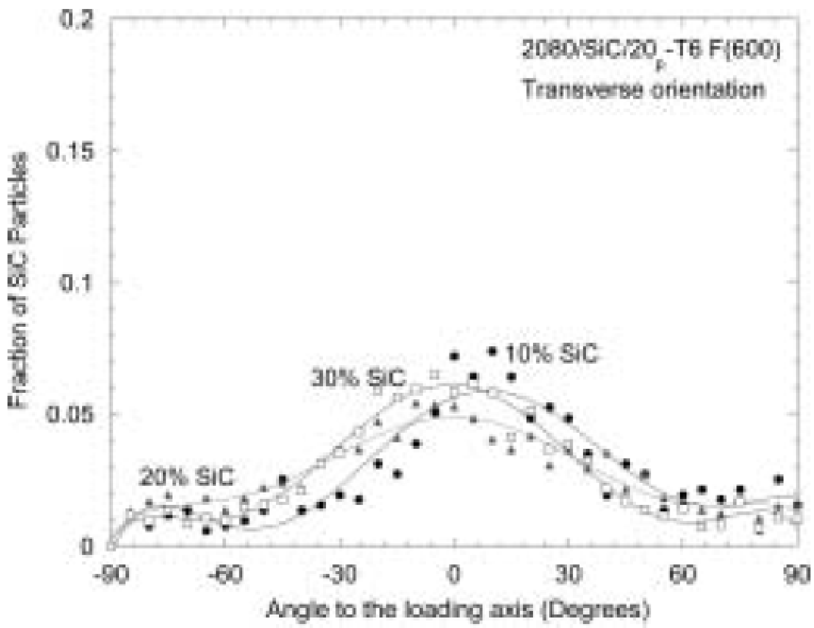
8.5 Reinforcement Orientation

a) Discontinuous Fibers

The strengthening provided by the short fibers is less than long fibers. This is because a segment at each end of the fiber is not fully stressed. The matrix transfers the applied stresses to the fibers through shear stresses occurring at the interface. Here the finite length at each end of the fiber reaches a maximum. The extrusion-generated particle-orientation anisotropy has an important role on the tensile and fatigue performance of a discontinuously reinforced MMC. The preferred orientation for reinforcements is parallel to the extrusion axis. The composites developed higher stiffness and tensile strength along the longitudinal direction than the transverse direction. The influence of anisotropy increases with increasing volume fraction because of the increasing influence of reinforcement on tensile strength and elastic modulus. This preferred orientation also develops anisotropy in the fatigue response of the composite. The volume fraction on reinforcements deeply affects the extrusion induced microstructural changes. The extent of microstructural anisotropy is greatly influences the tensile and fatigue behavior of composites[44]. Microstructure identification of the composite shows a preferred orientation of reinforcement particles in the direction of the extrusion direction. A quantitative analysis of the degree of orientation of reinforcements, given by the angle of inclination of reinforcements to the longitudinal axis is shown in figure 30[44].



(*a*)



(*b*)

Figure 40: Orientation of the Reinforcement Particles with increase in Volume Fraction (a) longitudinal plane (b) transverse plane [45].

Here we see that the degree of alignment of reinforcement for a given volume fraction is much higher in the longitudinal plane than that in the transverse plane[44]. The reason for the fine grain structure at the matrix/particle interface is the dynamic recrystallization of new grains at the reinforcement surface during hot extrusion. The morphology and size of individual grains and matrix bands are dictated by the rigid particles that act as obstacles for matrix flow. This reinforcement increases the macroscopic flow stress for the extrusion of the composite. A large degree of shearing between matrix and particles leads to a strong mechanical bond between matrix and the particle. A strong mechanical bond between reinforcement and matrix is strongly desirable for better performance of a composite because it maximizes the extent of load transfer from the matrix to the reinforcement. This increases the probability of that given particle loaded to its fracture stress. Thermal expansion mismatch results in thermal-misfit dislocations at the matrix/particle interface[44].

Short fiber and whisker reinforced composites have an apparent anisotropy due to the anisotropic orientations of its reinforcements. Reinforcements with higher aspect ratio result in greater extent of anisotropy. Preferential reinforcement orientation is sometimes desirable and a common outcome of processing. Short fiber composites and whisker reinforced composites can achieve true isotropy if full random reinforcement orientation is achieved (eg: powder metallurgy). Specialized preform preparation methods can also be used prior to infiltration[46].

The tensile strength of the composite that is independent of the orientation increases with volume fraction of the particles. But the strain to failure decreases with increasing volume fraction. A comparison of properties in the longitudinal and transverse directions demonstrates a pronounced anisotropy in the tensile behavior of the composites. The tensile strength and elastic modulus have higher values in the longitudinal orientation than in the transverse orientation. The anisotropy in strength and Young’s modulus increases with increased volume fraction of reinforcements[44].

If the particle size, particle volume fraction, and aspect ratio remain constant, the elastic modulus can be controlled by the degree of particle alignment. As the contribution of particulate reinforcements to the overall stiffness of the composite increases with increasing volume fraction, the influence of the reinforcement alignment also increases with the increasing volume fraction[46].

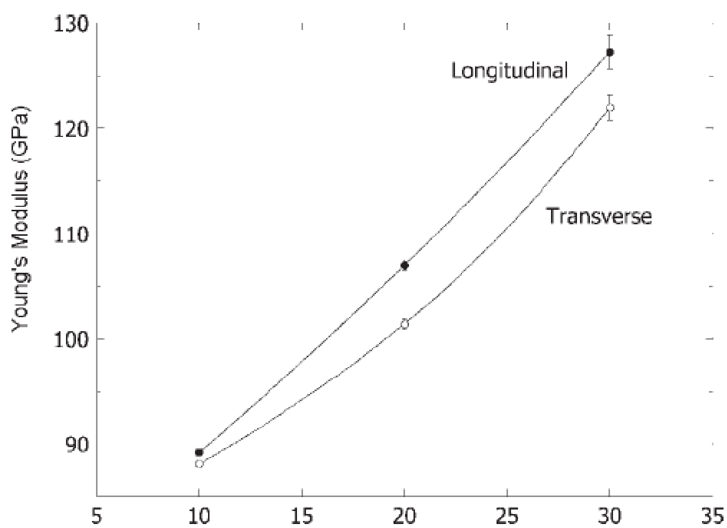


Figure 41: Effect of Particle Orientation, with increasing Volume Fraction on Young's Modulus of the Composite [45].

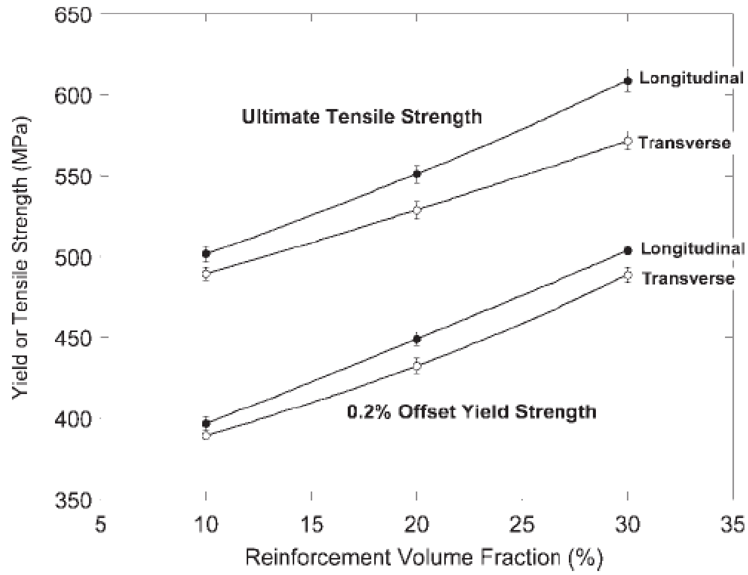


Figure 42: Effect of Particle Orientation, with increasing Volume Fraction on Tensile Strength of the Composite [45].

b) Continuous Fibers

The strength and failure mode of aligned continuous fiber matrix composites depend on the angle (θ) between the applied stress (σ) and the fiber direction. The maximum strength output is obtained when θ = 0 degrees, it is called longitudinal strength. The applied stress is shared between the fibers and matrix. The stress is transferred to the fiber by the shear stress at the fiber/matrix interface. If this interface is strong, the longitudinal strength follows a simple rule of mixtures[47].

$$\sigma_L = V_f\sigma_f + (1-V_f)\,\sigma_m \text{----------------------------------(1)}$$

where V_f =the volume fraction of the fibers

σ_f = the strength of the fiber; and

σ_m = the strength of the matrix

The presence of fibers modifies the microstructure of the matrix. Compared to a monolithic alloy with the same thermal history, the matrix of the composite will have smaller grain size or a higher dislocation density. So a matrix will be stronger than an unreinforced alloy[47].

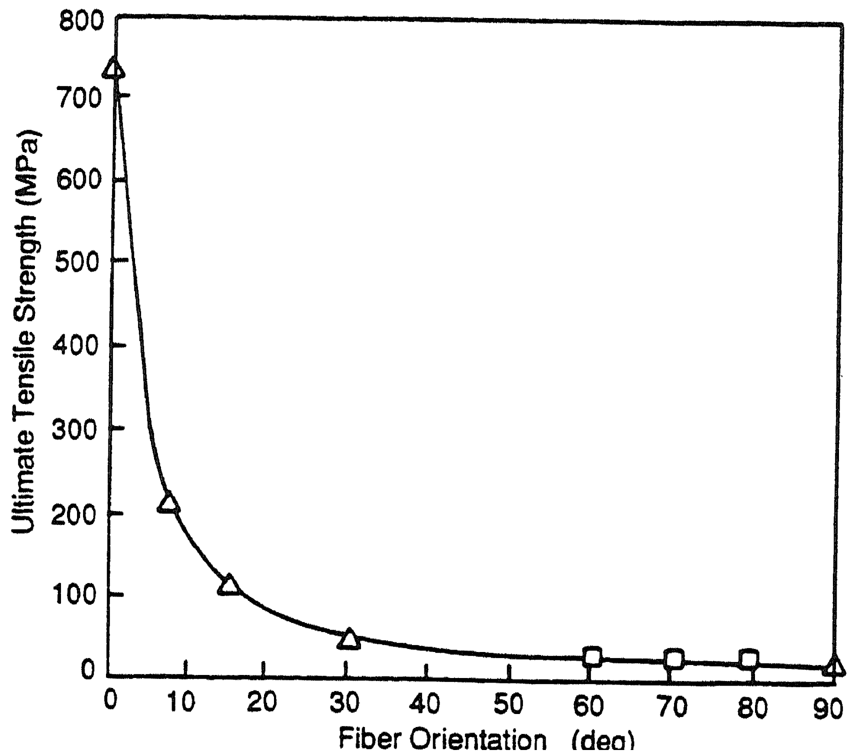


Figure 43: Variation of Ultimate Strength with Fiber Orientation [48].

In figure 33 when θ = 90°, there is little or no load sharing between the matrix and the fibers in the pure transverse mode. This may result in fibers causing stress concentration in the nearby matrix and result in failure at a lower stress level than that of the unreinforced matrix. The transverse strength is influenced by the strength of the interfacial bond. Two types of behavior can be observed:

If the interface bond is weaker than the matrix, fracture occurs at the interfacial separation. If the fiber has lower transverse strength, fiber failure occurs by fiber splitting. These failure modes can be modeled as fibers as cylindrical holes. This reduces the effective cross-sectional area of the composite[47].

If the fibers do not split and the transverse bonds are stronger than the matrix, failure occurs at the nearby matrix. In the case of a well-bonded interface, the increasing volume fraction decreases the transverse stress due to stress concentrations. This is applicable to large volume fractions and the magnitude of decrease in transverse stress depends on the geometrical arrangement of the fibers[47].

8.6 Heat treatment of the matrix/Microstructure of the Matrix

The factors that influence the matrix microstructure are size, spacing, and shape of precipitates, grain size, and inclusions and non-reinforcement dispersoids. The matrix alloys are moreover like the unreinforced metals means finer grain size matrix alloys have better properties. The fatigue behavior of the composite is influenced by the matrix microstructure. In metal matrix composites, ultimate tensile strength and high yield strength do not guarantee high fatigue strength (defined as 107 cycles). Also, the microstructure of the matrix is modified by the nature of the reinforcement[49].

8.7 Reinforcement Shape and Nature

The shape and nature of discontinuous reinforcement plays an important role in the mechanical properties of a metal matrix composite. In order to understand the influence of the shape of reinforcements, particles are enclosed in a matrix to simulate a composite with a periodic array of reinforcement. In figure 43, a unit- cell approach is used. The left vertical boundary represents the axis that is symmetric. Also, mirror symmetry exists about the boundary below. Different particles of different shapes are examined below, unit cylinder, truncated cylinder, double-cone, and sphere (Figs. 43a, b, c, and d respectively). In real life scenario, the particulates have sharp corners. Spherical particles cannot be chosen as a realistic choice here[50].

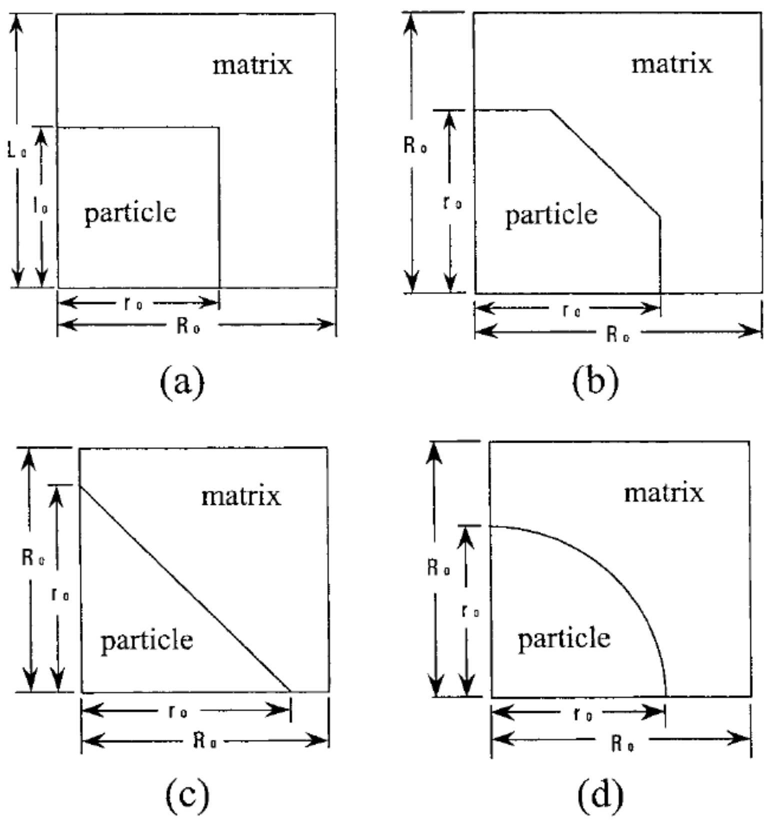


Figure 44: Type of unit cells used for simulating different reinforcement shapes in a composite: a) unit cylinder b) truncated cylinder c) double-cone d) sphere. The left boundaries represent the axially symmetric axes [51].

Here the reinforcement can be considered as an elastic solid and matrix as an isotropically hardening elastic-plastic solid. The resultant tensile stress-strain response of the composite is shown in Figure 44.

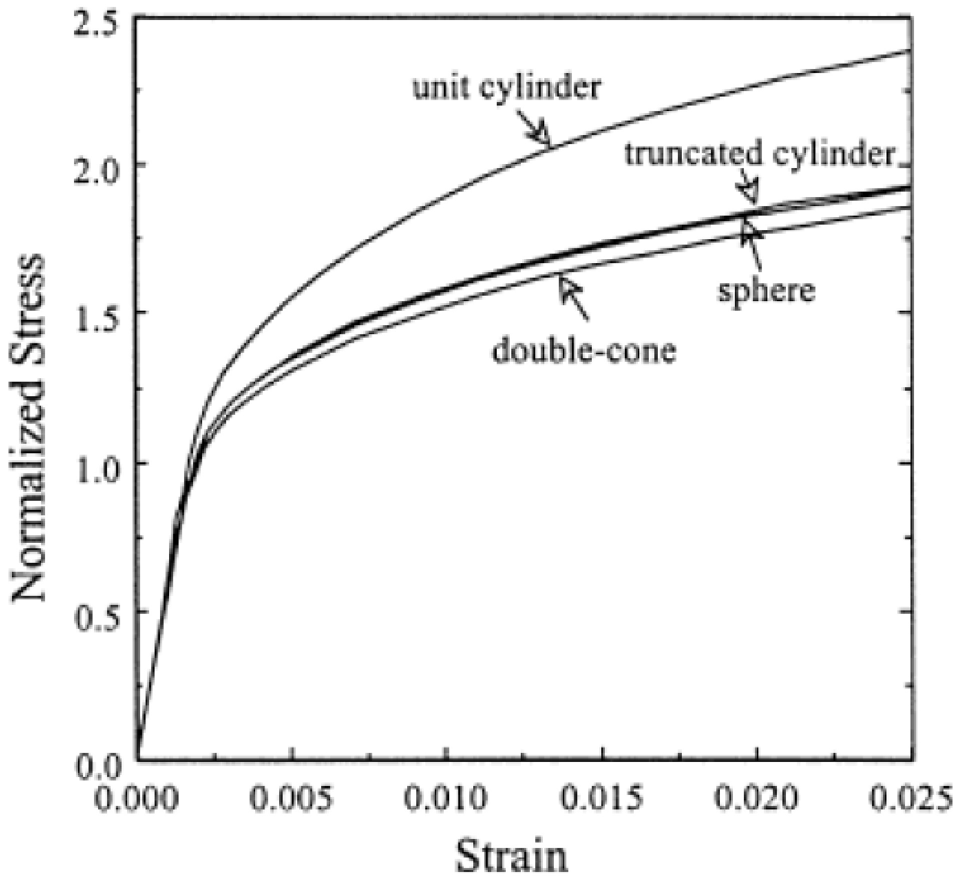


Figure 45: Tensile Stress-Strain Curve for various Reinforcement Shapes [51].

The volume fraction is kept constant in all the cases. It can be seen that the unit cylinder strengthens the matrix than all other shapes. This does not mean that reinforcements with pointed corners provide a larger strengthening effect, as seen in the case of double-cone particles, because this has the 'sharpest' type of corners. A thorough analysis proves that the unit cylinder and double cone particles result in the highest and lowest degrees of disturbance of the plastic flow paths in the matrix. This shows the extent to which the reinforcements can influence the local plastic flow paths in the matrix[50].

This model gives accurate results for small volume fractions, for instance less than 0.2. At higher percentage fractions, the composite behavior will be controlled by the boundary constraints acting on the unit cell. So the results have to be interpreted with care[50]. The surface reaction of particles with the liquid melt and each other influences the rheological action of the matrix alloy melt and reinforcement slurry. This influences the ability to wet the surface of the particles. This shows that fine and coarse nature of metal matrix composites play an important role in its final properties[50].

MMCs that contain finer reinforcements show better fatigue resistance than with coarser reinforcements[50].

8.8 Raw material for reinforcement/Different reinforcements made by different manufacturers and different grades/Heat treatment of the reinforcement:

Raw material of reinforcement influences the properties of a composite. For example, carbon fiber can be produced from polyacrylonitrile (PAN), pitch and rayon. About of 90% of carbon fibers are made from PAN and the remaining the made from petroleum pitch and rayon. Although all these materials are basically organic polymers made up of long strings of molecules adhered together by carbon atoms, they all have individual characterizations. Precursor is the raw material that is used to make carbon fiber. Certain ultra-high stiffness fibers made from petroleum pitch is termed as graphite fibers. Carbon fibers are generally classified by the elastic modulus of the fiber. Pitch based carbon fibers can be produced from petroleum pitch and coal tar. All these fibers have individual textures and microstructures that change the elastic modulus of the fiber. The fiber microstructure and texture significantly influences the tensile strength of the composite[52].

Different makers of carbon fiber produces the same fiber from the same precursor, however the processing and composition changes. This affects the mechanical properties. Also, the same manufacturer may produce different grades of fibers, like NS-20, XN-30, NS-30, P-55, NS-40, XN-60, NS-60, and XN-70. All these different grades have different mechanical properties. They are all different because they are made by different compositions and different processing techniques[53].

Graphitized carbon fibers are considered to be less reactive than PAN based carbon fibers when used in aluminum matrix composites. So pitch based carbon fibers are more desired for use in light-weight aluminum matrix composites[52].

8.9 Fiber diameter

The diameter of fiber is an important factor determining the mechanical properties for continuous fiber reinforced metal matrix composites. The strength of the fiber lowers as the diameter of the fibers increase. Thicker fibers fracture at lower levels stresses than thinner fibers. As the fiber gets thicker, the probability that it contain more microstructural defects increases[54]. The diameter of the fiber should be kept constant for higher tensile strength. The tensile strength, yield strength and scatter of fiber strength of composites whose fiber diameters is not uniform are lower than that of composites with uniform fiber diameter[54].

8.10 Mode of Manufacture of Composite:

Processing plays an important role in determining the inherent characteristics of the matrix, reinforcement, and composite. Different processing methods induce different microstructural changes in the matrix and fiber; this will influence the mechanical properties of the composite. Different processing techniques have been developed for the processing of MMCs; they are generally classified as liquid-phase processes and solid-phase processes [49].

Liquid phase processes like infiltration and casting are generally cost-effective. However, they pose several challenges like attaining uniform matrix microstructure, interfacial reaction between reinforcement and matrix (which is undesirable for the composite performance) and controlling particle distribution. Liquid phase processes can result in particle clustering due to sedimentation, insufficient mixing and slow solidification rates. The elastic ceramic particles exert constraints on the matrix that alter the stress field in the vicinity of the cluster. This result in the development of tri-axial stresses that are far higher than the remote stresses applied on the composite. This results in clusters acting like cracks or de-cohesion nucleation sites or a combination of both at remote stresses. This lowers the yield strength of the matrix resulting in the failure of the composite at unpredictably low stress levels [49].

The most commonly used solid-phase processes is powder metallurgy. The ceramic reinforcements and matrix powders are mixed and iso-statically cold compacted. Then they are hot pressed to full density; then they are subjected to secondary processing like forging or extrusion. Sinter forging can be used to eliminate hot-pressing step, this lowers the cost considerably [49].

Secondary processing (like extrusion) aligns fibers and whiskers predominantly in one direction. This produces anisotropy and finally a transversely isotropic material. Rolling operation results in orthotropic materials. Rolling and extrusion operations have to be carefully controlled because they can cause breakage of the reinforcement. The extent of damage goes to certain limit such that they behave like particulate reinforced composites after processing[47].

8.11 Reinforcement Distribution

Commercial metal matrix composites do not have uniform spatial distribution of ceramic reinforcements. The inhomogeneity of reinforcements has a significant influence on the plastic deformation and failure modes of an MMC. The non-uniformity can be described in terms of 'random' or 'clustered' distribution of reinforcements[55].

For reinforcement distribution, the centroid can be at any point in the matrix; the only condition is that no two reinforcements should overlap. The reinforcement volume-density and average spacing between two reinforcements are relatively constant for the entire system[56].

If the reinforcement's distribution is clustered, the distribution characteristics can be different for different regions in the matrix. This can significantly affect the fracture and plastic flow of MMCs. The work hardening and yield strength increases with increased clustering. However, the failure strain is significantly reduced in a clustered microstructure due to the stress concentration in the particle clusters, which may cause selective nucleation and propagation of damage in the clusters[56].

Some deformation and failure processes involve spatially correlated cases. The fracture phenomena in a clustered microstructure usually starts in one cluster and then it propagate through its near-by clusters. Understanding the sizes, positions and connectivities of the reinforcement clusters is important for modeling such an event. The agglomeration of fine powders (for mixing and blending) in a powder-processed composite and rate of casting (for a cast MMC) determines the degree of clustering[57].

Characterization of reinforcement distribution as "random" and "clustered" is useful for low-volume fraction MMCs. But it becomes harder for high volume fractions. Besides, some deformation and failure processes involve spatially correlated cases. The fracture phenomena in a clustered microstructure usually starts in one cluster and then it propagate through its near-by clusters. Understanding the sizes, positions and connectivities of the reinforcement clusters is important for modeling such an event. The agglomeration of fine powders (for mixing and blending) in a powder-processed composite and rate of casting (for a cast MMC) determines the degree of clustering.[55]

8.12 Porosity

Porosity is caused by the interfacial reaction, it is considered to be a defect that adversely affects the mechanical properties. Porosity usually occurs at cast, particle reinforced metal matrix composites. This reduces the mechanical strength of a composite[57]. Porosity occurs due to

a. air bubbles entering the slurry either independently or as an air envelope to the reinforcement particles
b. water vapor on the particles surfaces
c. gas entrapment during vigorous stirring
d. evolution of hydrogen
e. shrinkage during solidification

Stir casting method is the most common technique used for discontinuously reinforced MMC fabrication. A modified approach has been developed to eliminate the porosity to a great degree. However, there is at least a minimum micro-porosity present at volume fraction up to 0.07. If the porosity is reduced, the properties of a composite can be optimized[57].

Pores can be classified into four types: round pores, long and fissured pores, long and broad pores, and small, fissured pores[57].

Research has shown that casting parameters are the core reason that causes porosity formation. They are casting route applied, stirring speed and position of the impeller, volume fraction of the reinforcement material and process parameters that consists of holding time. The porosity content increases with higher aspect ratio, volume fraction, and increasing particle size[57].

The porosity formation is dependent on the percentage elongation or %e (ductility), stiffness (E), ultimate tensile strength (σUTS), yield strength (σY), and the matrix composition and microstructure. The formation and nucleation of porosity results in lowering of fatigue strength, yield strength of the composite and total life time. The higher volume fraction of the reinforcement and large reinforcement size corresponds to porosity formation that results in the decrease in instantaneous Poisson's ratio of the metal matrix composites. In many discontinuously reinforced metal matrix composites, the composite failure occurs from the development and growth of voids at the matrix-reinforcement interface[57].

Ductility of discontinuously reinforced metal matrix composites depend on the strain at which the damage nucleates and growth rate of the damage that causes failure. This can be predicted by studying the process coalescence that initiates failure. When a certain condition is applied, the cavities form at high hydrostatic stress areas that will work together by a ductile tearing mechanism[57].

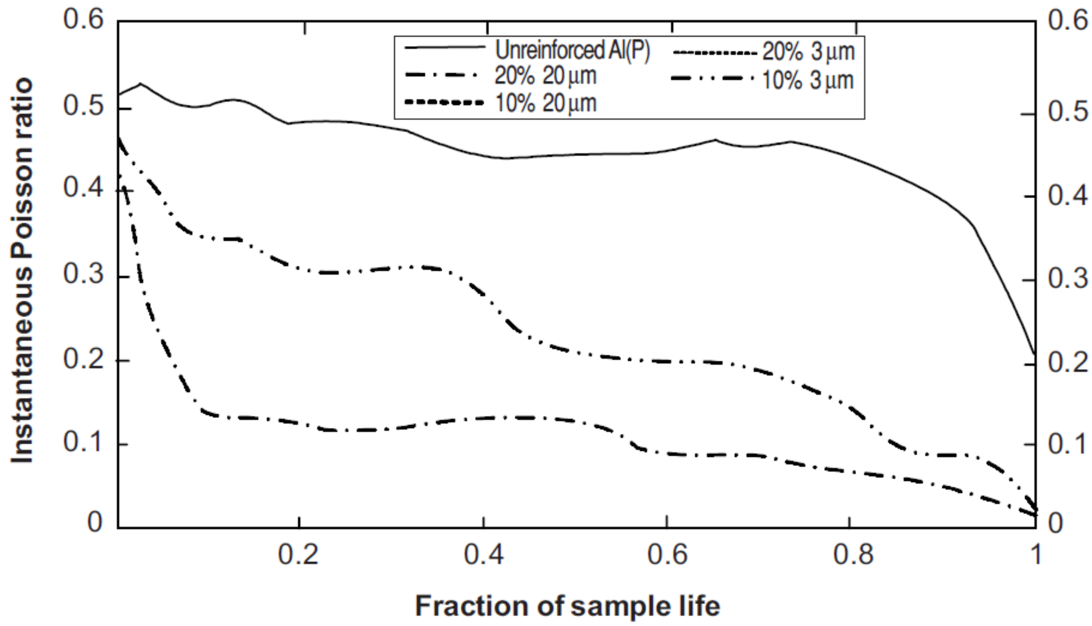


Figure 46: Poisson Ration as a function of Specimen Life [58].

From the creep data, the necked region has more void content than other deformed region. In the rest of the uniform deformation region, higher load applied and temperature increases the overall void contents. The specimen that has undergone creep was found to contain more voids than compared to ones that were subjected to tensile testing[57].

Damping capacity of a material increases with the porosity content. This is characterized using logarithmic decrement shown in figure 37[57].

The increase of volume percent of ceramic content reduces the fracture toughness of a metal matrix composite because it results in the formation and combining of voids within the matrix that can cause premature fracture. This is due to the increase in constraint on matrix deformation and consequent reduction in ductility. Fatigue cracks begin and propagate in regions where the strain is maximum. In highly stressed regions of component, fatigue cracks initiate from surface discontinuities (they are commonly seen in materials). In this case, porosity is the discontinuity. This leads to failure of the composite. Also, if the component is under elevated temperature and tensile stress, voids will be formed on the interface of the particle and matrix. This significantly reduces the fatigue life of the material[57].

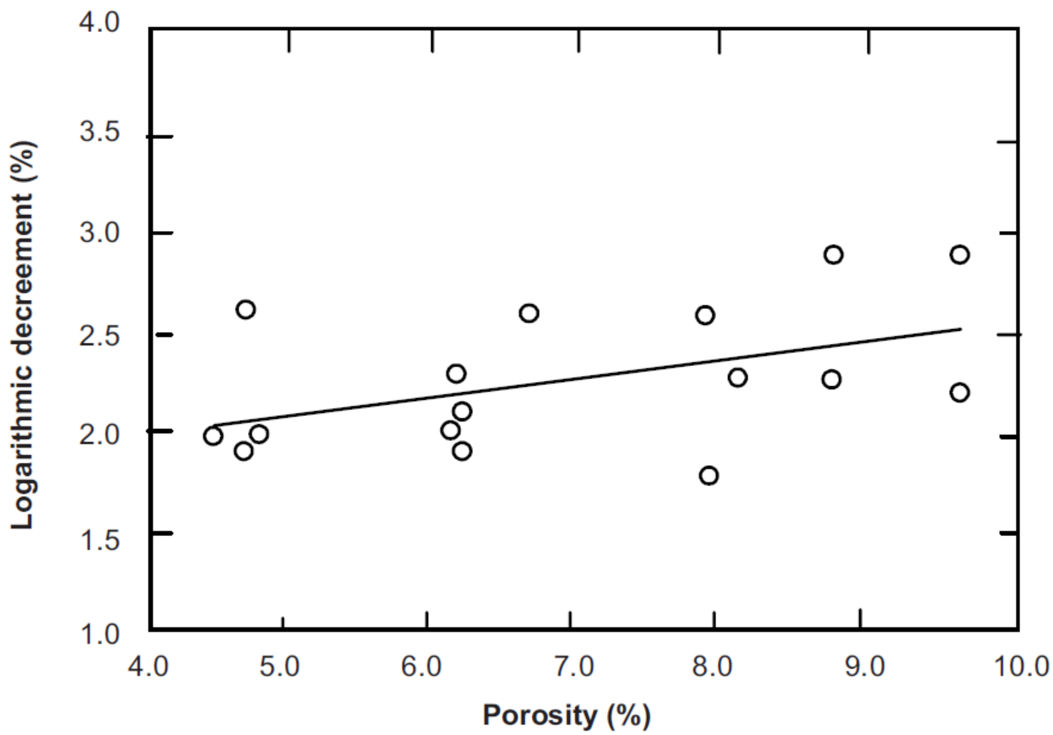


Figure 47: Relationship between porosity and damping capacity [58].

8.13 Fiber Spacing

The fiber spacing plays an important role in determining the mechanical properties of metal matrix composites. If the spacing between fibers in a composite is not uniform, that results in lowered strength of the composite than uniform fiber spacing due to the higher stress concentration due to breakage of fibers.Reduction in the strength of the composite due to scatter of fiber strength that occurs due to the increase in non-uniformity[59]. The yield strength heavily influences the strength of composite if the scatter of the fiber strength is large but not when it is small.

When an MMC is undergoing thermal cycling, a mismatch occurs between the coefficient of thermal expansion (C.T.E) between the matrix and fiber. High residual stresses develop inside the composite during the cool down from the consolidation temperature and during thermal cycling in its later operations. This adversely affects the physical and mechanical properties of composites. The fiber arrangement and volume fraction influences the determination of distribution, magnitude and sign of the residual stresses. These stresses are large enough to develop cracks, causing interfacial de-bonding and even plastic- deformation of a ductile matrix. Microscopic radial cracks can be observed at the fiber-matrix interface after thermal cycling. These cracks occur due to the tensile hoop stresses at the fiber-matrix interface[59].

The most significant amount of cracking occurs during the cool down from the consolidation temperature than the rest of the subsequent thermal cycling that occurs later. So this heating and cooling cycle can be considered to be the first cycle with the largest temperature variation to which the composite will most likely subjected to. Thus, it is important to identify and quantify the damage caused by the fabrication cool down before analyzing the subsequent thermal cycling. Oxidation may also contribute to the cracking of the composite at elevated temperatures[47].

There is a correlation between the edge-to-edge fiber spacing and the percentage of cracked interfaces. This indicates the presence of highly stressed regions in the vicinity of closely-spaced fibers. Furthermore, the location of cracks developed also indicated that the probability of occurrence of cracking is high at the closest distance between neighboring fibers because of the variation in the stress field around the circumference of individual fibers. The symmetry of fiber packing sequence controls the region of the highest stressed regions[47].

The relationship between matrix-cracking and fiber spacing suggests that more uniform arrangement of fibers can significantly reduce cracking. The radial cracking can be eliminated or reduced to a greater extent without significantly changing the fiber volume fraction. The processing techniques provide a better idea about the fiber spacing that has to be followed[47].

In the case of monofilament reinforced composites, individual fibers can be laid-up, and positioned accurately during the composite fabrication process. This means that the geometrical distribution of fibers can be easily controlled than the continuous fibers. For a given volume fraction, the interface area is less. So certain degree of matrix-fiber interaction is tolerable. Also, the toughness of the composite in longitudinal failure is directly proportional to the fiber radius in spite of failure mechanism. This makes monofilaments desirable in such applications[47].

Small ceramic spacers are deployed in metal matrices to keep the fibers apart, they also increases the strength of the composite at a given volume fraction of fibers (hybridization). In some cases, ceramic spacers are placed in tows to evenly spaced fibers; this is called ‘hybridization’ of pre-forms[47].

8.14 Interfacial Bonds

The strength of a composite is dependent upon the strength of the bond that exists between the matrix and reinforcement. Only a strong interfacial bond can effectively transfer and distribute the load from the matrix and reinforcement. The reaction between matrix and reinforcement results in a strong bond; this determines the nature of the bond. Other properties like stiffness, fatigue, co-efficient of thermal expansion, fracture toughness, thermal conductivity and creep are also affected by the nature of the interface. A brittle reaction product at the interface makes the composite crack at lower strains [60].

Mechanical bonding occurs when mechanical inter-locking between matrix and reinforcement. All chemical sources will be absent and it occurs only in the case of fiber-reinforced composites [60].

Chemical bonding arises when the atoms of reinforcement and matrix are in direct contact and is achieved by exchange or sharing of electrons. The type of bonding can be ionic, metallic, or covalent. The interface with a metallic bond is more ductile than other bonds, so it is more preferable in metal matrix composites [60].

During the processing of metal matrix composites, chemical reaction occurs between the matrix and reinforcement. In such cases, an interface reaction layer is formed. This reaction product may have different properties than that of the matrix and reinforcement. The kind of reaction products and the extent of reaction is dependent on the processing temperature, surface chemistry of reinforcements, pressure and atmosphere and matrix composition. The interfacial energy of the interface of matrix and reinforcement can be decreased by interfacial reaction and this in turn improves adhesion chemical bonding[56].

In uni-directionally reinforced composites, the nature of the interface is found to be insensitive to crack development initiation resistance and longitudinal tensile strength. But if the interface is weak, it results in reduced transverse and torsional strength of the composite and extensive de-bonding. Even the ductility is highly influenced by the interfaces[56].

In unidirectional composites, when a crack propagates along a fiber, toughness will increase for a weaker interface. However, when a crack is parallel to a fiber a strong interface is required to prevent low-energy failure. In the case of discontinuously reinforced composites, if the reinforcements are more rigid than the matrix, a weaker interface offers higher toughness. This is due to the crack blunting effect and this same effect can be obtained by dispersion of voids. However if the bond is strong and the particles are less rigid than the matrix, an increase in toughness can be obtained by raising the amount of material that undergoes considerable massive plastic deformation[56].

When a metal matrix is cooled down from the consolidation temperature to the room temperature, high residual stresses are developed inside the composites due to the mismatch in the C.T.E between the matrix and the fiber. This may result in the development of longitudinal, radial and circumferential cracks at the fiber-matrix interface region. In the case of particulate reinforced composites, the strengthening can be attained due to the thermal mismatch strain that exists at the particle-matrix interface[57].

The creep threshold stress is the index for creep resistance in a particulate reinforced composite. This creep threshold stress is dependent on the load transfer at the matrix-reinforcement interface. However, this is controlled by the integrity of the bond interface[55].

8.15 Reinforcement Coatings

The strength obtained by a composite is dependent upon the strength of the bond that exists between the matrix and reinforcement. Only a strong interfacial bond can effectively transfer and distribute the load from the matrix and reinforcement. Other properties like stiffness, fatigue, co-efficient of thermal expansion, fracture toughness, thermal conductivity and creep are also affected by the nature of the surface. Coatings on the reinforcements and surface treatments are some methods used to improve the interfacial properties[56].

The interface between reinforcement and matrix is the critical region that is affected during the fabrication. If the interface is not treated properly, it might result in the degradation of the properties like degradation of the reinforcement, lack of wettability with the matrix and interfacial chemical reaction. Some approaches that are employed to obtain desired interfaces are coating of the reinforcements, specific treatments to the reinforcements, modification of the matrix composition and control of process parameters. The most important among these methods is the coating of the reinforcement[56].

The coatings applied on reinforcements can be classified monolayer and multilayer coatings. Monolayer coatings can be sub-divided into metallic and non-metallic coatings. The multilayer coatings can be subdivided into bi-layer and multifunctional multilayer coatings. The reinforcement can also be classified according to the function of the coatings in the MMC such as multifunctional coatings, barrier coatings, wetting coatings. The wetting coatings supports wetting of the reinforcement with the matrix during processing and the barrier supports a diffusion barrier between the matrix and reinforcement. Multi-layer coatings have multiple functions like releaser of thermal residual stresses, wetting agent, and diffusion agent. Ceramic coatings act as a diffusion barrier between the matrix and reinforcement that reduces the interfacial reaction[61].

Wetting of reinforcement by molten metal helps in the formation of strong chemical bonds at the interface. Some methods used to enhance the metal-reinforcement wettability include coatings on the reinforcements and using reactive elements like calcium, titanium and magnesium and to melt and heat treat the particles before addition[62].

Besides functioning as a diffusion barrier and wetting promotion, the coatings act as “in-situ hybridizing” and “in-situ alloying” agents. This makes the coatings multi-functional and fabrication of MMCs become cost-effective. Selected metallic coatings on the reinforcements can acts as a wetting agent as well as an “in-situ” hybridizing agent. If an inter-metallic phase is formed between the coating and the matrix will improve the wear resistance of the composite. The dissolved coating in the matrix forms a second hybridized reinforcement by reacting with the coated material in the presence of a suitable non-metallic gas. This is called “in-situ” hybridization of composite because a second reinforcement is added into the matrix[62].

Inter-metallics improve the strength of the composite. When certain metallic coatings dissolve in the matrix after their primary purpose of wetting the reinforcement, alloying occurs. This improves the properties of matrix. This method is termed as “in-situ” alloying of composites. Here prudent selection of matrix alloy is required to obtain the desired result[62].

8.16 Alloys used for matrix and reinforcement

The alloys chosen for matrices and reinforcements influence the properties of metal matrix composites. The matrix alloy chosen for a particular application should be suitable for that particular application. Same metal matrix composite can have different properties if different alloys are used for matrices[52, 53].

8.17 Shape of the specimen (like Bar, Plate or Forging)

The shape of the specimen can be different for different specimens under investigation (eg. Bar, Plate, Forging). The values of mechanical properties vary for different shapes[52, 53].

8.18 Thickness of the specimen

The thickness of the specimen can be different for different specimens under investigation. The values of mechanical properties vary for different shapes[52, 53].

8.19 Design of experiments

Different sources give different values of the same MMC, because the experiments were designed differently in different cases[2].

8.20 Evolution of materials

Many issues mentioned by different sources will be solved as time passes by. Many research and commercial entities keep discussing the same issues unaware of that[2].

CHAPTER XI

9. Classification of Reinforcements

9.1 Particulate Reinforced Composites:

Reinforcements in the form of powders can be termed as particulates. They are discrete reinforcements that do not have one dimension more than five times longer than the other two. In other words, they have aspect ratio 5 or less than that. Particulate reinforced metal matrix composites usually contain less than 25 vol. % ceramic reinforcement when they are used for structural uses. These reinforcements are generally oxides or carbides or borides (Al2O3 or SiC or TiB2) and present in volume fraction less than 30% when used for structural and wear resistance applications. However, in electronic packaging applications reinforcement volume fraction could be as high as 70%[40].

According to this definition, long fibers are excluded from this class but not platelets. Spheres, rods, flakes and many other shapes of roughly equal axes may be collectively called particulate reinforced composites[40]. Considering the improvements in mechanical properties, particulate reinforced MMCs possess inferior gains in mechanical properties when compared with fiber whisker-, fiber-, and monofilament reinforced composites, because of the damage caused by the secondary processing in reinforcements. They can be produced using both solid state (powder metallurgy) and liquid metal techniques (stir casting)[3].

But they have some significant advantages over other reinforcements, viz.

a. Simple and comparatively cheap production procedures
b. Low cost for reinforcements
c. Isotropic properties for the composite
d. Compatibility with most practiced manufacturing process like welding, machining, deformation processing etc.(given the volume % is less than 40) [3]

9.2 Short Fiber and Whisker Reinforced Metal:

SFRM and whisker reinforced MMCs have reinforcements that have an aspect ratio greater than five but not continuous. Short fiber reinforcements and whisker reinforcements are elongated reinforcements when they are sold in bulk or after pre-processing into mats and preforms. But all continuous reinforcements are sold as tows of parallel and fibers wound on spools [3]. Short fibers (otherwise known as staple or chopped fibers) can be produced directly from a slurry or melt by spinning in highly turbulent atmosphere. Short fibers can also be produced by chopping or cutting continuous fibers. They have diameters in the order of a few micrometers. Short fibers have larger diameters to reduce health hazards [3]. These were produced by squeeze infiltration process. The mechanical properties are improved in short fiber reinforced composites compared to particulate reinforced composites.

Whiskers are reinforcements produced by usually vapor based processes. They are single crystals that have diameters in the range of 0.1 μm. Whiskers have an aspect ratio between 20 and 100. Whiskers have a drawback; they are known to be carcinogenic[63]. Better properties can be obtained from these composites due to the greater ability of elongated reinforcements to carry load transferred from the matrix compared with particulate (except platelets) reinforcements. Their application in automotive engines is well established. They are usually produced by squeeze infiltration[63].

Whisker reinforced composites are produced either by PM processing or by infiltration route. Mechanical properties of whisker reinforced composites are superior compared to particle or short fiber reinforced composites. However, in the recent years usage of whiskers as reinforcements in aluminum matrix composites is fading due to perceived health hazards and, hence of late commercial exploitation of whisker reinforced composites has been very limited[40]. Whiskers and SFRM reinforced composites are inherently stronger than equi-axed reinforcements, in addition for being single crystalline. So they display better mechanical properties when compared to an equivalent PRM at fixed volume fraction (given, that the fibers or whiskers are aligned in the highest principal axis)[40].

Short fiber reinforced MMCs display characteristics in between that of continuous fiber and particle reinforced MMCs [63]. Particulates, whiskers and short fiber reinforced composites are collectively called “discontinuously” reinforced composites. The reinforcing phase is discontinuous for the lower volume fractions typically used in MMCs [63].

9.3 Continuous Fiber Reinforced Metals:

CFRM are available as tows of hundreds or thousands of fibers wrapped as a tow onto a bobbin. They contain fibrous reinforcements and have diameters on the order of 10 µm (usually between 5 to 20 µm).Continuous reinforcement can be highly stiff and strong. So if the composites are designed and processed properly, exceptionally strong and stiff material can be produced that are highly anisotropic. They are also usually produced by squeeze infiltration. MMCs having fiber volume fraction up to 40% are produced by squeeze infiltration technique [40].

In continuous fiber reinforced metals, significant strengthening can be obtained when at least reinforcement volume fraction is at least 40% or greater [63].

Advantages of continuously reinforced MMCs are [40]:

(1) Low cost for reinforcements

(2) High stiffness and strength

(3) Low density

(4) Negative co-efficient of thermal expansion along the fiber direction

9.4 Monofilament Reinforced Metals (MFRM):

Monofilament reinforced composites are basically same as continuous fiber reinforced metals; the only difference is the large diameter (on the order of 100 µm). Monofilaments are also sold as individual elements wound on a spool. This is due to two reasons (1) size of the fiber and (2) they are typically produced by vapor deposition techniques. Three principal monofilaments have been used to produce metal matrix composites:

(i) Boron monofilaments

(ii) Silicon carbide monofilaments

(iii) Sapphire (nominally) single crystal monofilaments [40]

Monofilament reinforced metals are usually used in Ti matrix composites. They are usually fabricated by solid state processes that require diffusion bonding [40].

Usually they are produced by chemical vapor deposition (CVD) of either SiC or B into a core of carbon fiber or W wire. Bending flexibility of monofilaments is low compared to multi-filaments. Monofilament reinforced aluminum matrix composites are produced by diffusion bonding techniques, and is limited to super plastic forming aluminum alloy matrices [40].

MFRM has several advantages

Each monofilament can be handled individually, laid-up, and positioned with precision during the composite production process; thus geometrical distribution of monofilaments within the final composite can be controlled better than with continuous fibers.

There is less interface area per unit volume of composite, such that some degree of matrix-fiber interaction is tolerable

Monofilament reinforced metals typically have attractive longitudinal mechanical properties since the toughness of the material in longitudinal failure increases with fiber radius regardless of failure mechanism [40].

In CFMMCs and MFMMCs, the reinforcement is the principal load-bearing constituent, and role of the matrix is to bond the reinforcement and transfer and distribute load. These composites exhibit directionality. Low strength in the direction perpendicular to the fiber orientation is characteristic of CFMMCs and MFMMCs. In particle and whisker reinforced MMCs, the matrix are the major load-bearing constituent. The role of the reinforcement is to strengthen and stiffen the composite by preventing matrix deformation by mechanical restraint [40].

9.5 Woven composites:

Composites that have woven, braided and knitted fiber architectures are called woven composites. The bundle forms ‘tows’, which are produced from interlocking fibers. They orientations are slightly or fully in an orientation perpendicular to the primary structural plane. This approach results in structural, thermal, or electrical properties in the third dimension. This architecture is useful for “unwetted” or dry fiber preforms due to ease of fabrication of curved shapes. Also, it is of low cost [22].

In addition to five types of MMCs described above, another variant of MMCs known as hybrid MMCs have been developed and are in use to some extent. Hybrid MMCs essentially contain more than one type of reinforcement. Examples are mixture of particle and whisker, or mixture of fiber and particle or mixture of hard and soft reinforcements. Aluminum matrix composite containing mixture of carbon fiber and alumina particles used in cylindrical liner applications is an example of hybrid composite[22]

CHAPTER X

10. Concluding Remarks/"The World is getting Flatter"

The evolution of metal matrix composites has been closely analyzed from 1950 to 2010. The world has changed drastically over the past 60 years. The world was recovering from the aftermath of WW-II in the early 1950s. This was followed by the Cold War between the two superpowers at the time, the U.S.A and the U.S.S.R. This led to a bi-polar world. Both countries strived for technological supremacy that ignited the Space Race. This greatly boosted the growth of metal matrix composites. It was during this period that Japan emerged as a major industrial power with the aid of the U.S.A. By the late 1970s, China started to emerge as a major industrial power and they started to contribute to the scientific world by the mid-1980s, including metal matrix composites.

By the November of 1989, Berlin Wall collapsed. This symbolically ended the Cold War. The bi-polar world transformed into a uni-polar world. It remained like that for most of the decade that followed. After the collapse of the Soviet Union, many countries (like India, China, Russia etc.) that followed the Soviet economic model opened up their economies to the rest of the world. This brought new brain power into the field [64].

This decade also witnessed the emergence of the internet. This was a disruptive force for many, but it was a constructive force for many emerging technologies like metal matrix composites. Search algorithms like Google and Engineering Village made it possible for anyone with an internet connection to access the information about any subject. This greatly enhanced the research and commercialization efforts of MMCs. The internet helped corporations and research laboratories outsource, share, and offshore projects efficiently and helped groups collaborating on online projects from different parts of the world. Examples are open Wikipedia, blogs, and open source softwares.

If we observe the bar diagrams from 1965-1969 to 2010, we clearly see the changes that happened in the world mentioned above in those diagrams. During 1965-1969, the U.S.A. was the largest contributor of journal articles. They pioneered the research efforts in this field. The U.S.S.R. also contributed to the research efforts. 1975-1979 represents the height of the Cold War. The U.S.A. and the U.S.S.R. were the largest contributors; this is the perfect model of a bi-polar world. Japan emerged as a major industrial power and makes considerable contributions to the research efforts of MMCs. But it has its application in the commercial sector.

During 1985-1989, the U.S.A. was doing well under the Presidency of Ronald Reagan. But the U.S.S.R. showed clear signs of weakness. 1990-1994 represents the uni-polar world after the collapse of the U.S.S.R. China has also clearly emerged. 1995-1999 witnesses the emergence of China.

Another turning point after 1985-1989 occured in 2000-2004. China overtook the U.S.A. and we see some bars on the plots coming down and on the other hand some bars going up. One bar that went down was the U.S.A .and some bars that went up were China, Turkey, South Korea, Germany, UK, France, India, and Singapore. Now the whole graph seems to be a flatter than ever before. And finally, during 2005-2009, the flattening is more evident. This “flattening” demonstrates the emergence of the multi-polar world in beginning of the 21st century.

This finding reminds the author of the title of a book, “The World Is Flat: A Brief History of the Twenty-First Century” by Thomas L. Friedman that discusses globalization especially during the early part of the 21st century [64]. So the analysis done in the thesis helps the author to conclude that the world is *getting flatter*. The reason why the analysis of the evolution of metal matrix composites can be used as an index to study the global trends is due to the fact that metal matrix composites’ primary applications are in the strategic sectors like defense, aerospace, space and energy generation. A country’s future is directly dependent on its standing in the strategic sector.

Lastly, the author notes that even if quite a number of universities in the U.S.A. like the University of Texas at Austin, the University of Utah and Virginia Polytechnic Institute and State University are doing good research work in this field, not even a single university in this country has a laboratory exclusively for metal matrix composites research. On the other hand, at least six universities in China have labs exclusively for MMCs. The end use of metal matrix composites is in strategic applications like skins of hypersonic aircrafts, high speed jet engines, and nuclear reactors. If another country is getting far ahead of the U.S.A. in research fields like this, it is a matter that the policy makers, strategists, and technologists of this nation should pay attention to.

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APPENDIX-1

Detailed instruction of how to Find the Impact Factor of a Journal?

1. Go to http://www.library.okstate.edu
2. Click “Databases”
3. Click “J”
4. Click “Journal Citation Reports”
5. Click “Submit”
6. Select the required field
7. Click “Submit”
8. The table that depicts the impact factors will be displaye

APPENDIX-II

The number of papers published during each period and its country of origin is shown in tables.

Period	1965 - 1969
Country	**Numbers**
USA	8
Germany	4
UK	3
France	2
Australia	2
Japan	2
USSR	2
Chile	1
Error	5
Total	29

Period	1970-1974
Country	**Numbers**
USA	70
USSR	9
UK	11
Germany	11
Japan	6
France	4
Ukraine	3

Poland	3
Canada	2
Egypt	1
Denmark	1
India	1
Australia	1
Israel	1
Portugal	1
Total	125

Period	**1975-1979**
Country	**Numbers**
USA	46
USSR	29
Japan	12
Germany	9
France	5
UK	4
Brazil	2
India	1
Denmark	1
Australia	1
Romania	1
Canada	1

Italy	1
Iran	1
Total	115

Period	**1980-1984**
Country	**Numbers**
U.S.A	110
Japan	37
U.S.S.R	26
India	10
Germany	6
Sweden	4
United Kingdom	4
Bratislava	2
Canada	2
Qatar	2
France	2
Ukraine	2
Belgium	2
Turkey	1
Total	115

Period	**1985-1986**
Countries	**Number**

USA	36
France	6
USSR	3
Germany	3
Japan	3
UK	3
Switzerland	1
Australia	1
Poland	1
Israel	1
Italy	1
India	1
Denmark	1
Total	61

Period	**1987-1989**
Countries	**Number**
USA	13
France	3
China	1
Germany	1
Sweden	1
Japan	1
Canada	1

India	1
Italy	1
Total	23

Period	**1990-1994**
Countries	**Number**
U.S.A	59
China	10
U.K	8
Japan	4
Israel	3
Russia	3
France	3
India	3
South Korea	3
Germany	2
Canada	2
Taiwan	2
Greece	1
Jordan	1
Iran	1
Turkey	1
Denmark	1

Total	107

Period	**1995-1999**
Countries	**Number**
U.S.A	66
China	35
France	16
Israel	13
U.K	13
Japan	12
Australia	9
South Korea	8
Hong Kong	7
India	7
Singapore	4
Italy	4
Germany	4
Singapore	4
Slovenia	4
Canada	3
Turkey	3
Russia	2
Taiwan	2
Denmark	2

Iran	2
Spain	2
Austria	1
Ireland	1
New Zealand	1
Belgium	1
Switzerland	1
Finland	1
Ukraine	1
Total	229

Period	**2000-2004**
Countries	**Number**
China	34
USA	20
Turkey	22
South Korea	20
Germany	17
U.K	15
France	15
India	14
Japan	11
Singapore	9
Hong Kong	6

Italy	9
Canada	6
Russia	5
Australia	5
Spain	5
Switzerland	4
Egypt	4
Taiwan	3
Jordan	3
Netherlands	2
Mexico	2
Slovenia	2
Austria	2
Iran	2
Canada	2
Malaysia	2
Iran	2
Brazil	2
Chile	1
Ireland	1
Portugal	1
South Africa	1
Finland	1
Total	250

Period	**2005-2009**
Countries	**Number**
China 57	57
USA	35
Turkey	25
U.K	22
Italy	19
France	18
Singapore	18
Spain	15
India	15
Germany	14
Hong Kong	12
South Korea	11
Japan	9
Iran	9
Australia	7
Canada	5
Czech Republic	5
Slovak Republic	4
Sweden	4
South Africa	3
Mexico	3
Switzerland	3

Netherlands	3
Russia	3
Taiwan	2
Brazil	2
Ukraine	2
Slovenia	1
Venezuela	1
Vietnam	1
Finland	1
Egypt	1
Brazil	1
Portugal	1
Belgium	1
Poland	1
Jordan	1
Portugal	1
Total	342

Period	**2010**
Countries	**Number**
China	8
India	6
Singapore	4
Germany	3

Austria	3
South Korea	3
U.S.A	2
Switzerland	2
Spain	2
Japan	2
France	1
Netherlands	1
Egypt	1
Australia	1
Czech Republic	1
Iran	1
Saudi Arabia	1
Total	4 2

APPENDIX-III

Comprehensive list of papers that discuss the metal matrix composites from the period 1924 to 1986.

[1] E. Schmidt, "E. Schmidt, German Patents Nos 425451, 425452 and 427370, 1924" Germany Patent, 1924.

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The history, status, and future of metal matrix composites are presented by evaluating the progression of available literature through time. The trends that existed and issues that still prevail are discussed and a prediction of the future for MMCs is presented. The factors that govern the performance of metal matrix composites are also discussed. In many developed countries and in several developing countries there exists continued interest in MMCs. Researchers tried numerous combinations of matrices and reinforcements since work strictly on MMCs began in the 1950s. This led to developments for aerospace and defense applications, but resultant commercial applications were limited. The introduction of ceramic whiskers as reinforcement and the development of 'in-situ' eutectics in the 1960s aided high temperature applications in aircraft engines. In the late 1970s the automobile industries started to take MMCs seriously. In the last 20 years, MMCs evolved from laboratories to a class of materials with numerous applications and commercial markets. After the collapse of the Berlin Wall, prevailing order in the world changed drastically. This effect was evident in the progression of metal matrix composites. The internet connected the world like never before and tremendous information was available for researchers around the world. Globalization and the internet resulted in the transformation of the world to a more level playing field, and this effect is evident in the nature and source of research on metal matrix composites happening around the world.

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