

EMERGING CHARACTER OF METALLIC MATERIALS

U. P. Thakur

Additional Director

Defence Machinery Design Establishment,, P. B. No. 2043, Secunderabad – 500 003.

ABSTRACT

Despite the usefulness of metals, new alternative materials have been appearing on the scene everyday, threatening the metallic monopolies. Innovative developments in technologies and techniques make metals still the most sought after material for various applications including areas where non-metallic materials were dominating till recently. This paper highlights the technological advances taking place in the area of metallic materials meet to the exacting requirements of automobile, marine, space and knowledge based industries.

INTRODUCTION

Process metallurgy is one of the oldest art dating back to 6000 BC when gold was discovered. There are 86 known metals today, out of which only 24 were discovered before 19th century and 12 of them found in the 18th century. It took 7700 years since the discovery of gold to the end of 17th century to discover just 12 metals. Deeper understanding of behaviour of metals is opening up newer application areas. The requirement of properties for information related industries is entirely different and no doubt that these are being met by metals.

It is well known that the discovery of copper, tin and iron set the road to technological development the worldover(1). During 1970s and 1980s the metallic materials faced challenges of substitution by plastics, composites and ceramics. But the scenario changed amazingly with the growth of automobiles and aircrafts, shipbuilding and submarines, bridges and buildings, and machines. Copper is almost indispensable for all uses of electricity. Aluminium is second to none in everyday applications, and titanium and zirconium are essential for space applications. Metals and their alloys are so extensively exploited that many of them suffer from critical shortages, and have become strategic e.g. chromium, cobalt, manganese, platinum, columbium, strontium, titanium and tantalum(2).

THE ISSUE

Iron , aluminium and titanium are energy and capital intensive. In addition, new alternatives hit the headlines everyday. Where do the metals stand? What is their future and future of this mankind that is established on the metallic foundation? How do metals, metallurgists and scientists and engineers dealing with metals are responding to the multipronged attack from alternative materials, technologies and high performance requirements ? What is the direction of research and development taking place to meet the stringent demands of information age?

There have been three stages of economic growth – an agricultural economy followed by manufacturing economy and now a developing service economy, which is generating completely separate industries such as software, communication, the media and health care – all information intensive and knowledge – based. How are the materials and metals in particular shaping the course of this development? Do the metals matter to the technological innovations and discoveries that are changing the complexion of our life? Are they becoming communicative and interactive in this integrated world? How are the metallic products getting networked? Are they a part of the electronic revolution or are they out-of-date with the emerging technology of web-based engineering? How are the metals facing the new challenges – challenges thrown by networked world, and those by situations and conditions where lesser and lesser materials are required to perform better and higher, with higher efficiency?

The industry, research and development agencies are focused these days on improvements in the processing of metals and materials and incremental upgradation of properties to make them competitive in performance, cost and efficiency and reduction in the consumption of energy. How is the new thrust in research and development influencing the prospects of metals in the new economy? How best are the properties of other materials being ported to metals? What is the range of technological possibilities in metallic materials that is growing substantially and is opening new windows of opportunities for them currently and in future? Are they coming clean on environmental issues? Decrease of materials usage, sustainability and life cycle, product and materials recycling, and, energy efficiency are the new features that need close examination . How are the information technologies, nanotechnology, and biotechnology placed with the science and technology of metals? This paper in part addresses some of these and related issues in the present scenario and project the future shape of metals.

POTENTIAL OF R&D IN KEEPING THE METALS COMPETITIVE

Metals and alloys have exhibited a fair amount of versatility in their properties and applications and are amenable to adapt to various environments and workable to complex processing and newer techniques viz. virtual prototyping, rapid prototyping, rapid tooling, mould making and tooling. Today they are finding applications in areas away from their traditional fronts due to better understanding of material science and continues to dominate the information age (3, 4).

Metals created and drove the industrial revolution, it did help in agricultural revolution and it is creating and driving the service economy – as well as the environmental revolution. The current broad science and technological trends toward metals that have a greater information content per unit weight indicate we can design lighter components to save energy and materials, can design complex engineering structures to operate longer and be more reliable, and can avoid overdesign to reduce the abuse of scarce materials (5). This approach reflects a strong move towards the development of products with high added values, which in turn, require metals with greater sophistication of content, packaging more and more information into a product.

What started as extraction metallurgy extended to physical metallurgy and as a result added entirely new dimensions to technical application areas that include electronics. Developments in metals are strongly influencing the fields of biomaterials, biotechnology, photovoltaic, thin film devices, ferro electric memory devices, superconducting devices, sensors for monitoring the environment and many more(6,7,8,9,10,11).

Research and developments are leading to enhanced performance of the material system (12,13) and creating equivalences in many areas. There are even more opportunities in the areas of overlap between the metallic and non-metallic materials in industries such as automobiles, computers, medicine, agriculture and communication. Metals have joined the latest innovative surface technologies including surface pre-treatment, laser surface engineering, mechanical surface processing, electroplating techniques, lamination welding, lacquers, varnishes and enamels, thermal spraying, PVD and CVD surface refinement and nitriding and carbonitriding. Light metal world is opening an entirely new world of opportunities – titanium, magnesium, aluminium, and light metal composites. Metals have shown their mettle even in information technology, transportation technology, electrical power generation, and energy conversion, medical engineering, buildings and structures, nano and micro-technology, sports and adaptronics, aerospace, railways and shipping, optical and magnetic storage systems, electronic packaging and display technology, to name a few.

Newer avenues in surface technology involving protective coatings, advanced coating processes, coatings for tools and machine parts and multifunctional coatings are surfacing. Metals are showing their merit in the development of fuel cells, systems for renewable energy and implant materials (14,15). Metals will continue to be the enabler of future developments in micro electronics, information technology, transport and energy systems – is being recognized more and more and is accepted as "one of the basic resources of mankind, ranked alongwith living space, food, energy and human knowledge. This huge materials complex is now called "the materials cycle", said Morris Cohen, one of today's sages in materials science and engineering field.

OPPORTUNITIES IN METALS

With proper exploitation strategy, higher degree of sophistication can be achieved with lesser quantity of materials because metals have a fair degree of flexibility in their properties and behaviour which make them amenable to various processes and treatments to obtain new set of properties and characteristics.

It is only the bulk and structural integrity of metallic materials that have been exploited till now. Their capabilities of intelligent behaviour and responses are not yet fully understood and used (16,17). The work in this area is opening newer opportunities. Opportunities also lie in the ability of metals to join with plastics, composites, and non-metals. This overlap is creating new applications in industries such as automobiles, computers, medicines, agriculture and communication. Metallic materials have joined the revolution in polymers and ceramics world to tailor the properties to meet critical demands.

METALS IN AUTOMOBILES

As attempts are made to use metals in non-traditional areas, non-conventional qualities particular to the new environment are also being explored (18,19). The lateral shift of metals from space applications to sea and to automobiles and vice versa is being effected by incorporating changes in composition, processing and treatments.

The move of Magnesium from aerospace to high volume cars and trucks is being engineered. The US automotive industry has gone to realize the weight reduction benefits to be gained from the greater use of magnesium alloys in high volume cars and trucks for steering wheels, steering columns, dashboard parts, transmission housings and gear boxes (20). Higher temperature alloys are being developed, with emphasis on lower cost alloying additions. While development of wrought magnesium alloys is still in its infancy, elevated temperature forming of magnesium sheet could enable the manufacture of automobile body closure and structural panels to meet vehicle mass targets. The superplastic formability of the commercial magnesium alloys is being evaluated.

Titanium is replacing steel in many of automotive applications: High strength, low density, low modulus, and excellent resistance to corrosion and oxidation of titanium and its alloys make them the material for internal combustion engine components like valves, valve springs, retainers and connecting rods, and vehicle bodies and springs. Attention has been mainly on the development of low cost alloys, exploration of low cost manufacturing methods, and evaluation of treatments to enhance wear resistance.

Titanium has a unique combination of strength, density and modulus which make it ideal for spring for almost every application. Valve springs and the entire valve train will have ideal in titanium for automotive engines for the mass market (21). Surface treatment to improve the wear resistance of titanium alloys is a key to its successful application in the valve train. Factors such as reduced noise, vibration and harshness (NVH), improved durability, large interior space and reduced reliance on regulated coatings support titanium for selected automotive components.

A family of new aluminium alloys designed for direct injection diesel pistons has been developed at Federal-Mogul Power Cylinder Systems, Southfield, Michigan. Gravity casting aluminium alloys are being developed to provide high-temperature fatigue resistance for LVD (light vehicles diesel) pistons. New alloys and new production processes are also being investigated to provide greater fatigue resistance and lower expansion in the piston crown (22).

Developments in metallic alloys for automobiles have kept them at pace with the environmentally-aware customers who also want greater safety, minimum noise, maximum fuel economy and continued reduction in harmful emissions.

SEA FARING METALS

Navy presents a highly corrosive liquid containing aggressive ions, exacting dynamics, operational stresses and strain, severe shock, safety and ergonomic problems, and under water acoustics. And each of them has a bearing on the properties of material for every component.

There was a time when the materials used for marine applications on board warships were drawn from a restricted list of cast iron, carbon steel – copper, brass and bronze alloys. The use of this restricted list was quite often catastrophic for naval application owing to the hostile environment and process conditions they were subjected to. Post Second World War, there has been an enormous expansion in metallurgical research and newer alloys, both ferrous and non-ferrous are available today that provide better adaptability to the harsh marine environment (23).

Iron based superalloys are extensively used in heat exchangers for turbine, bolts, etc. They are incoloy, multimet, discalloy. Amongst the non-ferrous alloys, aluminium, copper and titanium alloys are much sought after. Aluminium alloys, because of their inherent low density and high corrosion resistance have found extensive application in ships super structures. However, the Falkland war showed they were very poor for explosion resistance and a potential fire hazard under enemy attack. The present day use of aluminium alloys is very restricted for onboard application. They are used only where strength is not a prime criteria and weight is of prime consideration like handwheels, enclosure, etc.,

Because of their good mechanical properties, easy fabricability, availability and above all good corrosion and biofouling resistance, copper alloys have seen widespread use in marine environment (24). Copper alloys of interest to marine engineers can be broadly classified as bronzes, nickel aluminium bronze and cupronickel. Bronzes are employed in bearings and bushings, pump impellers, heat exchanger tubes etc. Copper when alloyed with more 10% Ni forms an alloy called Cupro-nickel which have excellent resistance to corrosion and biofouling, and find applications in heat exchanger tubes, condenser shell, sea water system piping, fresh water piping, etc.

Nickel aluminium bronze, NAB is perhaps one of the most widely used copper alloy for sea water components. It has density comparable to that of steel, but has better corrosion resistance, same strength, better fatigue resistance and one of the best impact resistance. But its corrosion resistance is dependent on its casting and manufacturing perfection. Centrifugally cast NAB is perfect in corrosion resistance. NAB is one of the best materials for sea water systems, and has been extensively used in pumps, valves, heat exchangers, etc.

Titanium with low density and high strength, good thermal conductivity, ductility and high impact and fatigue resistance and above all the best corrosion resistance is the potential candidate for sea water applications like valves, heat exchangers, hulls, propeller shafts, etc. It is the metal that keeps sailing.

AEROSPACE METALS

Aerospace industry is witnessing increased focus on materials and manufacturing methods to produce high performance material structures at a lower total cost, to exploit material development and novel manufacturing techniques. The need for improved toughness, lower weight, increased resistance to fatigue and corrosion – are increasing as manufacturers strive to give the next generation of aircrafts with improved performance while making them more efficient. Aluminium is one of the key materials facing these challenges. Significant improvements to the

manufacturing route for existing alloys in response to the increasing demands of airframes are being made (25). The new routes of manufacturing have resulted in better properties, including short transverse (ST) ductility, fatigue performance, and fracture toughness. Improvements in material properties are being obtained by compositional changes, primarily of the main alloying additions, and by processing conditions. Lower density, with the retention of other properties is regarded as a key factor in improving flight efficiencies.

Trends in aerospace indicate toward the requirement for 25 years of reasonably maintenance free service leading to a different look to the properties. The issue of new and improved alloys to replace existing ones is also being tackled. Aluminium-lithium alloys, for example, have been removed from Airbus design due to cost and concerns over fracture toughness (29).

The commercial exploitation of high-strength Al-Zn-Mg-Cu alloys is often restricted by their increased susceptibility to stress corrosion cracking (SCC) when in their peak-aged condition. Many aerospace applications call for excellent resistance to SCC owing to the conditions of service (26,28). Artificial ageing treatments, such as retrogression and re-ageing (RRA) is used by BAP, to achieve the SCC resistance exhibited by over-aged alloys while maintaining peak-aged strength. Improvements to the fatigue, ductility, and fracture toughness of thick 7010 and 7050 plate have also been achieved.

Titanium base alloys and nickel base superalloys have shown improved performance through steady alloy refinement and advances in processing technologies such as unidirectional and single crystal casting for turbine blades and vanes, isothermal forging and powder metallurgy techniques for discs, etc (27). Introduction of composites both metal matrix and ceramic matrix and development of thermal barrier coating have also enhanced the performance limits.

Nickel-base alloys and titanium alloys are likely to be replaced by intermetallic and composites. Work on titanium metal matrix composite (MMC) is likely to offer weight savings due to higher specific mechanical property and dimensional stability. It is now established that addition of whiskers increases stiffness while addition of continuous fibre increases strength as well as stiffness.

Thermal protection system for hyperplanes calls for high temperature resistant materials for use as basic structural materials and coatings. Currently available candidate materials are titanium alloys like T₁-6Al-4V and titanium alloys with nickel and chromium as main constituents. Replacement of titanium alloy by boron-silicon-aluminium alloy results in a weight saving of about 25% for those components.

Today's high altitude, space and ocean centered programmes depend on the manipulation of metals and materials into reliable hardware. Most of the individual piece – parts used in spacecraft and ships and submarines are manufactured from standard commercial materials. However, while the materials themselves may not be novel, the fabrication processes of the components they form are often enterprising.

The environment encountered in space is not particularly aggressive but rather uncommon, depending on whether a satellite is in a low earth or geostationary orbit or inter-planetary travel etc, each requiring a different kind of material. For example,

vacuum exists everywhere in space varying from 10^{-1} Pa in poorly vented region which leads to the danger of electrical corona discharges to 10^{-12} Pa in deep space. In these conditions, organic materials must avoid out gassing, while metallics must resist sublimation. The high level of radiation in space, and other particles originating from deep space, are likely to degrade material surfaces and disrupt electronic devices. While solar reflecting surfaces can be protected by using white paints with an inorganic base and a silicate binder, black anodized aluminium with an inorganic nickel sulphide dye protects flat absorbing areas. Micro-electronic semi conductors are radiation-hardened by altering their manufacturing method, or by providing physical shields made from tungsten-copper composite. Protection from micro meteoroids and space debris is provided by having panels consisting of teflonized woven glass, woven kevlar-49 reinforced plastic and aluminium alloy sandwiched together.

Few metals such as silver in low-earth orbits are rapidly oxidized by atomic oxygen, which also erodes kevlar and teflon. Silicon layers, pure metal layers of platinum and aluminium and stable oxide layers of alumina, silicon and indium-tin-oxide can provide protection. Solar arrays are subjected to a cycle in orbit from -150°C in eclipse to $+100^{\circ}\text{C}$ in sunlight, leading to a variety of thermal fatigue mechanisms. This has led to the development of controlled expansion materials with the property to combat thermal fatigue. They are aluminium metal matrix composites with SiC particles and silicon-aluminium alloys with Al varying from 50 to 20%. High temperature fasteners for securing c-c-composite tiles are oxidation protected with coatings of aluminides (Al_{40}Si and Al-Si-Ti) or silicides ($\text{Si}_{20}\text{Cr}_{20}\text{Fe}$ & Si-Cr-Ti).

EXPANDING UNIVERSE OF PROPERTIES

Metals have been traditionally described as having certain physical, chemical, mechanical and electrical properties. They were later, with different requirements expanded to optical, and acoustic and still later to properties related to space, and deep sea applications. In recent times, electronic and biological properties are evolving to characterize the material to define their adaptabilities to information and biological systems. The triple technologies of information technology, biotechnology and nanotechnology are adding yet another list of properties. Properties related to specific functions and performances are being defined. Functionality of the use of the materials and the degree of their performance, have acquired prominence recently.

As the materials use increased laterally and vertically, their properties and behaviour have also been defined, redefined, modified and enlarged to describe these materials in the new situation and environment. Today the properties of durability, reliability, life cycle costs, recyclability, environmental concern, energy consumption are becoming universal without which the materials definition remain incomplete. Level of adequacy of properties has been increasing vertically as well as horizontally. Adaptability of materials, their ability to adjust, respond and interact with newer conditions has become a new characteristic that is hotly sought after. With this has grown the field of intelligent materials and adaptronics. Ability of the

materials to be designed into a useful product – the degree to which the total design reaches a “harmonic unity” or a solution, in particular the construction, assembly and functionality of the designed product is taken seriously. The days of single materials entity are over and in place are growing the concept of material system consisting of more than one material element, designed to perform a particular or more than one function not possible before, opening up a new set of behavioural characteristics. This expanding universe of properties and behaviour of metals have made them flexible enough to take new role in every age, more so in information age.

CONCLUSION

Researchers and developers, technologists and engineers are engaged in unearthing the hidden potential of metals and exploring the opportunities of applications.

The study of materials science and engineering today is an example of rapid adaptation. It began as extraction metallurgy, evolved to include physical metallurgy and has rapidly added new and exciting areas, such as ceramics, rubbers, polymers, and electronic materials. Metallic materials now find applications in biomaterials, biotechnology, photovoltaics, thin film devices, ferro-electric memory devices, superconducting devices, sensors for monitoring the environment, shape memory alloys.

Opportunities exist in the manufacturing industries to reduce cost and energy consumption, improve environmental condition by innovation technologies. Metals have joined the competitive and sustainable growth game of the development of economy.

Material science offers a new role for metals. Exploration of metals and their alloys have been limited to whatever the art of metallurgy could provide. As William Hume Rothery said, “metallurgy is one of the oldest arts but the youngest science” The science of metals and alloys is yet to be tapped.

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