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Challenges in joining emerging materials

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ABSTRACT

The revolution which has occurred in materials science and engineering over the past two decades has not been matched by improvements in joining science and technology. It is becoming increasingly apparent that the usefulness of many new materials is limited by our ability to manufacture products made from these materials economically, rapidly and reliably. As designs utilizing new materials require ever higher performance, the number of acceptable joining technologies becomes more restricted. As the functionality of materials becomes more specific, the number of joints and the number of dissimilar material combinations increases. This creates increases in cost and decreases in reliability. It is concluded that the science and technology of joining of both new and traditional materials must advance much more quickly in the future than it has in the recent past.

KEYWORDS

Welding, Joining, Advanced Materials.

INTRODUCTION

I often ask my students to think of the largest stand-alone manufactured product that does not contain a joint. For many years, the best response was a cast iron frying pan, but recently one of my faculty colleagues took up the challenge; he thought of an anvil. The point of this exercise is to emphasize that every manufactured product contains joints and that the quality of the product is directly related to the quality of the joint. Indeed, when teaching fracture to his students, another colleague is known to have said, "Something will not fail unless it has been welded!". This statement appears to be a terrible indictment of welding but there is some truth to it. Welds are often the weakest part of the structure and are generally located at the most highly stressed locations. In addition, joining often comes near the end of the manufacturing process when the cost of scrap is high.

Joining is truly a ubiquitous process ranging from minute integrated circuits to huge structures such as cargo carriers or as I often say "... from chips to ships". Rich dividends will be paid to the country that realizes the pervasiveness and importance of welding in their economy and in the development of world class manufacturing industries. Nonetheless, the welding profession faces a critical time. With new materials being developed on nearly a daily basis, we lack the knowledge or the processes with which to integrate these new materials into products. Improvements in joining science and technology must keep pace with advances in materials science and technology or else the benefits of these new materials will not be achieved in the marketplace. Unfortunately, few countries have committed the resources or the manpower to succeed in this part of the materials revolution.

THE INTERFACE BETWEEN MATERIALS SCIENCE AND JOINING TECHNOLOGY

Materials scientists describe their field in terms of processing, structure, properties and performance. A recent study by the National Academy of Sciences in the United States places these on the four corners of a tetrahedron, as shown in Fig. 1, in order to emphasize the interrelationships between each.

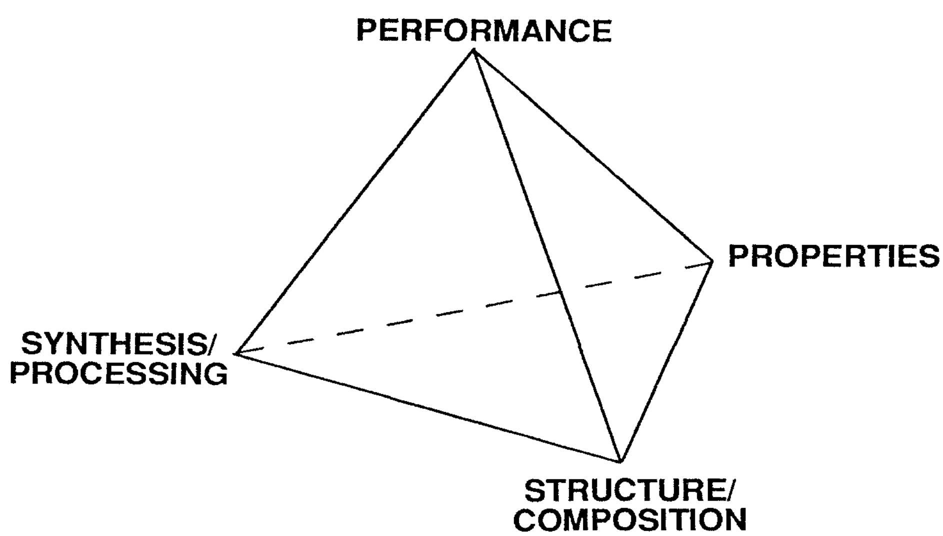

Fig. 1. The materials tetrahedron showing the four elements of materials science and engineering. (After Chaudhari and Flemings, 1989)

As a process, joining lies at the interface between materials science and manufacturing science. Figure 2 attempts to show the relationships between materials science, manufacturing science and fabrication, each of which contributes to the performance of a product in the marketplace. Many of the advanced materials being developed today will never be used in large volumes because of inattention to component fabrication and manufacturing science. Without geometry or shape, which produces function, the properties of the material are useless. Unless the shape and properties can be obtained economically, the product has limited utility.

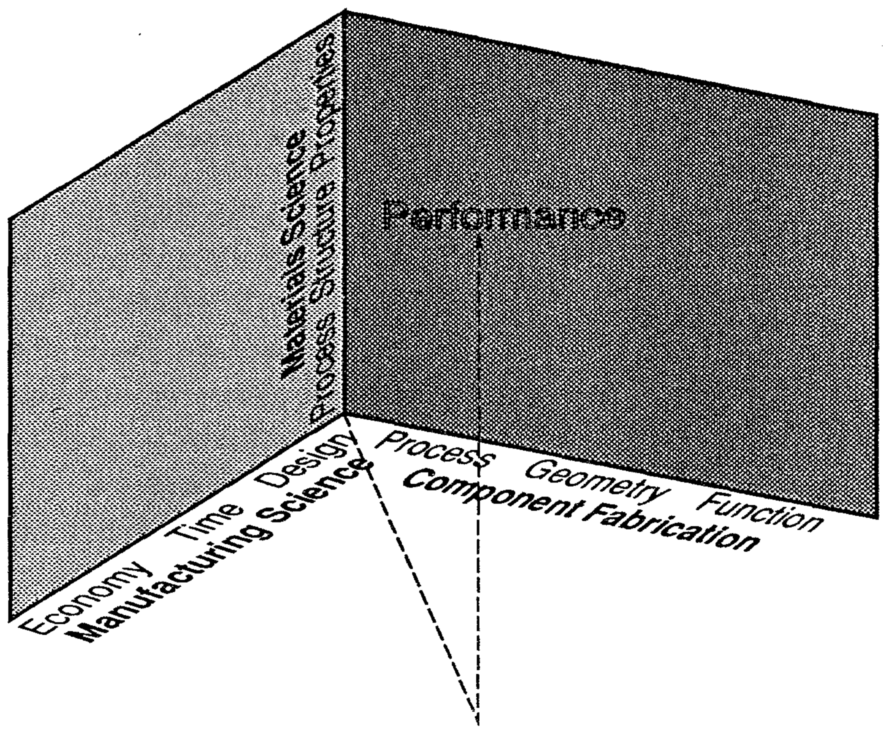

Fig. 2. Materials science, manufacturing science and component fabrication each contribute to the performance of a product.

As designers specify an increasing diversity of materials in their product, the number of joints increases. As the materials become more specialized, they are used closer to their performance limits and hence greater requirements are placed upon the joints. Thus, we are beginning to see an increasing number of joint failures in spite of the improved joining technologies and quality control processes which have been developed in recent years. The requirements of emerging materials are increasing faster than is joining technology.

WHAT IS EMERGING?

One commonly separates materials into classes including metals, ceramics, polymers, composites or electronic materials. In addition, when one asks what materials are emerging among any of these classes, it is necessary to specify the industry which one is considering. For example, joining of aluminum is hardly new to the aerospace industry, but aluminum sheet is an emerging material in the automotive industry. Each industry has different constraints. In aerospace, light weight and exceptional quality are primary, even to the exclusion of material costs, whereas in the automotive market, reasonable quality, obtained at high production rates and low materials cost is required. Each industry is cost-minimizing over the entire product manufacture and use cycle, but each has different constraints within the manufacturing portion of the cycle. One method of viewing this is the three dimensional matrix shown in Fig. 3. What is emerging depends on the industry as well as the type of material being considered. A novel material for one industry may be a traditional material in another industry; therefore, the challenges facing use of an emerging material are specific to that industry.

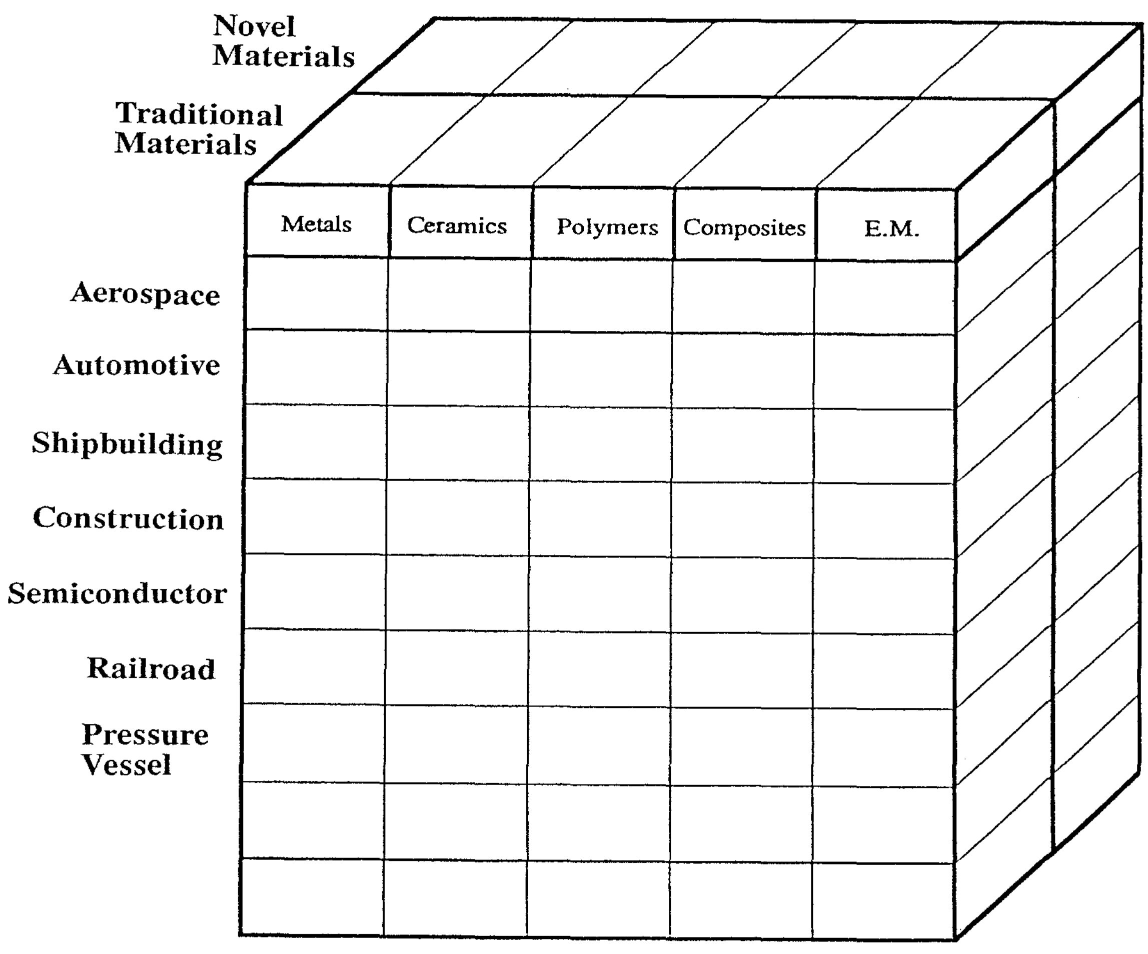

Fig. 3. The distinction between novel materials and traditional materials depends on the industry which one is considering.

In addition, emerging materials and processes vary from country to country. For example, in shipbuilding, some countries, such as Taiwan or Japan, already make extensive use of automatic or semi-automatic welding equipment. Korea has been rapidly increasing its use of such processes, but China still has opportunity to introduce more such technology. Similarly, Japan has made extensive use of accelerated cooled steels for nearly a decade while such materials are just emerging in many other countries.

Since few, if any, novel materials will be used in a monolithic form, they must be integrated into the structure or the product using joining technology. Unfortunately, joining technologies do not exist for many of these new materials. On the other hand, industry has a significant need for joining traditional materials more economically, at high productivity and with high quality. This may or may not require new joining processes, but it certainly will require new resources, many of which are shrinking rather than expanding. Thus, one may think of emerging joining technologies either in terms of methods of joining novel materials or in terms of improved or novel processes for traditional materials. Thus, what is emerging depends on the material, the industry, the country and the process. With such a broad spectrum of emerging technologies, I could end my discussion at this point; nonetheless, I believe there are some general features which categorize the challenges to joining of both traditional materials and novel materials in all industries.

CHALLENGES IN THE USE OF TRADITIONAL MATERIALS

The properties and functions of traditional materials are well known; hence, improved performance can be achieved best by increasing the economy, the quality, the reliability and the speed of the joining process (cf. Fig. 2). It is commonly believed that this can be done through automation and enhanced quality control procedures; however it is becoming increasingly apparent that automation of a process which is not under control merely produces scrap more quickly. Additional quality control requirements, or maintenance of quality by inspection at the end of the manufacturing process, escalates costs rather than reducing them. Quality must be produced in the part during manufacture, not inspected into the part after manufacture. Automation and development of quality control in welding and joining are not the keys to improved production of traditional materials; this can only be achieved by improved understanding of the process, which will require a more thorough education of the workforce. Few engineers or designers have any education in joining. Few technicians or machine operators have an understanding of the fundamentals of the joining process. Clearly the welding community must communicate what is known about welding of traditional materials to a broader group of professionals and laborers in the future. We must develop a wider spectrum of educational materials at every level and make them available to more people outside our profession.

In the fabrication of heavy structures, such as the shipbuilding, construction and pressure vessel industries, arc welding will continue to dominate due to the flexibility and economy of these processes. Automation will increase steadily, driven as much by a shortage of skilled labor as by new technologies. The most successful automation technologies will be simple and inexpensive rather than the high technology, high cost approaches which are so popular among welding researchers. It simply makes no sense to place a $50,000 sensor on a $10,000 welding arc unless one is working with materials of an extremely critical nature. High technology is not the answer to the challenge of welding automation. Some of the simplest control strategies work the best, and are always more economical to implement.

This lesson is vividly demonstrated by contrasting welding automation research in Japan and in the United States. In the U.S., great emphasis is placed upon elaborate sensing and control strategies such as machine vision, laser imaging, infrared cameras and the like; whereas in Japan research is often directed to "older", more simplistic methods such as tactile sensors, photodiodes or simple voltage monitors. Research colleagues sometimes suggest that the Japanese research is not advanced and is not leading the state of the art; but I try to remind them that the Japanese technology is actually used in production to make higher quality parts; whereas the U.S. research technology merely produces more research papers - not marketable products!

Even with traditional materials, the properties of which are well known, new uses or new designs can present tremendous new challenges. Figure 4 shows a new automotive design called a space frame structure. This can be built from low strength steel, high strength steel or aluminum alloys, the fabrication of which is generally well known. The challenge of this design is that the structure is no longer redundant. Failure of almost any joint, due either to an inadequate joint in manufacture or by fatigue or corrosion in service, could significantly compromise the strength and safety of the vehicle. Nonetheless, the flexibility that such a design provides in rapid introduction of new models or reduction of capital equipment costs, suggests that this new design will be implemented on a large scale in the future. Will joining engineers have the processes available to make this new product a success, both technically and economically?

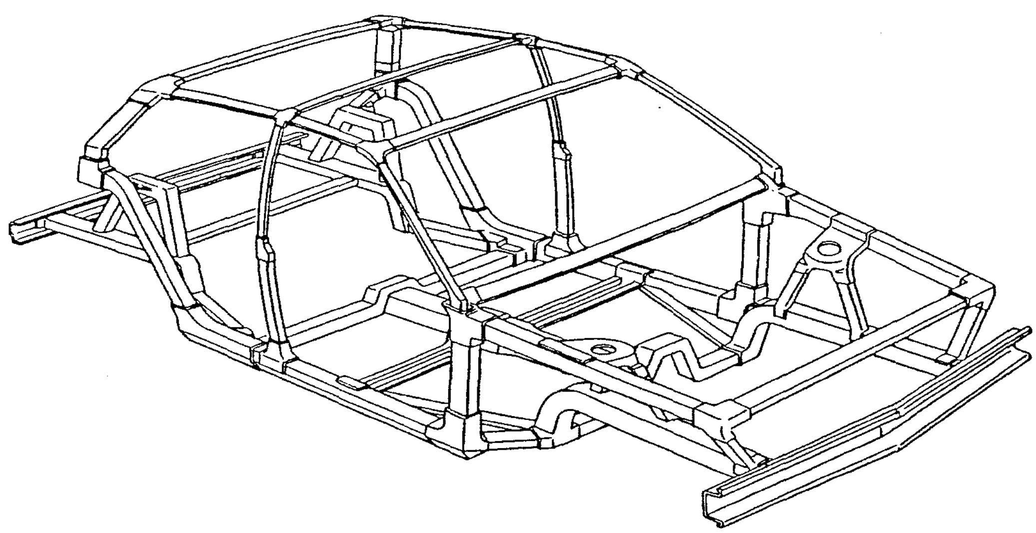

Fig. 4. Typical automotive space frame structure.

A number of people claim that resistance welding of automobiles is a dying technology; that lasers will dominate sheet metal fabrication in the future. This will be true only if the cost of laser equipment can be reduced significantly. Figure 5 shows the relationship between productivity, as measured by the length of sheet metal weld per second and the capital cost of the equipment. It is clear why resistance spot welding has been the process of choice in the automotive industry. Unless the cost of lasers can be reduced several fold, it will be difficult to compete in a capital intensive industry such as automobiles.

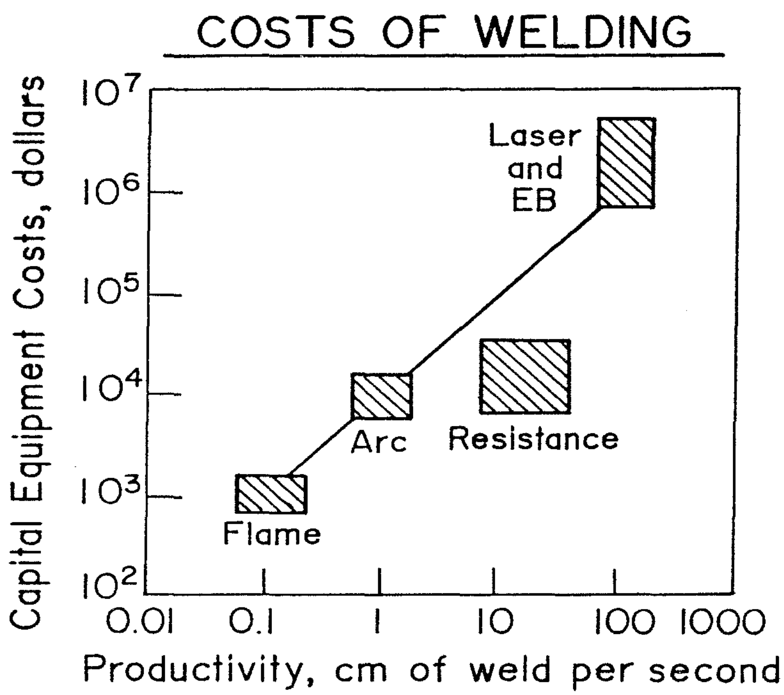

Fig. 5. Approximate relationship between capital cost of welding equipment and the speed at which sheet metal joints can be produced. For a description of how such a graph is generated see Eagar [1986].

Thus, it is seen that there are significant challenges even in joining of traditional materials. The country that does not continue to improve upon the methods of joining traditional materials may lose markets of significant size, even if they are not markets of great growth potential. Unfortunately, many managers do not appreciate the opportunities in advancing the joining of traditional materials and prefer to spend their resources on joining of new materials.

CHALLENGES IN THE USE OF NOVEL MATERIALS

Productivity is not the major challenge in joining of new materials; rather the question is whether some of these materials can be joined at any cost. Tremendous efforts have been made in improving the processing, structure, properties and performance of new materials, or as the Japanese often call them - "high function materials". Figure 6 shows how these features have changed over time. More elaborate processing produces more complex structures which are tailored to specific applications in which the material is pushed to the limit of performance. We have changed from design <u>with</u> available materials to design <u>of</u> materials for specific applications.

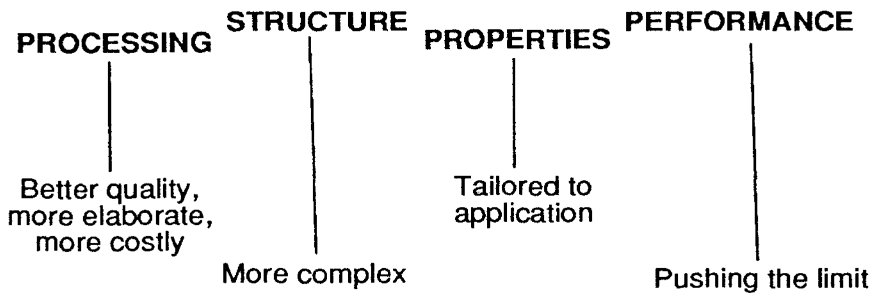

Fig. 6. Advanced materials create more complexity and specificity in every phase of materials science and engineering.

As an example, consider the production of aircraft structures. Fifty years ago, designers selected from available materials consisting of wood, canvas and aluminum. Today, designers dream of the Orient Express, which must endure surface temperatures of 1500^{o}C, in addition to being lightweight, having high strength and resistance to hydrogen degradation. Advanced intermetallics and composite materials must be developed to meet the design rather than the design being tailored to the properties of available materials. Unfortunately, joinability is rarely factored into the design of these new materials, creating great difficulties when an attempt is made to utilize the material in a real structure!

The cost of many of these new materials is so high and their properties are so specialized that they will only be used where they are essential. As a result, products will contain more joints and a greater fraction of these will be between dissimilar materials. This will only compound problems of quality and reliability in the final product. The common design rule of eliminating all possible joints is being violated at an increasing rate. Due to a desire to use the minimum amount of these costly, high function materials, the joints are being placed in more aggressive environments. The properties of the joint are pushed to the limit.

In many cases designers expect the joint to match the properties on either side of the dissimilar joint. If this were an easy task, one would not need to produce a dissimilar material joint. One could merely make the entire part from the joint material, if such a material with maximal values of all properties were available! Clearly, some designers assume too much of joining technology. Rather, the solution to the use of many new materials lies in improved designs which limit stresses placed on the joints. One challenge for joining engineers is development of new design rules which reduce the risk of failure at the joints. It is no longer possible to select the joint configuration or joining process as an after thought of the design. Joining technology must become an integral part of the product design. Again, we find that education of other professionals in joining technology, namely design engineers, will become a key to future manufacturing success.

In addition, within the joining community we must broaden our expertise. Few joining engineers are familiar with the fundamentals of some emerging materials such as polymers, semiconductors and composites. We must be knowledgeable enough about these materials to converse with those who are designing products with them.

METHODS OF JOINING EMERGING MATERIALS

Over a decade ago, Richard Weck [1976], who was Director General of the British Welding Institute, stated that fusion welding is so complex "that these processes are stretched well beyond their inherent capabilities", and that "the emphasis in research and development must move from our preoccupation with fusion welding to other areas." There is considerable wisdom in his approach when applied to high function, advanced materials, although in terms of traditional materials, the fusion processes will continue to dominate and will improve, albeit slowly, over the next decade.

A revolution is about to occur in arc welding power supply technology [Eagar, 1990] due to the introduction of inverter based supplies. There is insufficient understanding about how to apply the new flexibility provided by these machines, but within a decade we will see automatic welding equipment that can sense and control fusion weld pools as well as can many humans.

Another area of potential growth is high brightness lasers. These systems, capable of power densities more than ten times as great as conventional lasers, will provide new methods of cutting and machining a wide variety of materials, especially in thick sections. Whether such equipment will be useful in joining remains to be seen.

In spite of these and other improvements in fusion joining processes, Dr. Weck's comments are precisely correct for many of the advanced materials. It is a general, but not universal, rule that rapidly solidified or composite materials cannot maintain their improved microstructures when subjected to fusion processes. As Dr. Weck suggested, solid state processes are preferable for many new materials. Unfortunately, most solid state joining processes are either costly, slow or limited in geometry. Nonetheless, advances are being made. Linear friction welding is being developed for bladeless disk or "Blisk" fabrication of jet engine components. Microwave sintering of ceramics [Palaith and Silberglitt, 1989] provides one of the few new joining technologies of the past decade. In spite of these advantages, solid state bonding cannot solve all of the joining problems posed by advanced materials.

There are two fundamental limitations to joining of materials. These are surface roughness and surface contamination [Eagar, 1986]. If two materials are placed in contact, the true area of contact is much less than the apparent area of contact due to the inherent roughness and non-planarity of any surface on an atomic scale. The only methods of overcoming this roughness involve deformation, diffusion or infiltration of a liquid between the two solids. The solid state processes rely on deformation or diffusion, while soldering, brazing, adhesive bonding and fusion welding achieve intimate interfacial contact through interposition of a liquid. Since diffusion requires application of heat, generally over a prolonged period, and deformation requires relative sliding of the two parts with substantial applied stresses, these solid state methods of achieving full contact between parts cannot be used in all applications. Thus, the liquid processes which do not involve fusion of the base material must also be considered. More research and development, and at a higher scientific level, must be applied to soldering, brazing and adhesive bonding.

The second fundamental barrier to joining is surface contamination. The time-pressure relationship for one monolayer of gas to strike a surface is 10^{-8} atmosphere-seconds. This is clearly too small to permit cleaning of surfaces before joining in anything other than an ultra high vacuum. Instead, the methods of removing or displacing contamination and protecting against further contamination include material flow (i.e. local deformation), fluxes, reducing atmospheres or diffusion which creates displacement, reduction, absorption or incorporation of the contaminant into the base material, the flux or the atmosphere. Adhesive bonding represents a special case wherein contamination is not removed, but is merely buried under the adhesive. For this reason, adhesive joints are inherently weaker per unit area than are the true bonding processes of soldering, brazing or welding.

Some variations of soldering or brazing have tremendous potential for joining of new materials. Reactive brazing can join ceramics and metal matrix composites, although more needs to be understood about the interfacial reactions and wetting behavior. Transient Liquid Phase (TLP) diffusion bonding [Duvall et al., 1974] which starts as a braze and ends as a true diffusion bond, has proven in recent years to be a much more general process than was once believed. It can be used to fabricate dissimilar materials joints as in the case of the copper-molybdenum bond shown in Fig. 7.

Electronic packaging is representative of many of the problems encountered in joining of advanced materials. The package integrates metals, polymers, ceramics and semiconductors, using welding, brazing, soldering, adhesive bonding and solid state bonding processes. Solution of the joining problems requires an intimate knowledge of the design and function of the entire component, as well as the process by which it is manufactured. Clearly, the joining engineer of the future must have a broad knowledge of the product, as well as having a deep understanding of the joining processes. Rapid progress cannot be achieved through trial and error experimentation. Potential solutions must be evaluated theoretically, followed by experimental verification, if we are to achieve success quickly when faced with the expanding range of joining problems which are being presented to us.

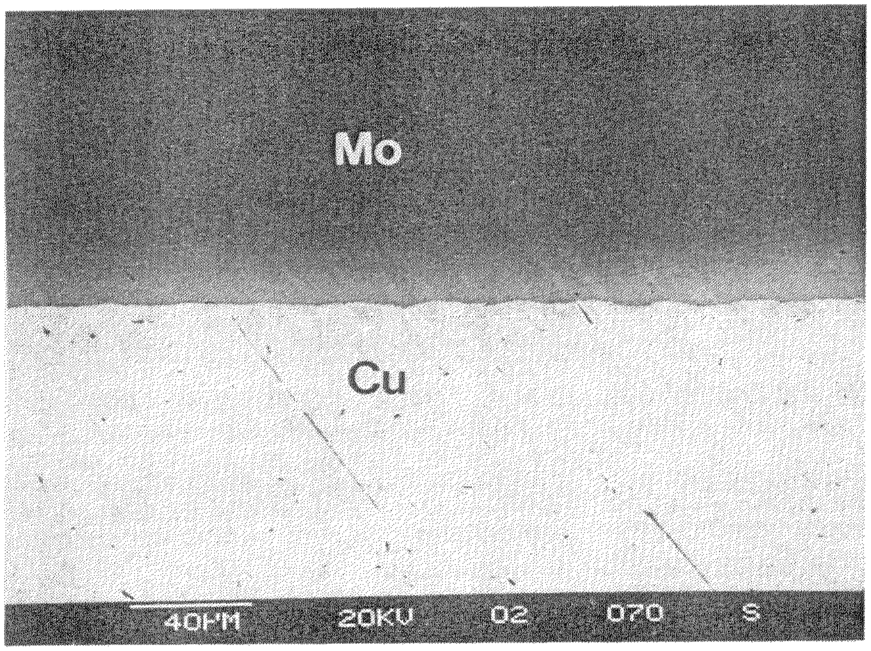

Fig. 7. TLP bond made between copper and molybdenum using a filler alloy of 34-36% Au, 61-63% Cu, 2.75-3.25% Ni. The joint is made using brazing techniques but provides a true diffusion bond upon completion.

Thus, some of the challenges in joining of emerging materials include faster new product development cycles; fabrication of smaller components, especially in the electronics industry; more dissimilar material combinations; and a decreasing ability to perform generic research as the applications of the joints become more specific. There are many new opportunities for engineers in developing methods for joining emerging materials. For every new material which is developed, there are many processes which must be re-evaluated or developed in order to utilize the material. Indeed, the utilization of new and emerging materials will be limited by our capacity to explore these processes rather than by our ability to design or produce these materials.

CONCLUSIONS

In summary, we must look at what is emerging in the context of the prior experience of the industry and the country using a given material or technology. With regard to traditional materials, whose properties and joining methods are well known, improvements will continue to be made in the quality and economy of the product. With novel materials, the challenges revolve around development of new joining procedures, especially for dissimilar materials combinations. As the use of these materials becomes more specific to individual applications, the development costs will escalate due to the relatively small volume of parts using the technology.

One must remember that while new materials are an enabling technology for future industries; joining is one of the enabling technologies to permit the use of these new materials in complex structures. This will require greater attention to joining research and development in the future. It will be a time of great challenge, but of even greater opportunity if we are able to meet this challenge.

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