METALLURGY AND THE EVOLUTION OF MATERIALS SCIENCE AND ENGINEERING

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Introduction

Only a minuscule fraction of matter in the universe is accessible to earthlings for useful purposes as well as for study. This “fact of nature” highlights the distinction between matter in general and materials in particular. Thus, materials consist of those substances, both natural and manmade, that society can employ for producing things, e.g., edifices, machines, devices, tools, utensils, clothing, weapons, ornaments, and products of all kinds. From the perspective of history, materials such as wood, stone, fibers, ceramics, and metals have played an intimate role in the advance of civilization, and have become thoroughly ingrained not only in human existence, but also in the quality of life. Clearly, then, materials must be regarded as an essential working medium of society; they constitute one of the basic resources of the human race — along with living space, food, energy, information, and manpower.

Inasmuch as materials thereby comprise an important part of the natural world that can be adapted to serve societal purposes, it is no wonder social and intellectual forces are tending to pull various disciplines and subdisciplines into a coherent body of knowledge in order to reveal more about the character and utility of materials. What has emerged in this evolutionary transition is Materials Science and Engineering (MSE). In a rather natural way, the well-established discipline of metallurgy — namely, the science and engineering of the metallic state — has provided an appropriate paradigm for the newer and broader field of MSE, within which metallurgy now functions as a vital and exemplary component in coordination with other classes of materials. The field of ceramics, like metallurgy, has also reached the status of a discipline in its own right, and is now likewise recognized as a prominent component of MSE.

Before examining the significance of MSE, in concept and in operation, it is well to visualize the scope of the overall materials enterprise.

The Global Materials Cycle

Some 15 billion tons of raw materials (ores, minerals, coal, crude oil, natural gas, rock, sand, timber, rubber, etc.) are extracted annually from natural sources by mining, drilling, and harvesting from land and sea, to be processed into bulk and engineering materials (metals and alloys, ceramics and glass, chemicals, cement, lumber, dielectrics, semiconductors, plastics and elastomers, paper, composites, etc.) for fabrication into articles of commerce in response to societal demand. In due course, after these materials have played out their respective functions in service, they are discarded as scrap, either to be recycled for use again, or somehow returned to nature whence they came. Accordingly, the total materials system is a cradle-to-grave circuit on a global scale, involving interdependence as well as competition among countries and companies. It is evident that this global materials cycle — so named by the COSMAT Report of 1974(1) — participates significantly in the foreign and domestic affairs of nations for both economic and strategic reasons. That study found, for instance, that the materials cycle accounts for about one-fifth of the gross national product together with one-fifth of the human employment in the United States, not including the production of food and fuel.

The materials cycle is driven by societal demand, with value being added progressively to the materials-flow around the circuit. A substantial portion of this added value is in the form of energy. Approximately one-half of the energy consumed by manufacturing industries in the United States is expended in the production, refining, fabrication, and assembly of materials into end-products. Conversely, materials are necessary for supplying energy in useful form. In addition to the indispensability of fuel materials for generation energy, virtually all advanced energy-conversion technologies are presently materials-limited from the standpoint of efficiency, reliability, safety, or cost-effectiveness. This is the case, for example, with gas turbines, nuclear reactors, solar-energy devices, magnetohydrodynamics, high-energy batteries, and fuel cells.

The flow of materials in the materials cycle can be greatly perturbed at any given point by economic factors (e.g., competitiveness), political actions (e.g., embargoes), or social decisions (e.g., environmental regulations), which may take place elsewhere in the world. Shortages in materials are usually due to man-made disruptions rather than to global scarcities in natural sources. It should also be recognized that the operation of the materials cycle inevitably taxes the environment through waste disposal, pollution, and landscape disfigurement, thus impacting the availability of clean living space and injecting real, but hard-to-assess, social costs. These are major issues which must be faced by those concerned with the overall human benefits to be derived from MSE. Metallurgy has had to cope with this problem for many decades.

The Nature of MSE

Materials science and engineering comprises a mixture of disciplines (branches of knowledge) that provide an intellectual approach for dealing with materials as a part of nature, and for harnessing them for human purpose. The aforementioned COSMAT Study (1) arrived at the model of MSE illustrated in Fig.1. It is a knowledge-generation and knowledge-transfer system which extends from basic science and fundamental understanding (on the left) to societal needs and experience (on the right). MSE attempts to relate the processing of materials (including their synthesis, specimen preparation for research, large-scale production in the materials cycle, and fabrication for end-use) to their inner architecture (comprising all levels of structure and composition) and their manifested properties (of all relevant types), and then to their ultimate performance in service applications. COSMAT defined MSE more succinctly but in similar terms: "MSE is concerned with the generation and application of knowledge relation the composition, structure, and processing of materials to their properties and uses." Metallurgy has functioned in this way for over a hundred years, since the momentous disclosure of microstructure, whereas MSE came into being in this mode only some 30 years ago.

Materials science and engineering is holistic in the sense that it emphasizes a continuity in the field of materials between science, engineering, technology, and the requirements of society. As such, it exposes humankind to the opportunities opened up by fundamental knowledge concerning materials, and conversely, it exposes scientific theory and experimentation regarding materials to the demands and experience of humankind. In fact, MSE operates most effectively for discovering and applying new processes and materials when the countercurrent flows (indicated in Fig.1) of scientific knowledge gained from research and empirical knowledge acquired from experience are so intimately mixed that each catalyzes the other. Thus far, MSE has not replaced or eliminated any of the disciplines or subdisciplines that contribute to it. Instead, MSE acts as a multidisciplinary arena for all branches of knowledge that can shed light on materials. In so doing, MSE promotes new interactions and interdisciplinary objectives that are not otherwise fostered among the separate disciplines.

Case studies of selected material innovations have been described in considerable detail (2), covering metallic, ceramic, polymeric, and electronic materials. Generally speaking, these advances were initiated by societal "pull" rather than by scientific "push," although science was invariably brought to bear in the progress toward successful utilization. Even the oft-cited transistor "breakthrough" — which emanated so spectacularly from brilliant theory, basic research, and novel processing — was actually first inspired (at the Bell Telephone Laboratories) by a perceived societal need to move well beyond the existing vacuum-tube technology in order to achieve more complex switching and multichannel transmission circuitry for future communication systems. This is a particularly revealing example of the synergistic interplay between experience and scientific findings in MSE. It is a functional style that characterizes the way MSE works, but it has long been exemplified in the operation of metallurgical science and engineering.

More recent examples in MSE continue to be consistent with this theme. Figure 2 portrays the "quantum" advances that have been attained in strong permanent magnets, notably in the discovery of the $Nd_{12}Fe_{14}B$-type intermetallic compounds and their appropriate processing (3). This development resulted from experimental research and societal pull. No theory was on hand to predict such magnetically strong compounds or to guide their improvement. Undoubtedly, the necessary theoretical work will be forthcoming in time and will contribute quite beneficially to both the understanding and the further progress of these technologically important materials, but MSE and society do not have to wait for that desirable occurrence. One can already see this materials advance is likely to exert a major influence on new motor and electronic device designs, featuring greater efficiencies and miniaturization.

The dramatic discovery of high-temperature superconductivity in layered copper oxides, more specifically $(La, Sr)_2CuO_4$ and YBa_2Cu_3Ox, offers another case in point, as denoted by the striking increase of the critical temperature (Tc) in Fig, 3(4). Here again, there was no theory even to hint at, let alone predict, this astonishing solid-state behavior. Indeed, the ensuing burst of excitement throughout the world has been due not only to the prospect of revolutionary new technologies (the societal pull), but also to the demonstrated inadequacy of existing theory for a physical property as noteworthy as superconductivity. And yet, in view of the very nature of MSE, experimental research on the associated processing/structure/property relationships in these ceramic materials is proceeding apace, with due attention to the combined effects of temperature, magnetic field, and current density for accessing and stabilizing the superconducting state of candidate materials, as suggested by Fig. 4(5). Furthermore, inasmuch as MSE carries over to materials performance and end-products, fabricability to useful shapes and suitable mechanical properties to withstand service stresses are also essential objectives, no less important than any further raising of Tc. This need to balance many factors for eventual performance in service highlights one of the significant differences between MSE and solid-state physics.

Predictability versus Reciprocity in MSE

In MSE, one would ideally like to use the structure of materials to predict properties, then to use properties to predict performance, and finally to select a sequence of processing procedures that will yield the desired material and inner structure at a reasonable cost. However, there is much that interferes with this simple logic, in view of the deliberate continuity of science and engineering in MSE. The properties which enable materials to perform their respective assignments in service, and in harmony with the diverse functions of their companion materials, are numerous and complex, and they must also manifest themselves satisfactorily under the multidimensional requirements of the designated application. There is just no way of itemizing all of the operating and environmental variables for complete property simulation in the laboratory; moreover, the properties that can be measured will, at best, be only simple images of what may be at play in service performance.

In a real sense, then, materials behavior in service is unknowable from properties alone (6). Properties can offer valuable guidance when combined with accumulated experience, but one would not expect to rely on prediction in the first instance, no matter how accurately the measurable properties might be known. As with a musical instrument, no one can truly deduce how well it will perform until it is actually played. Indeed, empirical knowledge is often needed first in order to decide just which properties should be evaluated to correlate with performance. It is not predictability but mutual reciprocity between properties and performance (with each reinforcing the other in a symbiotic interplay) that participates so successfully in the practical output of MSE. In line with the MSE model of Fig.1, we are referring here to a purposeful intermixing between scientific experimental knowledge relating to selected properties (mechanical, chemical, electrical, etc., as the case may be) and empirical knowledge arising from service experience.

Similar reasoning applies to structure/property relationships. Much of the science in MSE is directed to explanations of the observed properties of materials in terms of their internal structure. Such linkages are typically made through theories, models, or assumed mechanisms. However, the very idea of structure encompasses many levels of fine scale entities of "building blocks" nesting together in hierarchies of regularities and irregularities. The schematic structure of a macromolecular composite material in Fig.5 — specifically a tendon which connects muscle and bone in humans and animals — is particularly instructive; it illustrates several hierarchical levels, together with their respective size scales, nomenclature, and methods of detection (7). The many kinds of interfaces in Figure 5 must also be considered as important property-influencing elements of the structure. And not shown here are still finer constituents such as molecules, atoms, electrons, and ghostlike particles ranging on down through the subnuclear hierarchies until comprehension is exhausted. Under these circumstances, and in the context of MSE, one must surely question whether it will ever be possible to predict from first principles, or from structure alone, the relatively intricate properties that make materials useful to humankind. Fortunately, MSE can avoid this profound issue by depending on the mutual reciprocity between internal structure and measured properties, and not on a first-order predictablility of one from the other. Again, MSE promotes a synergistic mixing of scientific and empirical information — with structure and properties contributing, each in its own way, to a deeper and more helpful understanding of both.

It becomes evident that in its comparatively brief existence MSE has taken on the back-and-forth information-transfer features which have successfully evolved in metallurgy ever since, over a century ago, Henry Clifton Sorby opened up the science of metallography by revealing the microstructure of polished-and-etched iron and steel with the petrographic microscope (8). Plainly, the ultimate conversion of scientific understanding into societal well-being via MSE cannot be represented by a one-way stream of knowledge into practice. It depends more on turbulent, mutually interactive flows among the MSE components of processing, structure, properties, and performance. MSE seems to function most effectively as a dynamic system of knowledge generation and utilization when its elements are closely coupled, and are also subjected to the stimulating and biasing forces of human needs.

An Example of MSE in Operation: Rapid Solidification Processing

In MSE as well as in metallurgy, advances in structure/property relationships — and likewise in the development of new materials — are often crucially dependent on the emergence of novel processing methods. One such instance is rapid solidification processing.

With certain alloy systems, cooling rates of 10^4 — 10^6 degrees per second from the liquid state can avoid crystal nucleation, or solidification in the ordinary sense, and this results in the formation of metastable noncrystalline solids, otherwise termed metallic glasses. This phenomenon has been known since 1960 when the innovative experimental technique of splat quenching was introduced (9). It led to intensive scientific study of the structure and properties of metallic glasses, and at the same time stimulated the development of larger-scale rapid solidification processes such as melt spinning for thin-strip casting, and atomization for powder making. Correspondingly, much attention of a scientific nature was directed to the kinetics of solidification under conditions of rapid cooling and supercooling.

With regard to property measurements, it was found that iron-boron-silicon and iron-boron-silicon-carbon amorphous solids are not only ferromagnetic, but also exhibit very low hysteresis and eddy-current losses, primarily due to their high electrical resistivity as well as their relative freedom from magnetocrystalline anisotropy and from microstructural defects normally associated with the crystalline state. The prevailing societal pull for saving energy, in this instance through decreased core-losses in electric transformers, provided a strong driving force for further processes and alloy development based on these metallic glasses. The ensuing improvement in core-loss reduction is shown in Fig. 6, comparing the new amorphous materials with the more familiar silicon steels (10). The 60-Hz core losses of the metallic glasses going into the service testing of distribution transformers are less than one-third of the best silicon steels, and further reductions to one-twentieth have been achieved (10).

In the operation of MSE, it will be obvious that the effective utilization of metallic glasses in transformers depends not only on favorable magnetic properties, but also on mechanical behavior, formability, stability versus time and temperature, and, of course, on the overall economics. Such interacting factors can only be resolved and optimized by promoting a close interplay of scientific and empirical findings. It has been reported that the performance tests on the subject transformers have demonstrated improved service as expected, and valuable additional information has been accumulated. Actual production is now underway. Core losses in distribution transformers alone in the United States are estimated to represent a wastage of three-quarters of a billion dollars annually, of which approximately one-third can be saved by using the metallic glass cores (10). Opportunities for the still-larger power transformers lie ahead, while many applications for amorphous alloys in smaller magnetic devices are already at hand.

This example of a materials advance serves to illuminate the way in which novel processing methods can stimulate the detailed study and development of previously unavailable materials and, in turn, lead to new technologies and products for filling the needs of society.

When rapid solidification processing is directed to crystalline materials, a wide diversity of microstructures, not otherwise attainable, can be accessed. This includes microstructural refinement of the matrix phase, unusual dispersions of embedded precipitates, high degrees of solid-solution supersaturation, and formation of metastable states. The dispersed particles are of special interest here because they are extremely fine, well distributed, and can have limited solubility in the matrix phase. Because of the latter circumstance, the dispersed precipitates resist coarsening at high temperatures, and so tend to remain effective in pinning grain boundaries for inhibiting grain growth during subsequent thermomechanical treatments. For similar reasons, dispersion strengthening tends to be maintained at elevated temperatures. Moreover, rather large volume fractions of the dispersed phases are obtainable because the prior "solutionizing" is carried out in the liquid state, and precipitation into unduly coarse embrittling inclusions on cooling is avoided by the rapid solidification process.

Rapid solidificaiton by nitrogen-gas atomizing for achieving uniform dispersions of the primary carbides in high-speed steels has been in industrial practice since 1970 (11), benefiting from improved toughness at high hardness levels.* However, with the later innovation of centrifugal atomizing (12) and its potential for advanced superalloys, the U.S.Air Force became intrigued with the wider prospects for aerospace applications and initiated funding for more broadly-based research and development on new alloy systems, thus exemplifying another classic instance of societal pull in action. Because of the ultrafine-scale structures to be investigated, a need arose for the most sophisticated high-resolution electron microscopy and microanalytical instrumentation, and there erupted a spontaneous urge for scientific inquiry. Mutually stimulating interactions throughout the materials knowledge-transfer system of Fig.1 came into play, rebounding dynamically among scientific explanation, property enhancement, process improvement, and high-technology performance, while concomitantly inspiring the joint participation of governmental, industrial, and academic institutions.

Some property results on rapidly solidified aluminum alloys are summarized in Fig.7 (13). Unusual ranges of composition and exceptional dispersions of intermetallic phases are made possible by rapid solidification. The advantageous strength-retention at elevated temperatures shown in Fig.7 for this class of materials is a consequence of the resistance to coarsening of the relatively stable dispersed phases. It is significant to note that, on a density-compensated basis, some of these aluminum alloys now equal or exceed the high-temperature strength of titanium alloys. These aluminum alloys also exhibit marked resistance to saline corrosion (Fig.8), which probably arises from the alloy chemistry and microstructural uniformity attainable by rapid solidification (13).

Up to the present time, the cost of rapid solidification processing has tended to channel its commercial use toward high-value-added end-products that may not yet be in the public domain. But it is clear that the underlying features of MSE are at work.

Closure

Through the operation of the materials cycle on a global scale, materials now constitute a basic resource of society that only connects peoples and governments on this planet, but also joins humankind into a partnership with nature. The ultimate purpose of MSE is to help advance human understanding of nature by probing its materials thoroughly, and concurrently to help mankind live in harmony with nature by employing its materials intelligently. This dual objective, both intellectual and utilitarian, forms an integral part of the overarching contributions of science and engineering toward the general goal of human betterment and social progress.

At present, MSE functions as a mixture of disciplines, i.e., as a multidiscipline, rather than as an individual branch of learning like physics, chemistry, metallurgy, or ceramics. Of course, these disciplines originally did not enjoy sufficient coherence or identity to be recognized by society as unified fields of inquiry and endeavor. When such recognition does happen to emerge, it usually signals a recodification or repackaging of knowledge by society, and is characteristically reflected in the advent of university departments, curriculum, degrees, job titles, technical societies, and professional groupings. This state of cohesion has not yet been decisively reached by MSE, but events are certainly moving in that direction. MSE has already established sufficient integrity to provide an attractive framework for newer classes of materials coming on the scene. Indeed, it is no longer likely that polymeric, electronic, photonic, and biological materials will form separate disciplines by themselves, as was the case earlier for metals and ceramics. It may take another generation or two for society to determine whether the various fields of knowledge that contribute to MSE will converge into a single discipline unto itself. An interesting example of this kind of evolutionary change is the field of medicine, which became a recognized discipline in spite of its many disparate specialties and subdisciplines. MSE can attain a similar stage of intellectual and professional cohesion by demonstrating to society that it provides a new challenge for studying nature deeply and for using nature wisely.

In the meantime, MSE is passing through a vibrant period of ferment and wondrous change. Knowingly or unknowingly, a substantial part of the world's technical community is caught up in it; and human well-being everywhere depends on it.

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* When particulates are produced in rapid solidification processing, consolidation into bulk materials is typically accomplished by powder-metallurgy techniques such as hot extrusion and isostatic pressing.

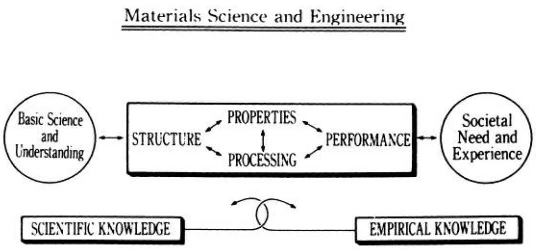

図1．コスマット報告（1974年）[(1)]に基づく材料科学・工学モデル。材料に関連した科学的知識と経験的知識は、互いに反対方向の流れとして示される。

Figure 1. A model of materials science and engineering, indicating countercurrent flows of scientific and empirical knowledge relative to materials. Based on COSMAT Report of 1974(1)

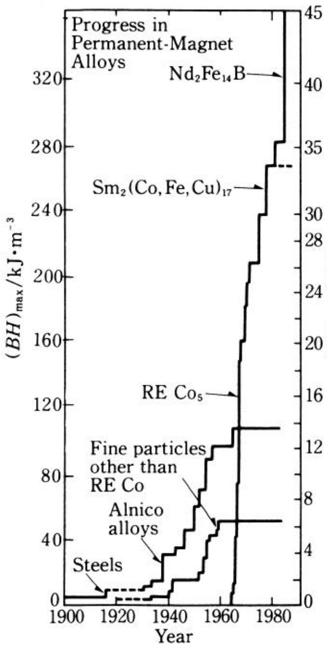

図2．1900年以降の永久磁石材料に関する進歩。性能を表す数字としての最大エネルギー積(@BH)$_{max}$を用いて示した。1985年のMNAB報告[(3)]による。

Figure 2. Advances in permanent-magnet materials since the year 1900, according to the energy product (BH) maxas a figure of merit. From NMAB Report of 1985(3).

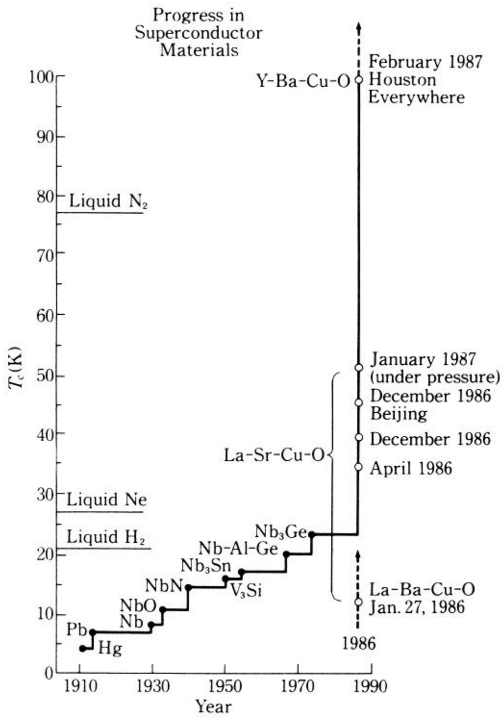

図3．超電導材料の臨界温度（Tc）の向上。ミューラーとベドノーズによる集録[(4)]より抜粋。

Figure 3. Advances in the critical temperature (Tc) for superconductivity. From compilation of Müller and Bednorz(4).

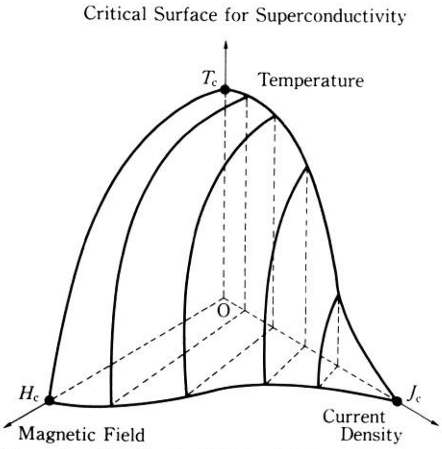

図4．超電導状態の存在範囲の決定する温度、磁界および電流密度の相互作用。リビングストン(5)による学説。

Figure 4. Interplay of temperature, magnetic field, and current density in defining the regime of superconductivity. After Livingston(5).

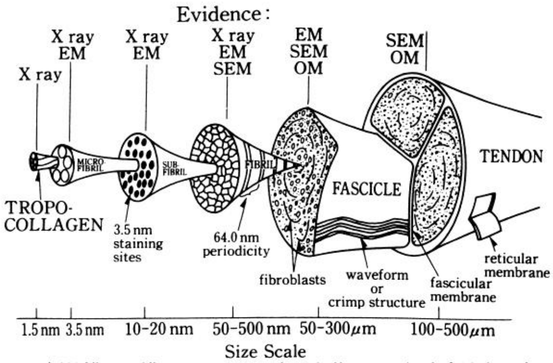

図5．生体物質（腱）の階層的構造の模式図。寸法尺度、名称および観察方法を示す。略語：ＤＳＣ－示差走査熱量測定、EM－電子顕微鏡、SEM－走査電子顕微鏡、OM－光学顕微鏡。カステリック、その他(7)による。

Figure 5. Schematic illustration of the hierarchical structure of a biological material (tendon), showing size scales, terminology, and methods of observation. Abbreviations: DSC-differential scanning calorimetry; EM-electron microscopy; SEM-scanning electron microscopy; OM-optical microscopy. From Kastelic etal.(7)

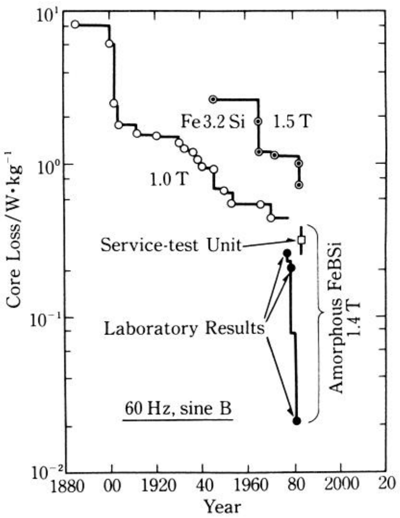

図6．過去100年間における電気変圧器材料の鉄損の減少に関する進歩。ルボルスキー(10)による。

Figure 6. Advances in the reduction of core-losses in electric-transformer materials during the past century. From Luborsky(10)

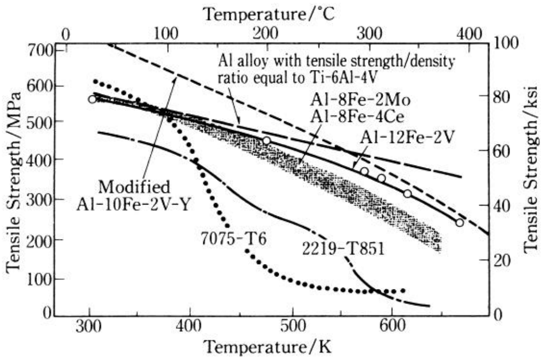

図7．急冷凝固アルミニウム－鉄基合金の高温強度を、従来の普通工程による2種類の高力アルミニウム合金（7075－T6と2219－T851）を比較して示している。破線は、実用チタン合金と密度で補正した強度が同じになるのに必要なアルミニウム合金の強度を示す。アダムとルイス(13)による。

Figure 7. High-temperature strength of rapidly solidified aluminum-iron-base alloys, compared to two conventionally processed high-strength aluminum alloys (7075-T6 and 2219-T851). Dashed line denotes strength required of aluminum alloys to have the same density-compensated strength as a commercial titanium alloy. From Adam and Lewis(13).

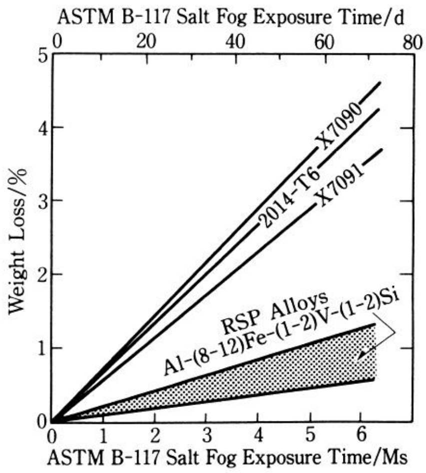

図8．急冷凝固アルミニウム－鉄基合金の耐蝕性を、従来の普通工程による3種類のアルミニウム合金と比較して示している。アダムとルイス(13)による。

Figure 8. Corrosion resistance of rapidly solidified aluminum-iron-base alloys, compared to three conventionally processed aluminum alloys. From Adam and Lewis(13).