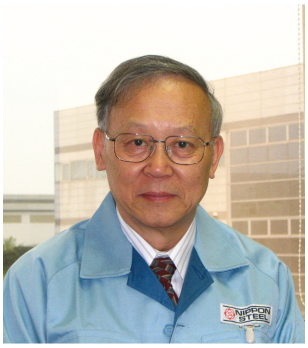

Steel, What a Fabulous Material !

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1. Introduction

Until retirement from the university upon reaching the age limit five years ago, I had been engaged in research on the microstructure control of steel for about forty years. The reason I could continue studying steel for so long is that, of all materials, I was moved and charmed by the wonder of iron and its alloys.

Recently, I was invited to write for the Centennial Commemorative Issue of Shinnittetsu Giho. I thought this would be a good opportunity for me to describe what I felt during my many years of research at the university and during my recent service at the Technical Development Bureau of Nippon Steel Corporation—the charms of iron, the future of iron and steel, the difficulties involved in research on iron and steel, the pleasure of working with iron, the expectations entertained of iron and steel researchers—as they come to mind. This is my message of hope to iron and steel researchers and engineers, especially those of the younger generation.

2. Charms of Steel from a Microscopic Perspective

Steel is a structural material which is indispensable to our life. It is far more abundant than any other metallic material and is essentially as common as water and air. For those reasons, many people are unaware of the importance and usefulness of steel. Why is steel used in such huge quantities? Several reasons may be cited. It is relatively inexpensive and has good workability. The major reason for the exceptional versatility of steel lies in its excellent strength-toughness (ductility) balance and its ability to cover a wide range of strengths. In fact, the tensile strength of steel ranges from about 200 MPa (soft steel) to about 5 GPa (strong, hard steel). This is the extraordinary and incredible charm of steel.

The ability of steel to manifest a very wide range of strengths is attributable to the fact that it is an alloy of iron and carbon. Looking at the phase diagram of iron-carbon alloys from the standpoint of microstructure control or strengthening, it can be seen that the alloy has a wonderful constitution. The fact that carbon in steel is an interstitial element not found in any other alloy adds to the uniqueness of steel. Through an understanding of the phase diagram of iron-carbon alloys, any person who deals with iron should recognize the remarkableness of steel as a structural material.

It is important that the iron-carbon alloys have a solid phase called austenite at the high-temperature side. This austenite serves as the starting structure (mother phase) in heat treatment of the alloy. By varying the carbon concentration and cooling rate during the heat treatment, it is possible to obtain various transformation structures—ferrite, pearlite, bainite, and martensite—which differ widely in strength. Namely, by utilizing different transformation structures, we obtain different alloy strengths for different uses. In the case of aluminum alloys, since it has no solid phase, like austenite, at the high-temperature side, no phase transformation occurs, making such versatile heat treatment, as is applicable to steel, impossible. If you compare steel with aluminum alloys, you are sure to discover how wonderful and useful a material it is.

As mentioned above, thanks to the presence of austenite, various phase transformations can occur with iron-carbon alloys. At room temperature, any of the transformation structures consists of two phases—ferrite and cementite (Fe_3C)—as indicated by the equilibrium phase diagram of the alloy. (It should be noted that only martensite in as-quenched state consists entirely of ferrite supersaturated with carbon.) Why, then, does the alloy strength vary so much with the change in transformation structure even though its composition is the same (i.e., ferrite + cementite)? The answer lies in the volume fraction and the condition of the existence of cementite.

Carbon is barely soluble in ferrite (1 ppm or less at room temperature). Therefore, the carbon added virtually all turns to cementite. Since the volume fraction of cementite is expressed as $15.3 \times$[mass%C], the concentration of cementite in 0.8%C eutectoid steel, for example, can reach as much as about 12%. Generally speaking, in the case of metallic materials, it is desirable that the volume fraction of the second phase should be large, since that facilitates controlling and strengthening the material structure. Compared with ordinary nonferrous alloys, the iron-carbon alloy contains a much larger amount of the second phase (cementite). The wide range of steel strength is made possible by varying the carbon concentration to change the amount of cementite and by applying heat treatment (phase transformation) to change the morphology and size of the cementite.

One of the phase transformations of iron-carbon alloys is the pearlite transformation (eutectoid transformation). The pearlite structure formed as a result of this transformation consists of a ferrite matrix on which lamellas of cementite are stacked at extremely small intervals of 0.1 to 0.5 μm. This is an amazing natural composite material. Is it possible to make such a fine lamella structure artificially? Pearlite transformation is a valuable asset of steel. Thanks to this transformation, pure iron, whose tensile strength is 200 to 300

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MPa, can be enhanced to provide a tensile strength of 900 MPa simply by adding 0.8% carbon—an inexpensive alloying element.

The very high strength (hardness) of steel owes to martensite. Ordinarily, martensite is tempered before it is used. Therefore, the main factor in its strength is precipitation strengthening. In order to enhance precipitation strengthening, it is necessary to increase the amount of precipitates or decrease the size of precipitates. Since martensitic transformation is a diffusionless transformation, the carbon that has been dissolved in the mother phase (austenite) is forced to dissolve directly in the martensite (ferrite). Namely, martensitic transformation is an effective means of obtaining a supersaturated solid solution. Besides, the martensite contains a high density of dislocations, which become nucleation sites for the precipitation of cementite. Thus, the martensite in steel is a superb structure that is naturally provided with conditions favorable for forming large amounts of fine precipitates uniformly and that permits making the most effective use of precipitation strengthening. Because of all this, the martensite in steel displays higher strength than many other metals.

As has been described above, the individual transformation structures of steel have their own characteristics, calling for different methods of microstructure control and strengthening. This makes steel both interesting to study and difficult to handle. You must be well informed of all the transformation structures before you can really sense the wonder and profundity of steel. I think it is important that researchers and engineers who deal with steels have a thorough understanding of as many transformation structures as possible.

3. Does Steel Have a Future ?

Steel is an indispensable structural material. Although there are many other structural materials, none of them will take the place of steel in terms of supply scale, economics, engineering reliability, etc. As long as steel is destined to play the leading role among industrial materials, not only must we strive to supply cheaper steels, but also to continue developing new steels with superior performances and higher functions. So, does steel have a bright future?

From time to time, I hear someone say that: “Steel is so ripe as a material that it just does not seem to leave any room for further research”, “Since the steel industry is mature, steel itself does not seem to have any room for further development”, and so on. Actually, however, it is fair to say that steel is still very much under development and that the steel industry is a growth industry full of vigor supported by a rapidly expanding market. Steel is by no means a completely ripe material, nor does it have no room for further research. From the standpoint of metallography alone, there is still an untapped or unexplored region for steel. Thus, this material still has enormous growth potential. Let me present two or three examples below.

Concerning the strength of steel, the highest strength of steel in practice currently is about 2.5 GPa in the case of bulk maraging steel (about 5 GPa for ultrafine wire). This value of 2.5 GPa is just 20%-25% of the ideal strength of steel. This means that we have not fully derived the potential for steel strength yet. Steel can be made much stronger. The highest strength mentioned above (2.5 GPa) was attained more than forty years ago, and has not changed much since then. True, various difficulties are involved in significantly increasing the strength of steel. But, the major reason why the highest steel strength has remained almost the same is that there are now very few researchers who are tackling the limit of strengthening of steel in earnest, because it is no longer an industrially important theme appealing to many steel researchers. In principle, by using various strengthening mechanisms in combination, it should be possible to attain a very high strength, say, 5 GPa. The reason why such a high strength has not been achieved in reality is that with increasing steel strength, the possibility of an early fracture (i.e. the fracture preceding yield deformation) in the steel becomes greater. One method of restraining the occurrence of an early fracture when the steel strength is greatly increased is to refine the grain size of the steel. Namely, substantive refining of the grain size is key to realizing extremely strong steel.

In the first place, we have not fully utilized the steel strengthening mechanisms yet. There are four steel strengthening mechanisms—solution strengthening, grain boundary strengthening (fine grain strengthening), dislocation strengthening (work hardening) and particle dispersion strengthening (precipitation strengthening). At present, only precipitation strengthening is fully utilized. In principle, a substantial effect can be expected of grain boundary strengthening (strength is inversely proportional to the square root of the grain size) and dislocation strengthening (strength is proportional to the square root of the dislocation density). On the other hand, the smallest grain size and maximum dislocation density that have been obtained so far with practical steels using various methods are approximately 5 μm and $1 \times 10^{15}/\text{m}^2$, respectively. Ironically, those values correspond to a steel structure whose strength is just beginning to increase sharply. In short, we have brought neither grain boundary strengthening nor dislocation strengthening into full play yet. In other words, luckily, there are still untapped methods of strengthening steel. That untapped region of steel strengthening, or creating an ultrafine crystal structure and an ultrahigh density dislocation structure, is nothing but an unexplored region in microstructure control. It is considered one of the challenges that may help clear the longstanding hurdle on the road to ultrahigh strength steel. The above situation explains why severe plastic deformation is attracting attention in the field of microstructure control and being studied in earnest in recent years.

Steel undergoes various phase transformations, and each individual transformation structure has its merits and demerits. By combining two or more appropriate phases, it is possible to make the most of the merits and compensate for the demerits. The ferrite + pearlite structure of hypo-eutectoid steel is a representative multiphase structure. Also well known are dual-phase steel with its soft ferrite matrix dispersed with hard martensite, and the 9%Ni steel having a strong martensite matrix dispersed with tough austenite. Taking the strength-ductility balance, for example, as strength is increased, ductility normally steadily decreases. From time to time, however, it can happen that the ductility sharply increases discontinuously. In many cases, such a discontinuous improvement in property appears in multiphase steel. It is multiphase steel that permits making the most effective use of the merits of steel with various transformation structures. We know many combinations of two or three different phases (transformed products). But there must be other promising multiphase structures that are still unknown to us. These also represent an explored region. The representative heat treatment that is used to obtain a multiphase steel utilizes a two-phase region, such as ferrite + austenite. This heat treatment is interesting in that it utilizes the distribution of alloying elements between the two phases that occurs during heating in the two-phase region, thereby making it possible even for a low-alloy steel to be dispersed with the second phase having the properties of high-alloy steel. In addition, since the multiphase structure exhibits slow growth of grains during the heat treatment, it permits obtaining fine grains easily. Therefore, it is desirable that the use of multiphase structures should be further promoted in the future.

As mentioned earlier, a wide range of steel strengths is covered by utilizing various transformation structures that appear in steel. Of those transformation structures, bainite is the one whose transformation mechanism has been least clarified and which has been least used for industrial purposes. In terms of strength, bainite falls between martensite and ferrite (+ pearlite). Therefore, martensite has been used when high strength/hardness is required, whereas ferrite has been largely used for steels not requiring high strength. Thus, bainite has so far been a bit player with a rather modest role. It is fortunate that bainite—an important transformation structure—has remained almost unexplored. If it becomes possible to use bainite just like martensite through thorough research, it should give rise to a variety of new steels with superb properties.

4. Difficulties Involved in Steel Research and the Importance of Continuance

The steels used today are the results of many years of hard work by countless pioneers. Developing sophisticated new steel products with far superior properties to existing options or innovative new steelmaking processes calls for higher skills and harder work than ever before. It is a task requiring concerted effort; it can never be achieved in passing.

During the period of rapid economic growth, from the 1960s to the early 1970s, when Japan's steel industry was making remarkable progress, both businesses and universities, staffed with many talented individuals (researchers), were actively engaged in basic and applied research while competing with one another and maintaining their utmost potential at the same time. The potential accumulated along the way contributed much in the subsequent development of new steel products and new steelmaking processes. Steel researchers in those days had a strong feeling of romanticism and pride in steel research. With the subsequent change in the social situation, however, many researchers (especially those who were working at universities) quit steel, and moved into the field of new materials. In the industry as well, the number of steel researchers has decreased.

At universities, the number of people who study steel has drastically decreased and is still decreasing. As a matter of fact, it is extremely difficult for any former steel researcher to resume steel research in earnest or for anyone unfamiliar with steel to start steel research from scratch. The reason is that when viewed as a research field, steels are exceedingly varied and complicated. Besides, since there are huge volumes of research results accumulated so far and steel technology has been steadily progressing markedly, one great difficulty is identifying relevant problems and setting original research themes. These are some reasons why a high level of competence is required of steel researchers. In order to maintain high potential for steel research, it is necessary for steel researchers to keep themselves abreast of steel developments and conscious of current problems at all times, so as to continue their research.

In the field of steels, we have a vast trove of research results accumulated in the past. In them, there are many phenomena which have proved to have theoretical importance, but which have been left untapped because of the difficulty involved in the related processes or the absence of a contemporary need for further research. Taking thermomechanical treatment, for example, ausforming and TRIP (martensitic transformation induced plasticity), which attracted much attention in the 1960s, were not put to practical use because of various restrictions, although they proved to be very effective in increasing the toughness of steel. Public interest in them rapidly faded in the late 1970s. However, any phenomenon that is very important in principle but that has remained obscure because it came into being far ahead of its time will surely come back into the limelight some day when conditions change or some innovative new ideas support it. In fact, TRIP and ausforming were revived twenty to thirty years later and now, they have come to be applied to practical steels.

There are many other phenomena and technologies which are important in principle but which have remained untapped because they were discovered too early. Thus, past steel research represents a treasure trove, which is a valuable asset for steel. Finding out important phenomena and technologies that are hidden amongst such treasure and reviving them in practical new forms is one of the respectable abilities required of steel researchers/engineers. I wonder how many of those important research and technologies, or valuable intellectual assets, young researchers and engineers know about or have inherited. From the standpoint of handing down intellectual property too, I think it is important that individuals or organizations should conduct more steel research.

5. Importance and Pleasure of Observing Microstructures

At the university, I was studying microstructure control, mainly in the field of steels. To me, therefore, structural observation was the most important means of research. While observing the microstructures of metals, I can steep myself in a metallic world. I am moved by the exquisite world of microns. Metals appear to me as if they were living things. Therefore, I cherish the belief that the photographs of microstructures must be absolutely beautiful.

Much difficulty is involved in structural observations. In the study of structural changes/structural formations accompanying heat treatments, the photographs of microstructures themselves constitute experimental data. For example, when a tensile test is done to measure strength, everyone can obtain the same result as long as they use the same test procedure. That is not the case with microstructure observation, in which the observer's ability to read the microstructure is important, because none of the photographs of one and the same structure are exactly the same. The finer the structure, the more conspicuous the above tendency becomes. Namely, it is more conspicuous with electron micrographs than with optical micrographs. Ultimately, one or more (a few) of the photographs that best show the general structural characteristics are adopted as observation data. Picking up just one (or only a few) from many photographs requires careful observation and judgment. To that end, it is important to photograph (or look at) many structures and grasp a general feeling for the structures. This is one reason why microstructure observation is painstaking work.

On the other hand, structural observation affords us great pleasure—the pleasure of conversing with metals. Assume, for example, that I test a new type of heat treatment with the aim of creating the optimum structure (controlling the structure) to make the most of a specific property. The test result is manifested in the micrographs. While examining them, I wonder why a structure like this came about and why I could not get the structure I wanted. Then, I must test another heat treatment, observe the structure and clarify the reasons. In so doing, I use all my knowledge and perform calculations as required. In many cases, however, the clue to solving the problem is hidden in the micrographs at hand. The question is whether or not we can find it.

In this respect, it is important to carefully look at every nook and corner of many micrographs, under the microscope if possible, over and over again. Then, consider how and why a structure like this has come about while conversing with the metal. In short, it is important to keep thinking. You might then hear the metal say: “How come you don’t notice this part of the structure? Here’s the clue to the solution. The heat treatment you’ve done is just not right, but you’ve come very close to the structure you want.”

It is not that structural observations are done simply for the purpose of explanations. The importance and pleasure of observing microstructures lies in the fact that we can obtain clues to solving various problems and find astonishing new phenomena through conversations with metals. In my opinion, the researchers and engineers who handle metals should all be able to have a conversation with their metals. It is observation of the metallic structure that affords an effective means of doing that. In recent years, the techniques and analytical devices available for structural observations have made remarkable progress. Even so, I think that what matters most today is, as in the past, the researcher’s ability to read the metallic microstructures, which remain a treasure trove of valuable information.

6. Expectations Entertained of Young Steel Researchers

Steel is a wonderful material all right. But, whether or not it can be put to good use depends on us — steel researchers and engineers. In this section, let me briefly express my opinion as to what research is like and how researchers should be.

Research is interesting. When you feel excited doing your research, it must be going smoothly. Because of that feeling of excitement, you can continue working hard every day. Researchers should experience such pleasures and sensations as much as possible.

Devoting yourself to something is important. When it comes to research, however, strenuous efforts do not always bring about good results. Earnest efforts will lead to a measure of success. Producing better achievements, however, requires not only hard work, but also an excellent capacity for, and high sense of, research. One can cultivate a sense of research only under guidance if one’s superior is equipped with a high sense of research. The capacity for research includes expert knowledge, and the ability to analyze and observe, etc. In addition, presentation and communication capabilities are called for. All these can hardly be acquired unless one has a flexible way of thinking and high powers of concentration. As one gets older, one’s knowledge readily increases in width, but not in depth. In this context, now is an especially important time for young researchers.

When you use a computer in an experiment, the desired data is output automatically. In this case, you might become self-satisfied thinking that you are doing research. However, if you begin by simply seeking results and end with listing out the obtained results without any explanations for them, you are just doing a job, not research. If you continue doing that routinely, you might come to think some day that it really is research. You must not accept ‘pseudo-research’ as real research. True researchers must continue thinking at all times—asking why and why. Flashes of inspiration only come from those who are constantly pondering the issues. Thinking about things is a custom. Researchers who have stopping thinking are no longer researchers. Young researchers should acquire the habit of always returning to the basics and thinking things through according to the fundamental principles.

Research must be original. Anyone can replicate other research. A researcher’s pride lies in doing original research. Continuing the research theme is also necessary. It is important to tackle research tenaciously and unyieldingly without resignation. Struggle up untrodden mountain paths and stand at the peak, and you will find invaluable treasure there.

Research is only complete once the research results are compiled in the form of a paper. Research conducted by a business is not done with the intention of publication as a paper. Yet, all research should be of such quality that its results are worthy of publication in the form of a paper. As researchers grow in experience in writing research papers and presenting them at various society meetings, their potential steadily and naturally improves, making them highly respected researchers who can contribute much to their company.

I sincerely hope that you will grow into real, high-minded researchers.

7. Conclusion

Steel is undoubtedly a wonderful material. Those who deal with such a splendid material and who are engaged in research and development on steels, which is certain to continue being a major structural material, should be grateful for and take great pride in their situation. It is our important task to further promote the development of steels, which still have so much growth potential.

It is indispensable for steel researchers and engineers dealing with steels to know the charms of steel as a material and appreciate it. I hope that they will become real researchers and engineers who are able to converse with steels as if they are alive. I am confident that as long as there are able individuals who love steel and are high-minded and passionate about steel, the future of steel will remain bright.