

# Lawrence Berkeley National Laboratory

## Recent Work

### Title

SOME ANTICIPATED DEVELOPMENTS IN PHYSICAL METALLURGICAL RESEARCH

### Permalink

<https://escholarship.org/uc/item/27j956qq>

### Author

Zackay, Victor F.

### Publication Date

1969

*cy. Z*

LIBRARY AND  
DOCUMENTS SECTION

SOME ANTICIPATED DEVELOPMENTS  
IN PHYSICAL METALLURGICAL RESEARCH

Victor F. Zackay

January 1969

TWO-WEEK LOAN COPY

*This is a Library Circulating Copy  
which may be borrowed for two weeks.  
For a personal retention copy, call  
Tech. Info. Division, Ext. 5545*

LAWRENCE RADIATION LABORATORY  
UNIVERSITY of CALIFORNIA BERKELEY

*cy. Z*

25

## DISCLAIMER

This document was prepared as an account of work sponsored by the United States Government. While this document is believed to contain correct information, neither the United States Government nor any agency thereof, nor the Regents of the University of California, nor any of their employees, makes any warranty, express or implied, or assumes any legal responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by its trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof, or the Regents of the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof or the Regents of the University of California.

Paper presented at the April 1969  
Centenary Celebration of the Iron  
and Steel Institute; J. Iron and  
Steel Institute

UCRL-18676  
Preprint

UNIVERSITY OF CALIFORNIA  
Lawrence Radiation Laboratory  
Berkeley, California  
AEC Contract No. W-7405-eng-48

SOME ANTICIPATED DEVELOPMENTS  
IN PHYSICAL METALLURGICAL RESEARCH

Victor F. Zackay<sup>v</sup>

January 1969

SOME ANTICIPATED DEVELOPMENTS IN PHYSICAL METALLURGICAL RESEARCH

Victor F. Zackay\*

Synopsis

There is ample evidence to suggest that significant changes are taking place in the conduct of physical metallurgical research in the United States. These changes are being brought about by complex economic, managerial and technical forces. Several of these forces are identified and discussed.

An analysis of the available statistics suggests that a greater emphasis will be placed on applied rather than on fundamental research in the United States in the ensuing decade. The forces active in producing this change in emphasis are discussed.

The continuing heavy demands by industry for improved materials are affecting changes in both the objectives and the methods of physical metallurgical research. An example is taken from the nuclear power industry to illustrate some of these changes.

The specific metallurgical problem of the limited strength, ductility and toughness of high strength steels is examined. Processes are suggested whereby high strength steels of greater toughness can be made.

A newly developed class of steels is described having both high strength and high ductility. Lastly, the present upper limits of the strength and ductility of steel are defined.

---

\* Professor of Metallurgy, College of Engineering, University of California, and Principal Investigator, Inorganic Materials Research Division, Lawrence Radiation Laboratory, Berkeley, California

### Introduction

The phrase "climate of research" is often used to describe the sum total of all those forces that are active in shaping the direction and determining the content of research. It is the intent of the author to identify several of these and to predict their probable influence on the course of physical metallurgical research in the next decade.

One of the most important of these forces is a non-technical one, i.e., the pattern of research sponsorship. Changes in this pattern are likely to have a profound influence on both the orientation and the objectives of research. An attempt will be made in the first section of this paper to establish the pattern of research sponsorship in the United States and to detect any changes that might be occurring.

Many, if not most, of the physical metallurgical developments of the future will be dictated by the requirements of industry. The act of fulfilling industrial needs not only establishes the objectives of research but can profoundly influence the methods of research. This is especially true for the large, complex and expensive projects undertaken in the basic industries of power, transportation, communication and heavy chemicals. In the second section of the paper, an example will be taken from the nuclear power industry to illustrate these effects.

Some of the future developments in physical metallurgy will no doubt have their origins in research currently being done in metallurgical laboratories throughout the world. As shown in the third and last section of the paper the extrapolation of some of the current research results of the author's laboratory allows a definition of the potential upper levels of strength, ductility and toughness in steel.

The Pattern of Research Sponsorship in the United States

There are developments and trends of a general nature whose anticipation would be of interest and of use to the metals scientist and engineer. The anticipation or at least the early detection of major changes in the overall character of a nation's research effort is a subject of concern to many people in government, industry and university circles. Useful barometers of this research effort are the trends established by the allotment of funds for research. A knowledge of these trends with respect to the magnitude of the funds allotted as well as their distribution between the different types of research, i.e., basic, applied and developmental, is useful for planning or forecasting purposes. The basic data required for establishing these trends in the United States are readily available in various reports published by the Federal Government. One of the most highly regarded of these is compiled by the National Science Foundation (NSF). The most recent volume of this series serves as the source of much of the data used in the following discussion.<sup>(1)</sup> It should be noted that the statistics on research supplied by the NSF pertain to funding by the Federal Government alone. Statistics on funds expended by industry for research are not included in this compilation and, in general, such data are not as readily available. However, in the United States the Federal Government is the largest source of research and development funds by far, having provided 63 percent of the Nation's expenditures for this activity in 1966. Thus the trends that are exhibited by the use of the NSF data can be considered to be reasonably representative of the Nation's total research and development effort.

The trends in Federal funding for research and development for the

period 1954 to 1968 are shown in Fig. 1. The fraction of the total expended for nondefense and defense-related research is also shown. The data are shown plotted as a percent of the total Federal budget in Fig. 2. It is evident from these data that either in terms of dollars or as a percent of the total Federal budget the expenditures for research and development in the United States have risen more or less continuously since 1956.

Although the funding for research and development has risen over the past 14 years, the annual growth rate has not been constant. As shown in Fig. 3, the trend line for each of the different types of research climbed at a steep rate from about 1956 to 1964 but, following 1964 and continuing to the present time, it rose at a much diminished rate. This abrupt change in the rate of expenditure of funds for research is clearly revealed if a comparison of the average annual growth rates (percent) for the two periods, i.e., 1956 - 1964 and 1964 - 1968, is made as shown in Table I.<sup>(1)</sup> It is evident that the average annual growth rate for both basic and applied research in the period 1964 - 1968 decreased by about two-thirds relative to that of the eight year period preceding it. The precipitous drop in the growth rate of funding for development in the 1964 - 1968 period reflects the completion of large programs in the space and defense areas.



TABLE I

The Average Annual Growth Rate  
of Federal Expenditures for Research and Development  
(percent)

	1956 - 1964	1964 - 1968
Basic Research	29	10
Applied Research	21	9
Development	21	2
Research and Development Total	22	4

Before any inferences can be drawn about the present and likely future research and development climate in the United States from the trends discussed above, we must consider another important factor, i.e., escalation of costs. We have assumed in our discussion of these trends in Federal expenditures that the purchasing power of the dollar has not changed during the last 14 years. In reality, the cost of goods and services in the United States has risen an average of three percent a year for the past decade.<sup>(2)</sup> As a consequence, the purchasing power of the dollar has decreased an equivalent amount. The accumulative effect of this yearly increase in the cost of doing research or yearly decrease in the value of the dollar is to alter significantly the trends portrayed in Figs. 1 through 3. This effect of escalation can perhaps be best illustrated by a specific case, viz. that of the Division of Research of the Atomic Energy Commission of the United States. The author is indebted to Mr. George Pappas of the Lawrence Radiation Laboratory for kindly

supplying the needed data. It may be added parenthetically that the Division of Research is the sponsor of the author's own research.

The actual dollar funding per fiscal year allotted for the operating and equipment budgets for the Division since its inception is shown as a solid line in Fig. 4. If the amount of actual dollars funded is corrected for the escalation in costs of goods and services (using 1959 as a base) then a new curve results which is shown as a dashed line in Fig. 4. It is evident that the purchasing power of the funds allotted has continuously decreased since 1959 relative to the actual dollars funded because of the accumulative effects of escalation. In fact, while the actual amount of dollars allotted has increased continuously since 1956 the purchasing power of these dollars has fallen off until in 1966 a value of about 22.5 million dollars was reached and has since remained virtually unchanged. It is of interest to note that in the period 1966 - 1968 there was essentially no change in the purchasing power of the available funds yet in the same period there was an increase of more than three million dollars in actual funds.

We have attempted to show how the trends in Federal funding for research and development may be used as indices of change in the Nation's total research effort. Recent shifts in these trends suggest a period of change and readjustment in the research establishment. It is the consensus of most of the leaders in government and in industry that the nation has reached a plateau in the magnitude of its research efforts. This plateau is a consequence of two principal forces, i.e., curtailment of funding and escalation of costs. The latter tends to off-set or eliminate any actual increases in funding.

The cessation in the growth rate of the nation's research effort has been the occasion for alarm by some and a concern for all. However, if the growth rate would have continued at its 1960 level, by the year 2050 it would be approximately equal to one-half the Federal budget! For this reason alone an adjustment was inevitable and should cause no surprise, as Chairman Seaborg of the Atomic Energy Commission has remarked.<sup>(3)</sup> The signs of this coming adjustment are already in evidence. They are especially strong in the universities which depend in large measure on Federal expenditures for basic research in the physical and life sciences. If the present trend in research sponsorship continues there seems to be little doubt that increased emphasis will be placed on developmental rather than on basic research. This expected change in research emphasis will have, in turn, its repercussions not only on the choice of the objectives of future research but, equally important, on the methods by which research is done. These repercussions can already be felt and are the subject of the following section.

#### Future Developments Dictated by the Needs of Industry

In an evolving technology there is a continuous demand for the improved performance of structural materials. Innovations in virtually all the basic industries clearly emphasize the trend to higher operating temperatures and pressures, to increased exposure to hostile environments and to increased size in engineering structures. Structural materials must not only perform their engineering functions in complex environments but must do so safely and reliably for periods of time that are often measured in decades. It is little wonder that much of the research and development

done today is directed toward fulfilling the basic needs of industry. Further, some of the industrial requirements of the future are so demanding, expensive and complex that a massive attack across a broad research front must be mounted. Projects of this scope and magnitude are appearing with increasing frequency on the research scene. Because of their importance and of the impact they have on the research establishment it is perhaps worthwhile to review some of the principle features of one such project recently started in the nuclear reactor field.

A large program, funded by both government and industry and designated the Heavy Section Steel Technology Program (HSST) was recently inaugurated to study the structural behavior of very thick nuclear pressure vessels used in advanced designs. The primary objective of the program<sup>(4)</sup> is to provide an answer to the question, "What effects do flaws, variation of properties, stress raisers, and residual stresses have on the strength and structural reliability of present and contemplated water-cooled reactor pressure vessels?" Before discussing the various tasks of this program it is perhaps helpful to recall the qualitative effects of plate thickness on the fracture behavior of steel.

The effect of thickness has been known for many years. In general, the problem of brittle fracture becomes more acute with increasing thickness, and for the thickness used for nuclear pressure vessels, i.e., six to twelve inches, it is one of the critical problem areas. Some representative data illustrating the effect of thickness on the fracture of annealed structural steel are shown in Table II, taken from the work of Parker et al.<sup>(5)</sup> Increasing the plate thickness by a factor of four decreased the minimum reduction in area by a factor of ten and changed the type of

TABLE II

Summary of Results of Tests on Geometrically Similar Specimens

Size of Specimen	Temp. of Test, F.	Type of Fracture	Nominal Stress of Max. Load, psi	Reduction in Thickness, %	
				Maximum	Minimum
3" wide	0	Shear	47,900	30.0	18.9
9" long	32	Shear	45,200	26.7	15.6
3/16" thick	74	Shear	47,700	30.0	18.5
	74	Shear	45,800	33.3	...
6" wide	32	Cleavage	45,500	22.3	9.0
18" long	50	Mixed	44,200	23.1	7.8
3/8" thick	70	Shear	44,500	25.7	15.1
	90	Shear	44,400	25.6	17.7
12" wide	32	Cleavage	40,900	16.2*	1.4
36" long	70	Cleavage	39,900	17.9*	1.4
3/4" thick	102	Cleavage	39,100	19.7*	1.7

\*At base of notch

fracture from shear to cleavage.

The problem of brittle fracture in actual structures is intensified by the presence of numerous types of stress raisers, weld defects, variations in microstructure and residual stresses. The size of some of the vessels contemplated for use in large scale power generating plants is awesome. A pressurized water reactor vessel for a 1000 megawatt plant may weigh over 900 tons, have a wall thickness of 12 inches, and may exceed 20 feet in diameter. In view of these and other considerations, it was the opinion of the United States Atomic Energy Commission's Advisory Committee on Reactor Safeguards that an ambitious and massive attack on the problems of design and constructing these vessels was in order. Therefore, the HSST program was initiated.

The tasks of the HSST program have been summarized in a recent paper by Witt and Steele.<sup>(4)</sup> They categorized the essential tasks of the program as follows:

1. Program administration (including material control).
2. Material properties and material integrity (nondestructive examination, characterization, and variability).
3. Fracture behavior (transition temperature and fracture mechanics investigations, fatigue crack propagation, irradiation effects, and the influence of complex stress states).
4. Periodic proof testing.
5. Simulated service tests.

There are several aspects of these various tasks that warrant further comment. The Program Planning Committee (Task I) whose members were drawn

from government, industry and universities has the function of defining the details of the program and to serve in a general advisory capacity. This committee, when supplemented by additional members from the industrial and academic fields, comprises the Program Review Committee whose function is to provide a critical analysis of the overall general progress of the program. In the various subcommittees that are part of the organizational structure there are representatives of virtually every major steel company, nuclear plant manufacturer and pressure vessel builder, and user, in the United States.

The task force on materials properties and material integrity (Task 2) has already obtained some interesting nondestructive testing results on thick plate before and after heat treatment. The results strongly suggest that some significant flaws were introduced into the 12 inch plate by the heat treatment itself.

There is at present no theoretical analysis capable of predicting the fracture toughness of very thick plates. In its place there are a variety of empirical tests all using small standard size specimens whose applicability to heavy section plates and pressure vessels is largely unknown. Much attention will be given in the program (Task 3) to establish the validity of these tests using specimens varying in thickness from 5/8 inches to 12 inches. A parallel program will evaluate the validity of the several types of tests and specimens currently used to measure the plane stress,  $K_c$ , and plane strain,  $K_{Ic}$ , fracture toughness criteria that are based on elastic - plastic analysis.

One of the principal objectives of the entire program is to predict the behavior of a welded pressure vessel fabricated from heavy section plate

with a known size of flaw (Tasks 4 and 5). Full size plates with varying flaw sizes will be tested at different temperatures in a 15 million pound tensile machine. Finally a full-size pressure vessel weighing about 300 tons and having a wall thickness of 12 inches will be tested in a variety of conditions closely simulating actual service.

Projects similar in scope and magnitude to the HSST are underway in every basic industry and many of them have certain features in common. First, the newest and most sophisticated techniques in management, organization and finance are involved. Second, the complexity of the problem to be solved invariably requires the "systems approach" for its solution. Third, a completely interdisciplinary approach to all problems is used. Fourth, the research results of such projects almost invariably have broad applicability not only to the sponsoring industry but to others as well. In this regard it is safe to assume that the conclusions and the experience derived from the HSST program will also have a profound influence on the design and construction of pressure vessels in the basic chemical and petro-chemical industries.

The previous sections of this paper have dealt with the increasing emphasis on applied research in the United States. However, it is not the intention of the author to imply that basic research will be seriously neglected or that it will cease to be either vigorous or creative. As shown in a previous section the United States continues to expend more than 12 percent of its total budget for research and development. Although readjustments will have to be made in the future on the part of some individuals and institutions, it is unlikely that the existence of fundamental research, especially in the materials field, will be seriously threatened.



An example of continuing basic research on the mechanical properties of steel is discussed in the following section.

#### Attainable Values of Toughness in High Strength Steels

In this section we will discuss the present limits of strength and toughness of low alloy high strength steels and attempt, by the use of extrapolative techniques, to establish potential upper limits as goals for physical metallurgical research in the next decade.

There is an inverse relationship between yield strength and elongation for low alloy high strength steels, as shown in Fig. 5. The useful strength of these steels is thus limited for structural purposes to about 200,000 psi. Above this yield strength the elongation and the toughness decrease to unacceptable values for most structural applications. Since the theoretical strength of iron has been variously estimated to be between one and two million pounds per square inch,<sup>(6)</sup> it seems reasonable to suppose that the upper limits of the useful strength of steel can be significantly increased.

The mechanical properties of steel, including the yield strength and the elongation, are primarily determined by the composition and the heat treatment. In recent years another dimension has been added to the traditional processing of steel, i.e., the inclusion of plastic deformation in conjunction with heat treatment. A brief review of progress in this field is relevant because thermomechanical processing can increase both the strength and the toughness of steel. Two of the simplest and the oldest of these processes will now be considered.

The schematic time-temperature-deformation diagrams of two similar

thermomechanical processes, strain tempering and dynamic strain aging, are shown in Fig. 6. Both processes involve a small amount of plastic deformation (1/2 to 5 percent) at elevated temperatures. The primary difference between the two processes is that in strain tempering the deformation is done at room temperature between the two stages of tempering, while in dynamic strain aging the deformation is concurrent with tempering. Both processes produce an appreciable increase in yield strength, as shown in Fig. 7. The elongation is reduced only a slight amount by strain tempering and dynamic strain aging.<sup>(7,8)</sup> The amount of deformation is an important variable in both processes. The effect of the amount of deformation (see Fig. 6) on the yield strength of a dynamically strain aged Fe-Mo-C(0.20%) steel is shown in Fig. 8.

Similar increases in the strength of more highly alloyed steels can be achieved by complex thermomechanical processes such as ausforming and similar processing of multiphase alloys (e.g. mixtures of austenite and bainite).<sup>(9,10)</sup> In the ausform process austenite is warm-worked prior to its transformation to martensite. A schematic time-temperature-deformation diagram of this process is shown in Fig. 9. The subsequently tempered martensite is not only stronger but tougher as well, as shown in Fig. 10. At a yield strength of 240,000 psi the pre-cracked Charpy impact values of a low alloy steel (Ladish D6aC) are almost four times greater in the ausformed state.<sup>(11)</sup>

A promising modification of this process is the thermomechanical processing of austenite and bainite, which produces a microstructure of martensite plus lower bainite.<sup>(12)</sup> A schematic time-temperature-deformation diagram of this process is shown in Fig. 11. The incremental gains in

tensile strength,  $\Delta TS$ , vs the amount of deformation for both processes are shown in Fig. 12. For deformations greater than ten percent, it is evident that the increase in strength in the martensite-bainite steel is about twice as great as in its ausformed counterpart. For more complete discussions of these and other thermomechanical processes, the reader is referred to recent comprehensive reviews. (9,13)

We have examined a number of thermomechanical processes which appear promising as a means of increasing the useful strength of steel. An estimate of the upper limits of strength and toughness likely to be attained in the next decade can now be made. In making this estimate, it is assumed that the effects of certain thermomechanical processes are additive. This assumption is based on the results of a recent study where it was shown that a combination of ausforming and dynamic strain aging added about 80,000 psi to the yield strength of a tempered martensitic steel whereas each process alone added about 40,000 psi. (7)

The work of Zackay et al (7) revealed that the toughness of steels subjected to combinations of thermomechanical processes was not adversely affected even though the yield strength increased as much as 25%, as shown in Fig. 13. The measure of fracture toughness that we use here is based on the intensity of stress near the tip of a crack that is required to make the crack unstable. The symbol,  $K_C$ , designates the fracture toughness in a thin section, the plane stress condition, while the symbol,  $K_{IC}$ , designates the fracture toughness in a thick plate, the plane strain condition. Higher values of  $K_C$  or  $K_{IC}$  thus signify a greater resistance to crack propagation, i.e., a greater fracture toughness. A detailed discussion of  $K_C$  and  $K_{IC}$  is given in several review papers. (14,15) In

Fig. 13 the ratio,  $K_c/\sigma_{y.s.}$ , is plotted against  $\sigma_{y.s.}$ . This type of plot is convenient for displaying the effect of strength on toughness for various alloys and processes. In practice, it is desirable that steels be used at yield strengths corresponding to a value of one or greater for the ratio,  $K_c/\sigma_{y.s.}$ . It is evident from this type of plot that deformed martensite plus bainite is superior to the combined processes of ausforming and dynamic strain aging, as shown in Fig. 13.

If it is assumed that the thermomechanical processing of mixtures of austenite and bainite, like ausforming, can be advantageously combined with dynamic strain aging, one can, by extrapolation of the data in Fig. 14, obtain a value of the maximum useful yield strength. The yield strength so obtained, i.e., by extrapolation to a value of one for the ratio,  $K_c/\sigma_{y.s.}$ , is about 320,000 psi. It is evident from Fig. 14 that a steel having this yield strength and plane stress fracture toughness would be superior to the best of the newer high alloy steels.

#### Attainable Values of Elongation in High Strength Steels

In the previous section it was demonstrated that the useful strength of steel could be significantly increased by thermomechanical processing. However, the limited elongation of high strength steels curtails the use of several of these processes. Perhaps of even greater importance, it severely restricts the employment of fabrication techniques that are desirable in the production of high strength steel parts. For the past several years the author and his colleague, Professor Earl R. Parker, have studied the problem of ductility in high strength steels. Based on the results of this study, a new class of steels was developed which had

combinations of strength and ductility superior to those of current commercial high strength steels. Further, a present upper limit to the attainable strength and ductility of steel was defined. To begin our discussion of these developments it will be helpful to recall the differences between the two different kinds of ductility observed in metals.

Uniform elongation is but one manifestation of the ductility of a metal; reduction of area, a highly localized form, is another. A number of useful observations about the nature of these forms of ductility in steel can be made by the examination of the true stress - true strain curves of a typical martensitic steel (A.I.S.I. 4340) heat treated to produce several yield strengths,<sup>(16)</sup> as shown in Fig. 15. It is evident that the ductility as measured by the true strain at fracture is large at all levels of strength. However, the uniform strain, i.e., the strain at which necking begins, is relatively small and is almost non-existent for the highest yield strength.

The criterion for necking, viz.,  $\frac{d\sigma}{d\epsilon} = \sigma$ , postulates that the strain hardening rate must increase in direct proportion to the yield strength if the uniform strain preceding necking is not to diminish as the yield strength is increased. It is of interest to note that the structural factors which determine the yield strength are not the same as those which determine the rate of strain hardening, as shown by the fact that the slopes of the true stress - true strain curves remain the same with increasing yield strength (see Fig. 15).

The pivotal question with respect to the design of a high strength steel with enhanced elongation can now be stated as follows: Can we introduce barriers to slip during straining that result in greater rates

of strain hardening than those observed in commercial quenched and tempered steels? There are very few changes in internal structure other than those associated with dislocations that can be made to occur as a consequence of plastic flow. There is one, however, incorporated in high carbon - high manganese steels by Sir Robert Hadfield more than 86 years ago that has a major effect on mechanical properties.<sup>(17)</sup> This is the strain-induced transformation of austenite to martensite. Since Sir Robert's time this hardening mechanism has been widely exploited, particularly in the instance of metastable austenitic stainless steels. A distinctive property of these steels is their high rate of strain hardening. However, substantial modifications of the composition and of the processing of these steels are required to preserve this property at yield strengths above 200,000 psi. A brief description of these modifications is the subject of the following discussion.

The composition of the steel selected is such that its  $M_s$  after solution quenching is at or near room temperature. The fully austenitic steel is then severely warm-worked above the  $M_d$  temperature (the lowest temperature at which martensite is produced during straining). The  $M_d$  of these steels is typically about 100°C above room temperature after solution quenching. After warm working the  $M_d$  is usually increased about 100°C and the  $M_s$  decreased an equivalent amount. A schematic time-temperature-deformation diagram of the process is shown in Fig. 16. After warm working the room temperature yield strength of the fully austenitic steel is characteristically between 200,000 and 225,000 psi.

There is a wide latitude in the selection of compositions for steels amenable to this type of processing; however, one steel which has been the

subject of detailed study has the following nominal composition: 9Cr - 8Ni - 4Mo - 2Mn - 2Si - 0.30C. The carbon content (0.20 - 0.30%) is somewhat higher than that of commercial austenitic stainless steels (0.10 - 0.15%). As a result, the strain-induced martensite is hard and tough, i.e., it is an effective obstacle to slip at high yield strengths. As shown in the true stress - true strain curves of both the new steels and those of A.I.S.I. 4340 in Fig. 17, the strain hardening rates and the uniform strains are higher for the new steels. Thus, a steel of the composition mentioned above and processed in the manner previously described is fully austenitic, has a yield strength of at least 200,000 psi, exhibits a high rate of strain hardening and, as a consequence, has an elongation two to three times that of a conventional ultra high strength steel of comparable yield strength. In previous papers<sup>(18,19)</sup> on this subject, the author and his colleagues suggested that the class of alloys exhibiting the enhanced ductility afforded by the deformation - induced transformation be given the name "TRIP" an acronym from letters of the words "Transformation Induced Plasticity".

The progress made to date in the improvement of the strength and ductility of this class of materials is illustrated in Fig. 18 where the elongations of tempered martensitic and TRIP steels are plotted against their respective yield strengths. The present upper limit to the attainable strength and ductility of steel can now be defined by converting the known reduction of area values of representative high strength steels to their equivalent values of elongation. Specific values of the reduction of area were selected from the published literature for high strength steel wires, maraging steels, and tempered martensitic steels. The known upper limit

of strength and ductility is shown as a dotted line sloping downward from the upper left toward the right in Fig. 18. It is evident that although some progress has been made in the enhancement of the elongation of high strength steels, there is much room for further improvement.

#### Summary

An attempt has been made to anticipate some of the developments of physical metallurgical research in the coming decade. Developments of both a general and a specific nature have been considered.

Trends in the pattern of research sponsorship in the United States were examined and it was concluded that the twin forces of Federal budget curtailment and the escalation of costs would tend to emphasize applied rather than fundamental research in the next decade.

The role of physical metallurgical research in the fulfillment of the future needs of industry was studied and it was concluded that significant changes in the methods of doing applied research were likely. These changes will be especially evident in the large scale and complex projects of basic industry. These will include a "systems approach" to the solution of problems and the utilization of the most sophisticated techniques in management, organization and finance.

The problem of toughness in high strength steels was reviewed. By the extrapolation of current research results in the area of thermo-mechanical processing it was shown that it should be possible to produce steels having both high toughness and high yield strength (above 300,000 psi).

Lastly, the problem of ductility in high strength steels was studied. A new class of steels was described which had combinations of strength



and ductility superior to those of commercial high strength steels.

Further, a present upper limit to the attainable strength and ductility of steel was defined.

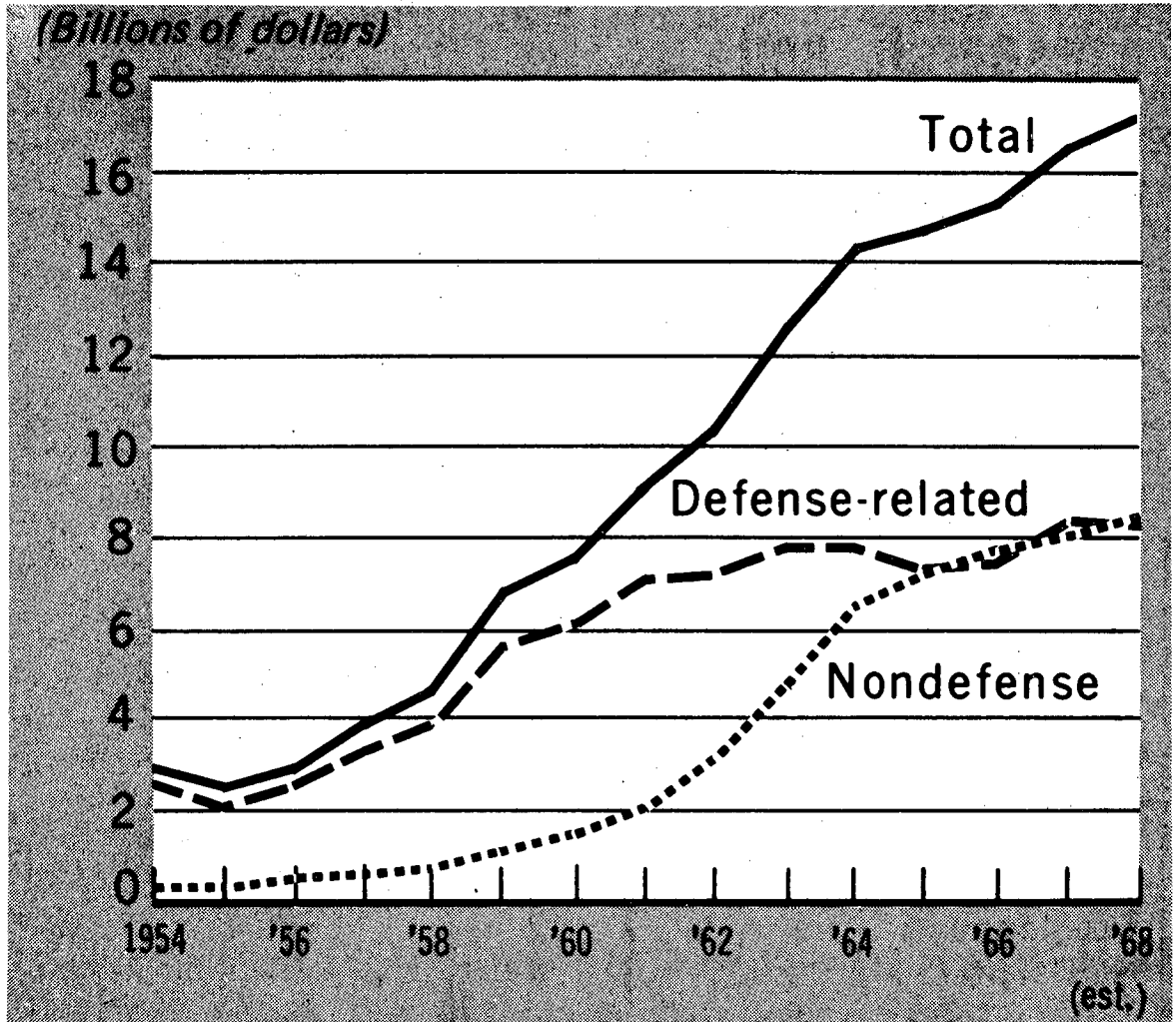
Acknowledgements

The author gratefully acknowledges the advice and information given by many of his friends and acquaintances including E. R. Parker and W. W. Gerberich of the University of California, E. H. Edwards of Standard Oil of California, W. R. Smith, Sr. and L. Chockey of the General Electric Nuclear Energy Division, S. Bush of Battelle Memorial Institute - Northwest, R. Decker, S. Floreen, W. Schillmoller, F. Schaller, R. Schiver, A. F. Kravic and W. A. Koppi of the International Nickel Company, D. Wilkes and G. Pappas of the Lawrence Radiation Laboratory, S. Goldberg and T. Kearns of the United States Navy, E. R. Morgan of Jones and Laughlin Steel Company, D. Blickwede of Bethlehem Steel Corporation, H. Greenberg of Westinghouse Corporation, M. Tannenbaum and C. E. Roden of the Bell Telephone Company, and S. Gertsman, Department of Energy, Mines and Resources, Canada. The author also thanks Mrs. Susan Arnold for typing the manuscript and Mrs. Gloria Pelatowski for preparing the figures. The author's research was supported by the United States Atomic Energy Commission.

References

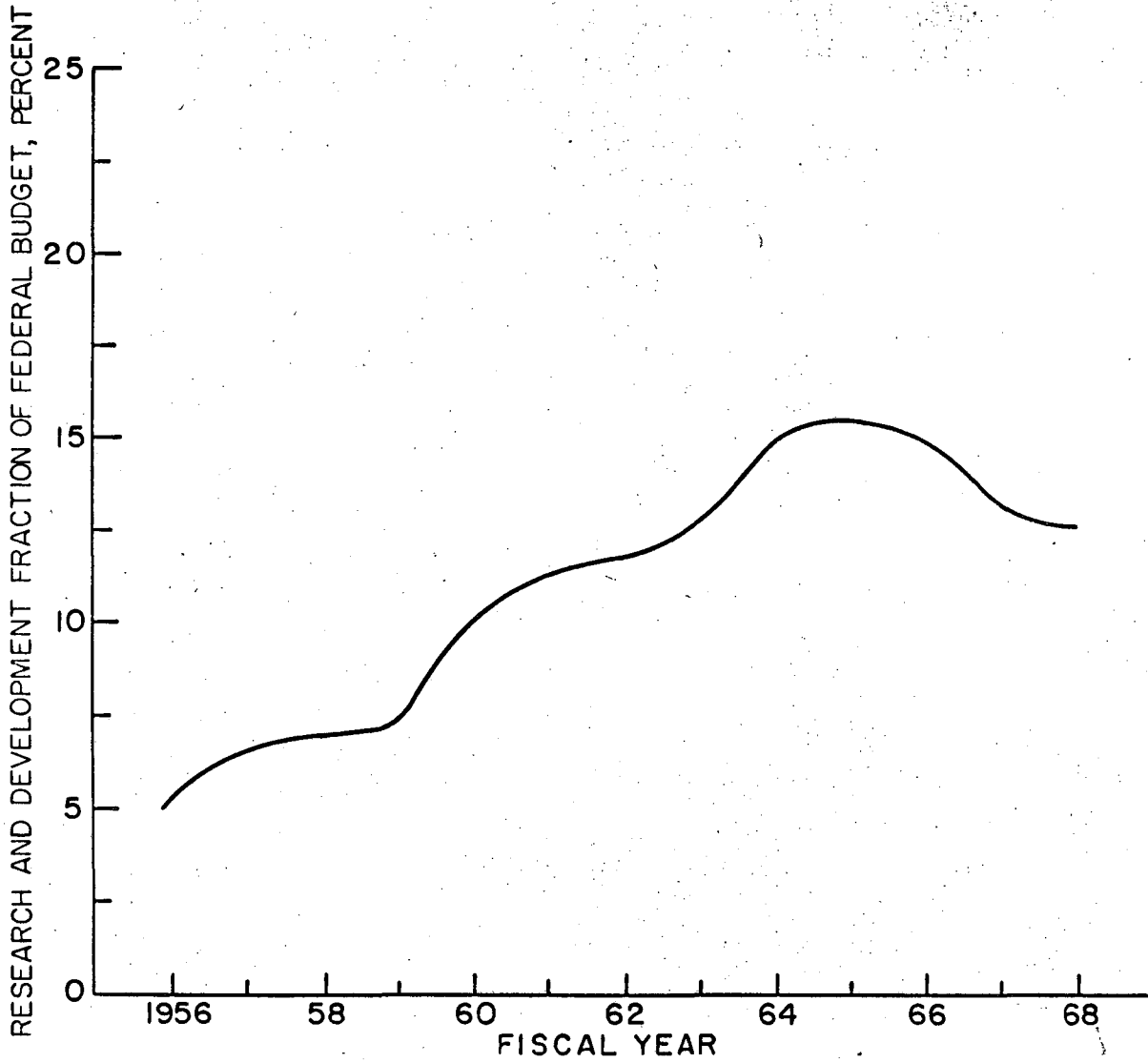
1. Federal Funds for Research, Development and Other Scientific Activities - Fiscal Years 1966, 1967 and 1968, 16, NSF 67-19, U. S. Government Printing Office, Washington, D. C. 20402.
2. Survey of Current Business, 1968, November, U. S. Department of Labor, Superintendent of Documents, U. S. Printing Office, Washington, D. C., 20402.
3. G. T. Seaborg, Speech S-50-68, Atomic Energy Commission, Washington, D. C., 20545.
4. F. J. Witt and L. E. Steele, Trans. ASME, Paper No. 67-WA/ER-2, 1968.
5. E. R. Parker, "Brittle Behavior of Engineering Structures", 1957, John Wiley & Sons, 146.
6. S. S. Brenner, J. Appl. Phys., 1956, 27, 1484.
7. V. F. Zackay, W. W. Gerberich, R. Busch, and E. R. Parker, Intern. J. Frac. Mech., 1966, 2, No. 4, 638-644.
8. D. Kalish, S. A. Kulin and M. Cohen, Metals Engr. Qrt., 1967, 7, No. 4, 54.
9. W. E. Duckworth, BISRA Rep. MG/A/60/67.
10. W. W. Gerberich, A. J. Williams, C. F. Martin and R. E. Heise, 1965, ASTM Special Technical Publication No. 370, 154-171.
11. R. T. Ault, K. O. McDowell, P. L. Hendricks and T. M. F. Ronald, Trans. ASM, 1967, 60, 79-87.

12. L. Raymond, W. W. Gerberich, and W. G. Reuter, Air Force Report No. SSD-TR-66-89, Aerospace Corporation, El Segundo, California.
13. E. B. Kula, "Strengthening Mechanisms", 1966, Syracuse University Press, 83-122.
14. J. E. Srawley, M. H. Jones, and W. F. Brown, Jr., Materials Research and Standards, 1967, 7, No. 6, 262-266.
15. W. F. Brown, Jr., and J. E. Scrawley, ASTM, 1967, Special Technical Publication 410.
16. F. R. Larson and J. Nunes, Trans. ASM, 1966, 53, 663.
17. R. A. Hadfield, "Metallurgy and Its Influence on Modern Progress", 1925, Chapman and Hall, London.
18. V. F. Zackay, E. R. Parker, D. Fahr, and R. Busch, Trans. ASM, 1967, 60, 252-259.
19. E. R. Parker and V. F. Zackay, Scientific American, 1968, 219, No. 5, 36-45.



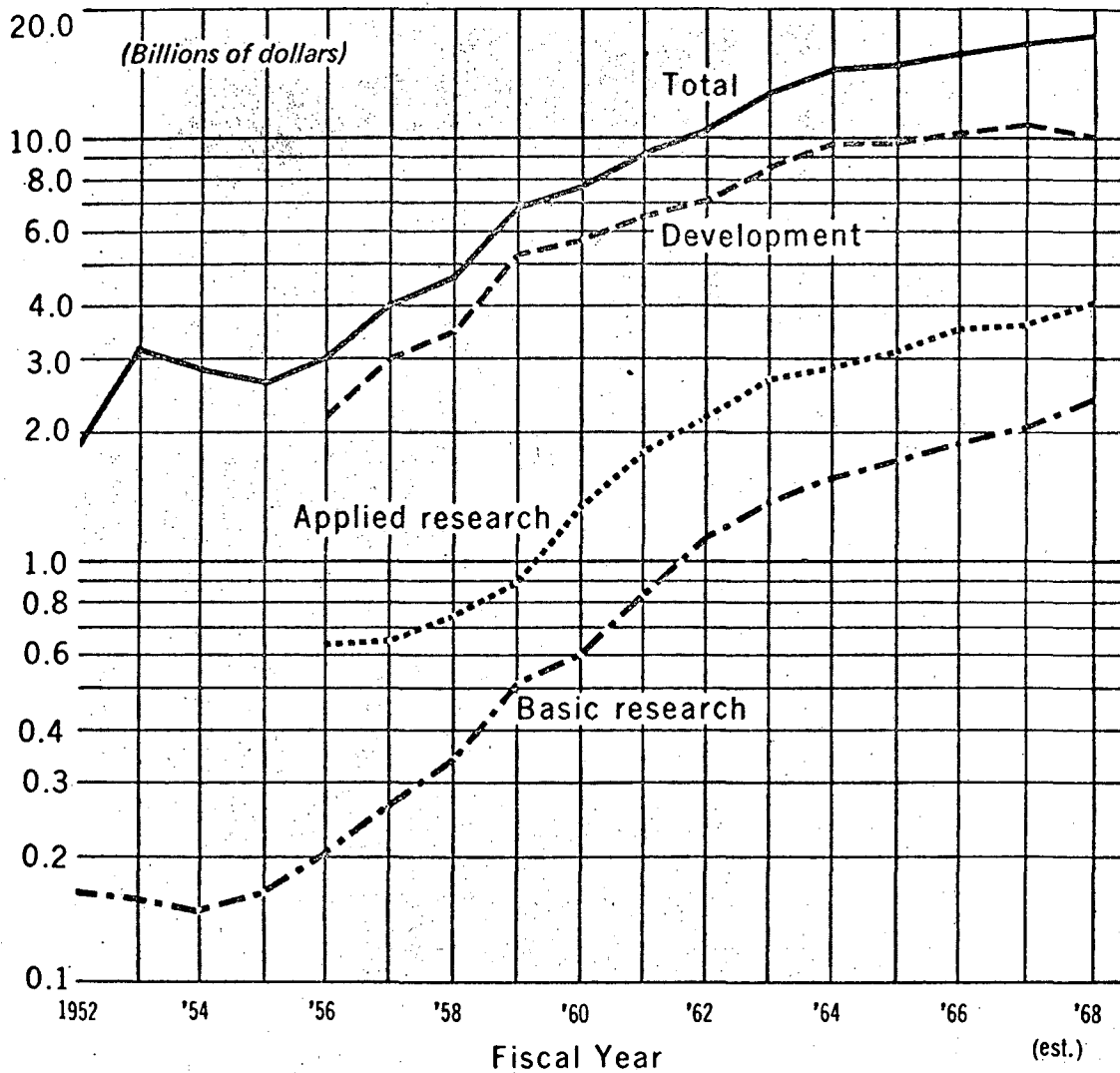
XBL 6812-6445

Fig. 1 The trends in Federal funding for research and development for the period 1954 to 1968. (Ref. 1)



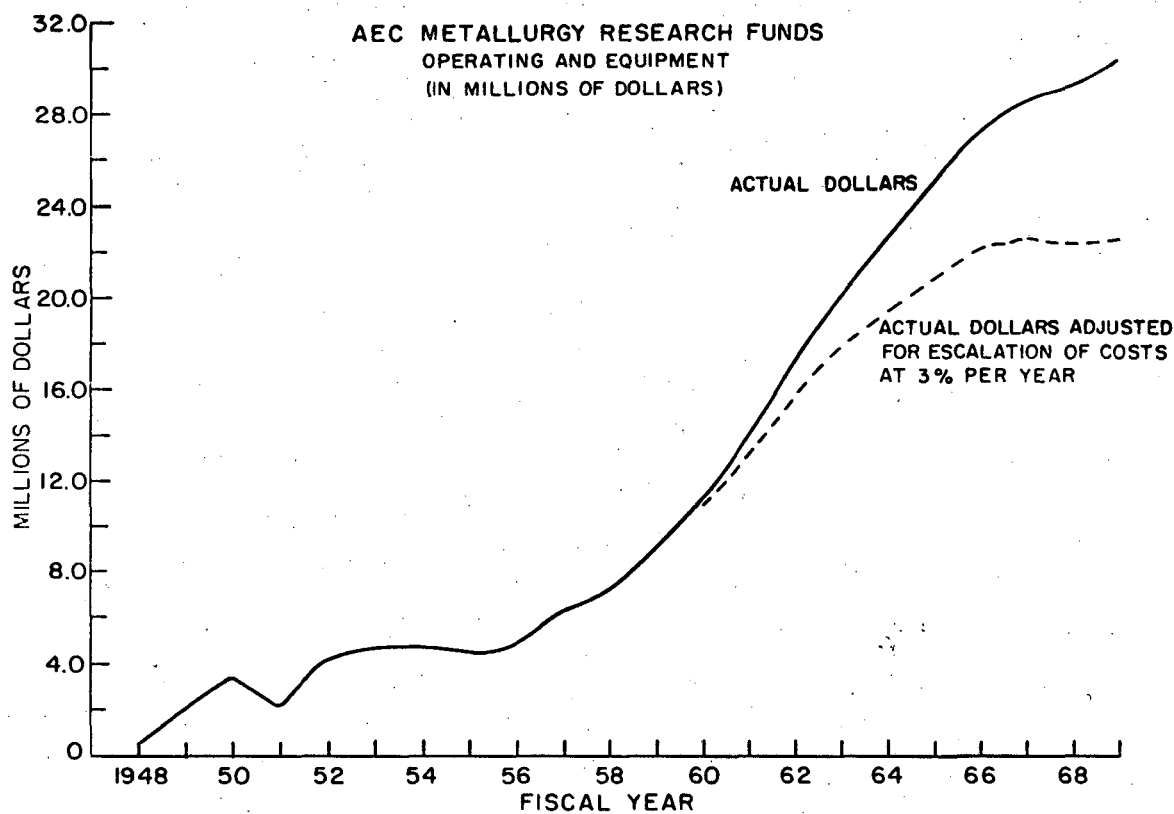
XBL 6812-6438

Fig. 2 The trend in Federal funding for research and development shown as a percent of the total Federal budget. (Ref. 1)



XBL 6812-6446

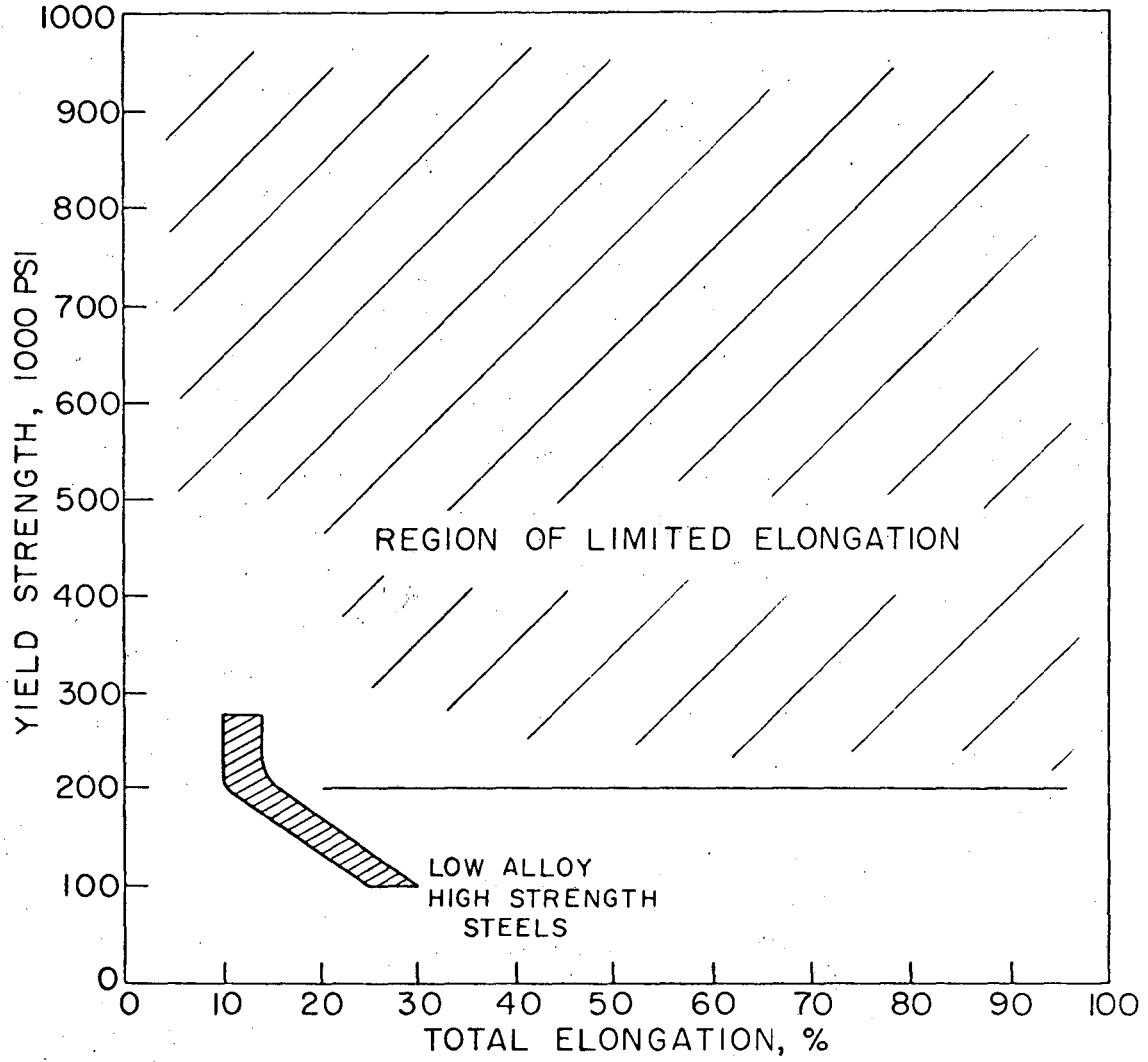
Fig. 3 The trend in Federal funding for each of the different types of research for the period 1954 to 1968. (Ref. 1)



XBL 6812-6439

Fig. 4 The actual dollar funding per fiscal year allotted for the operating and equipment budgets of the Division of Research, Atomic Energy Commission of the United States, is shown as a solid line. The actual dollar funding corrected for the escalation of costs is shown as a dashed line. The average escalation of costs per year is assumed to be three percent. (Ref. 2)





XBL 684-399-A

Fig. 5 The relation between yield strength and elongation for low alloy high strength steels

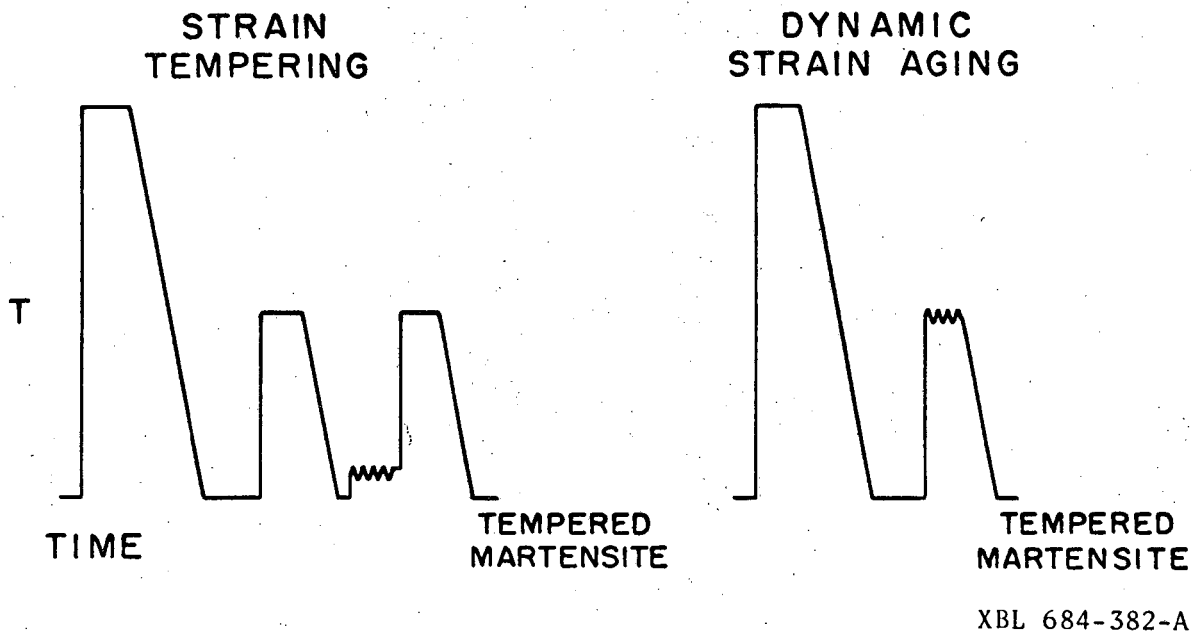
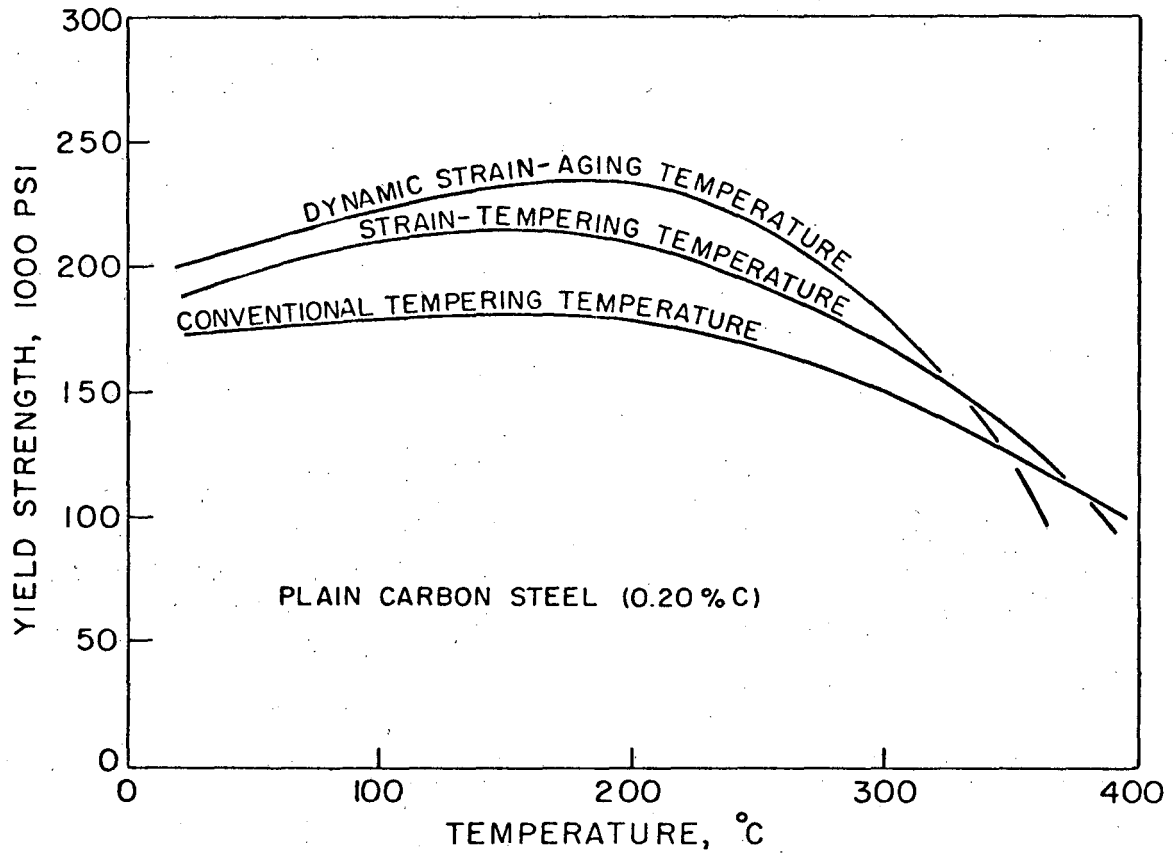
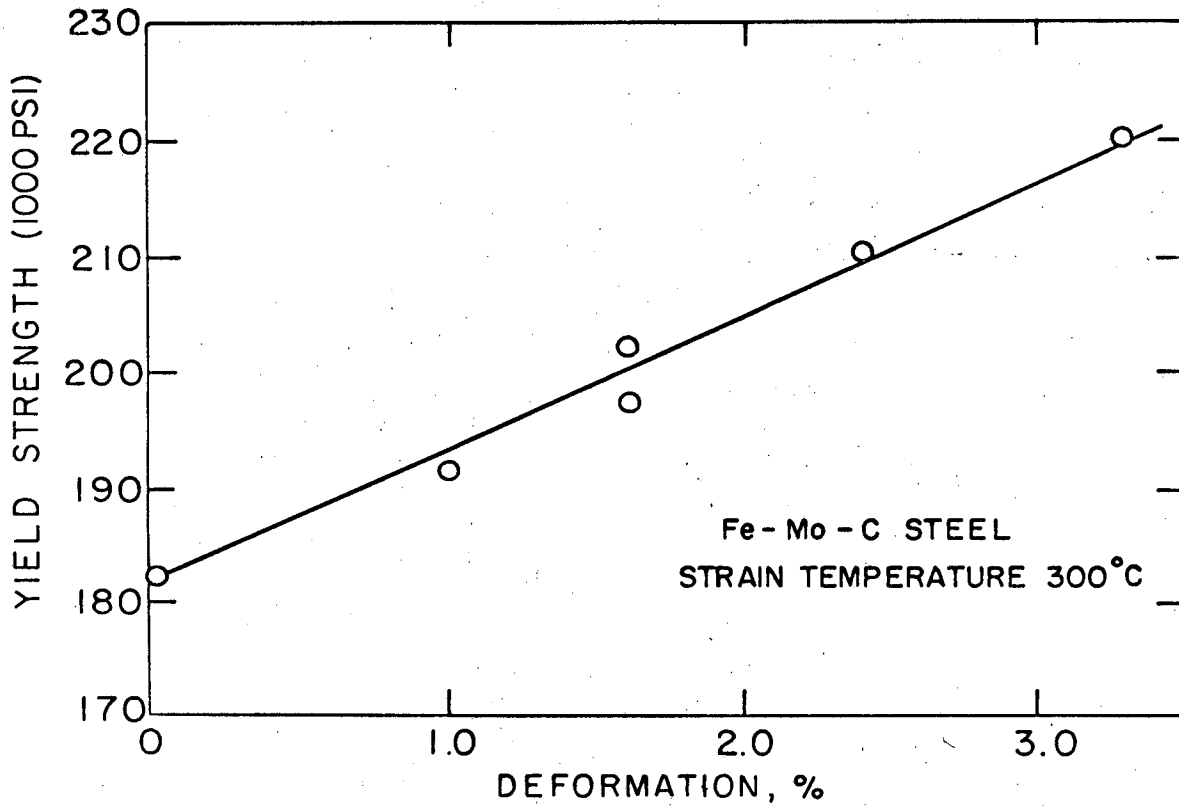


Fig. 6 Schematic time-temperature-deformation diagrams of two similar thermomechanical processes - strain tempering and dynamic strain aging



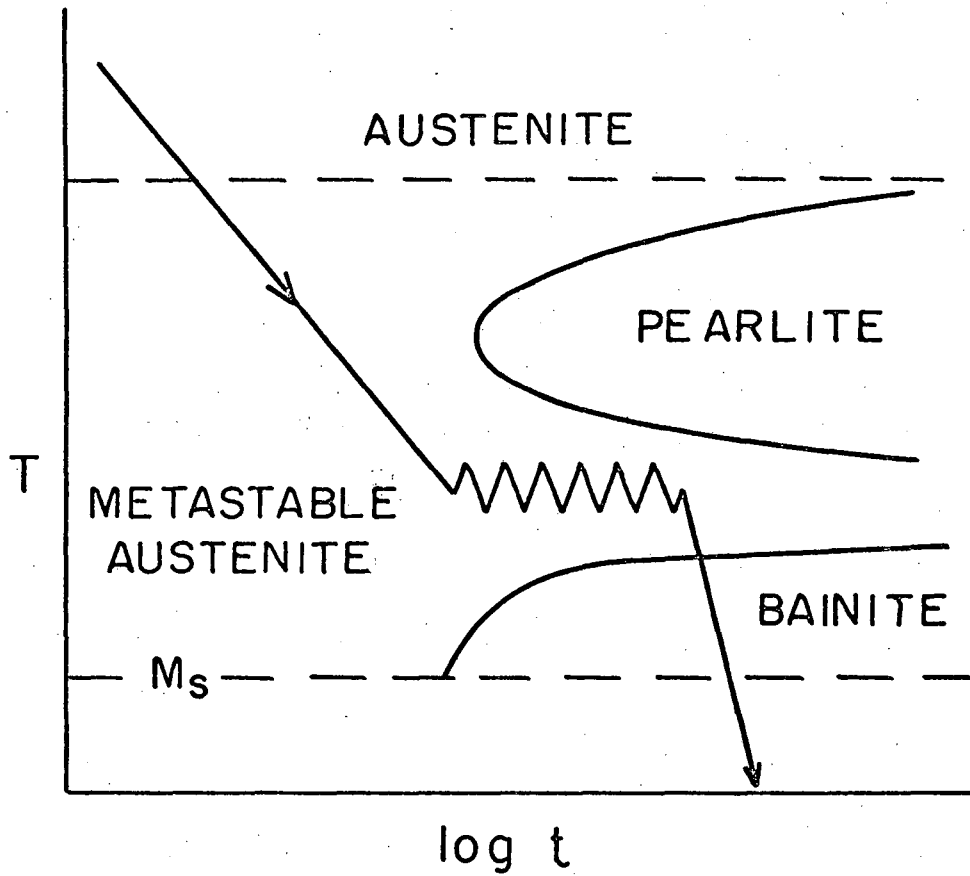
XBL 6812-6440

Fig. 7 The variation in strength with processing temperature of a plain carbon (0.20%) steel for the processes of quenching and tempering, strain tempering, and dynamic strain aging. The amount of deformation for the latter two processes was two percent



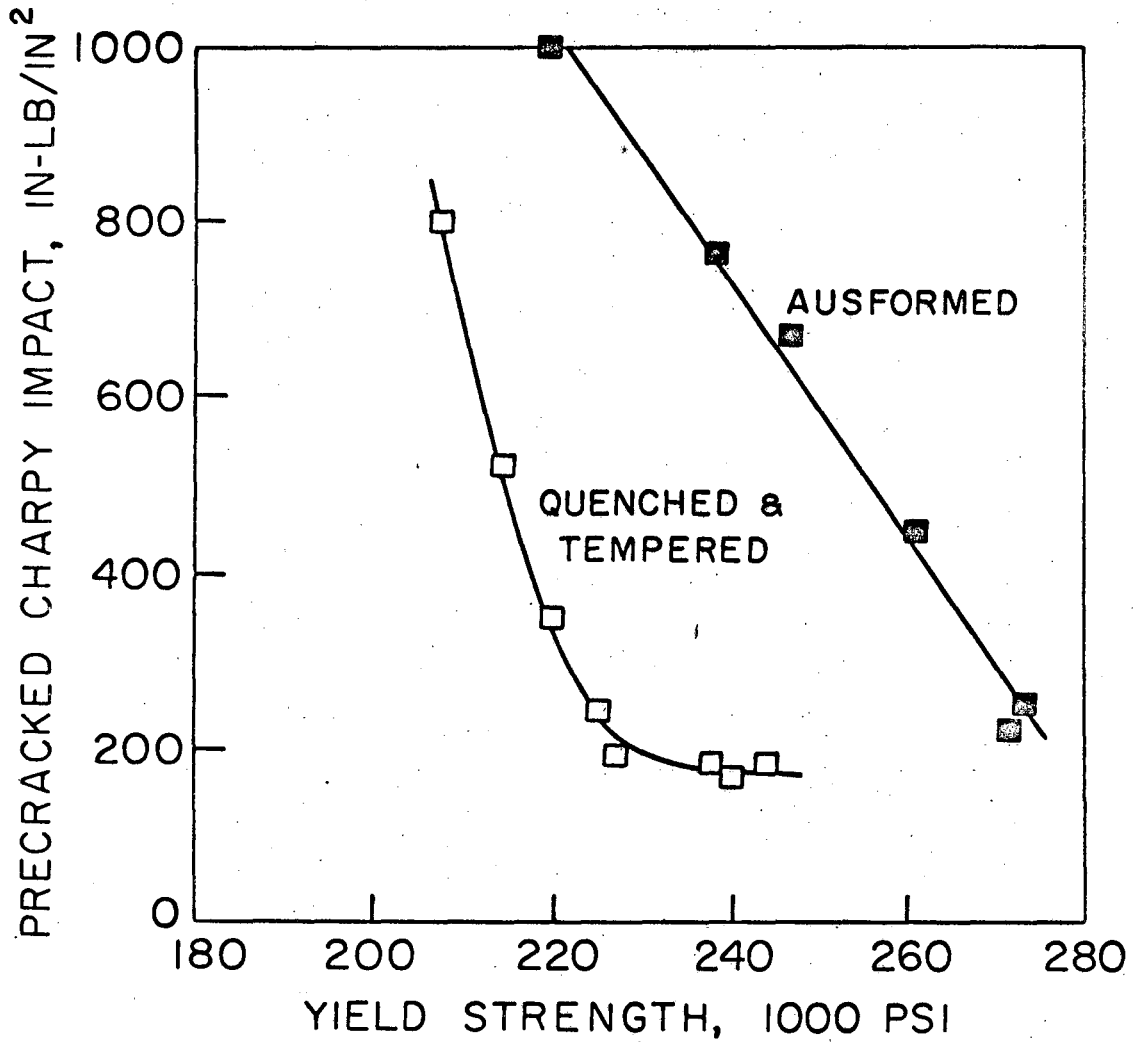
XBL 684-407-A

Fig. 8 The effect of the amount of deformation on the yield strength of a dynamic strain aged Fe-Mo-C (p. 20%) steel



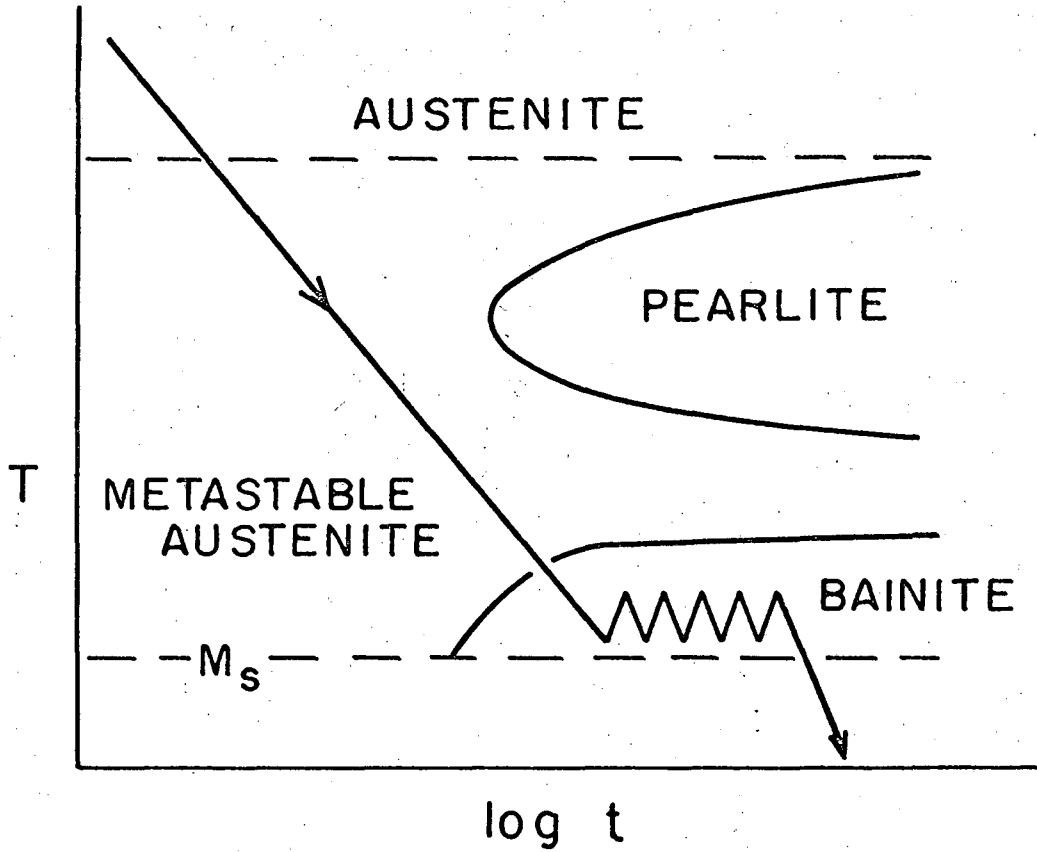
XBL 684-384-A

Fig. 9 A schematic time-temperature-deformation diagram of the ausform process



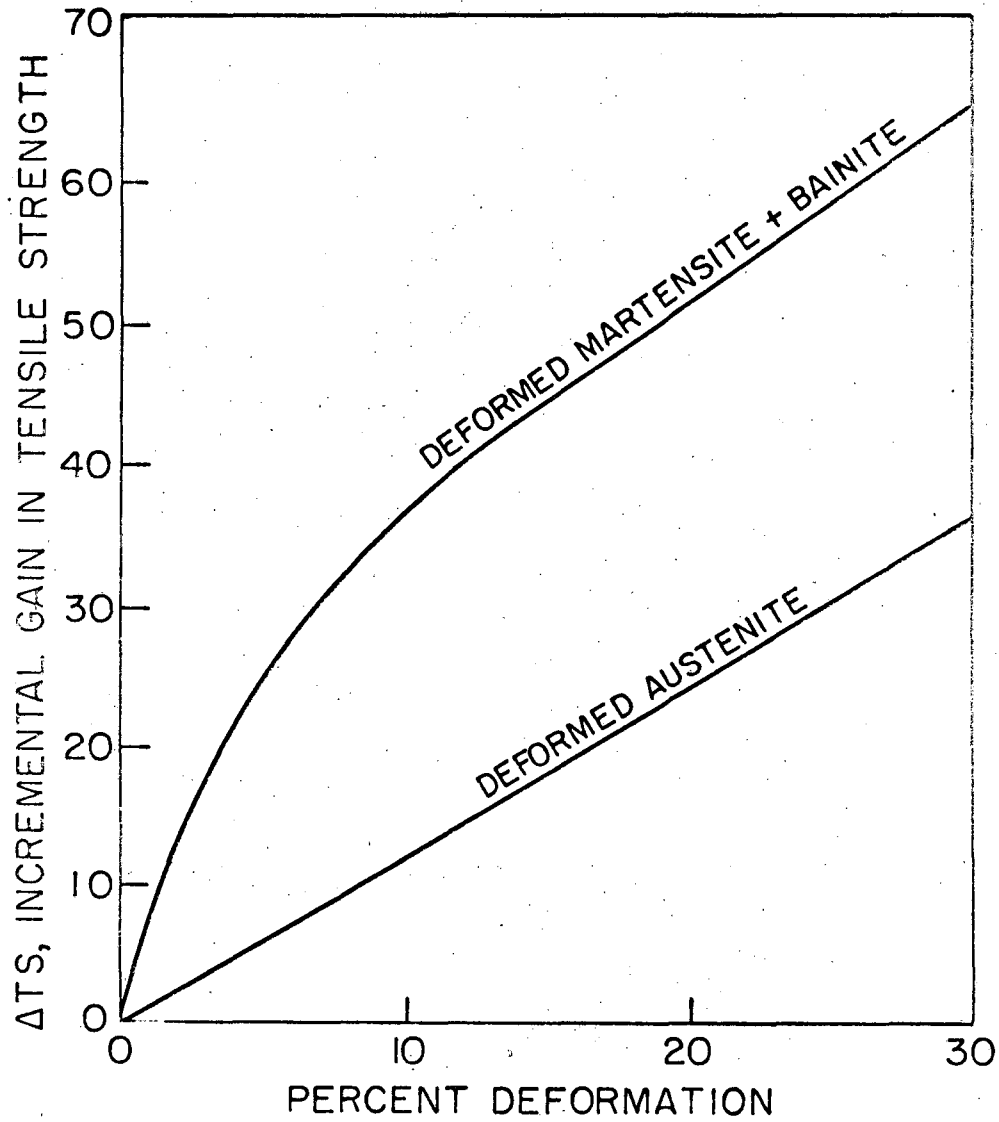
XBL 684-388

Fig. 10 The variation in impact toughness (pre-cracked Charpy specimens) with yield strength of a low alloy steel (Ladish D6aC) for the quenched and tempered and for the ausformed steels. The data of this figure are taken from the work of Ault et al. (11). The nominal composition (%) of Ladish D6aC steel is as follows: 1.00Cr, 1.00Mo, 0.75Mn, 0.65Ni, 0.20Si, 0.10V and 0.40C



XBL 684-385-A

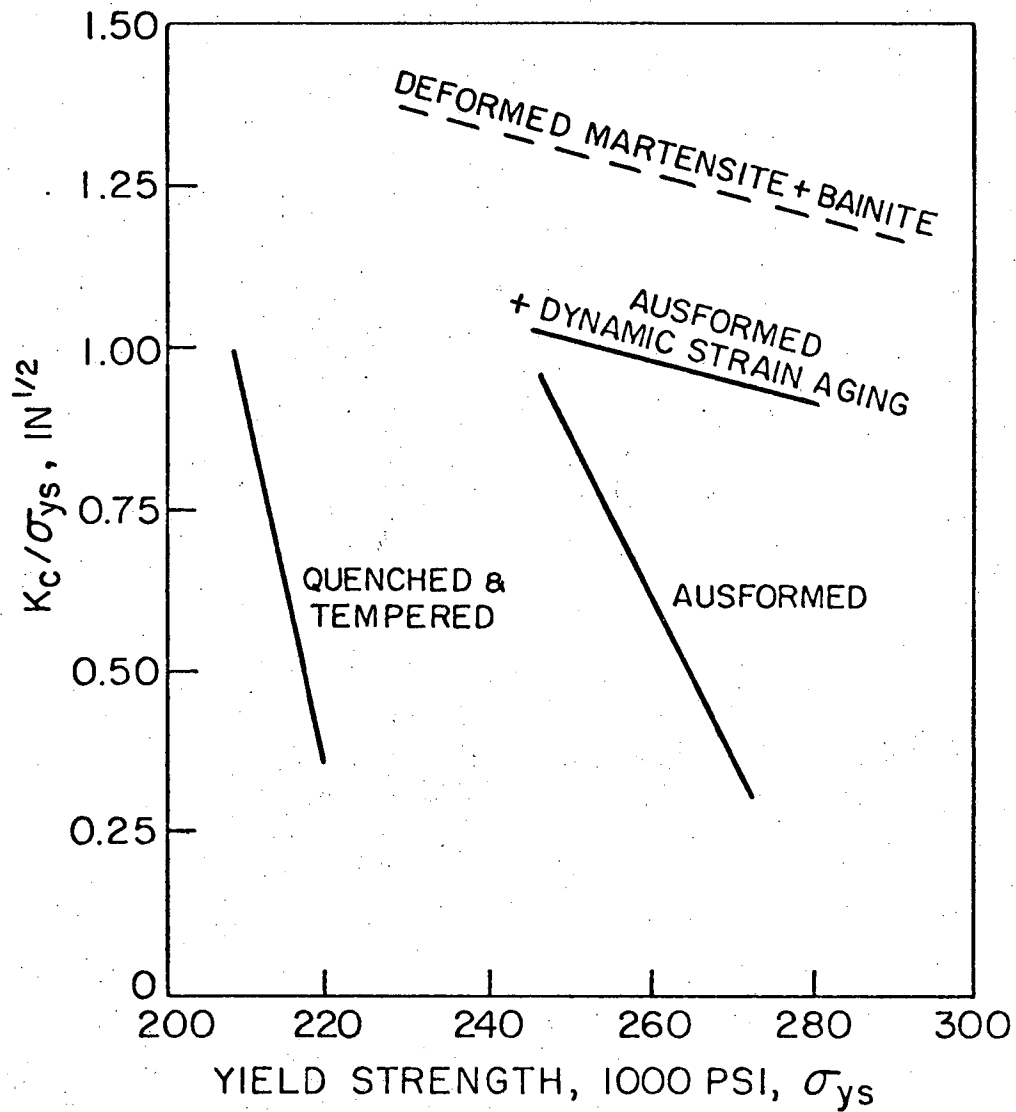
Fig. 11 A schematic time-temperature-deformation diagram of the thermomechanical process which produces bainite and martensite



XBL 6812-6442

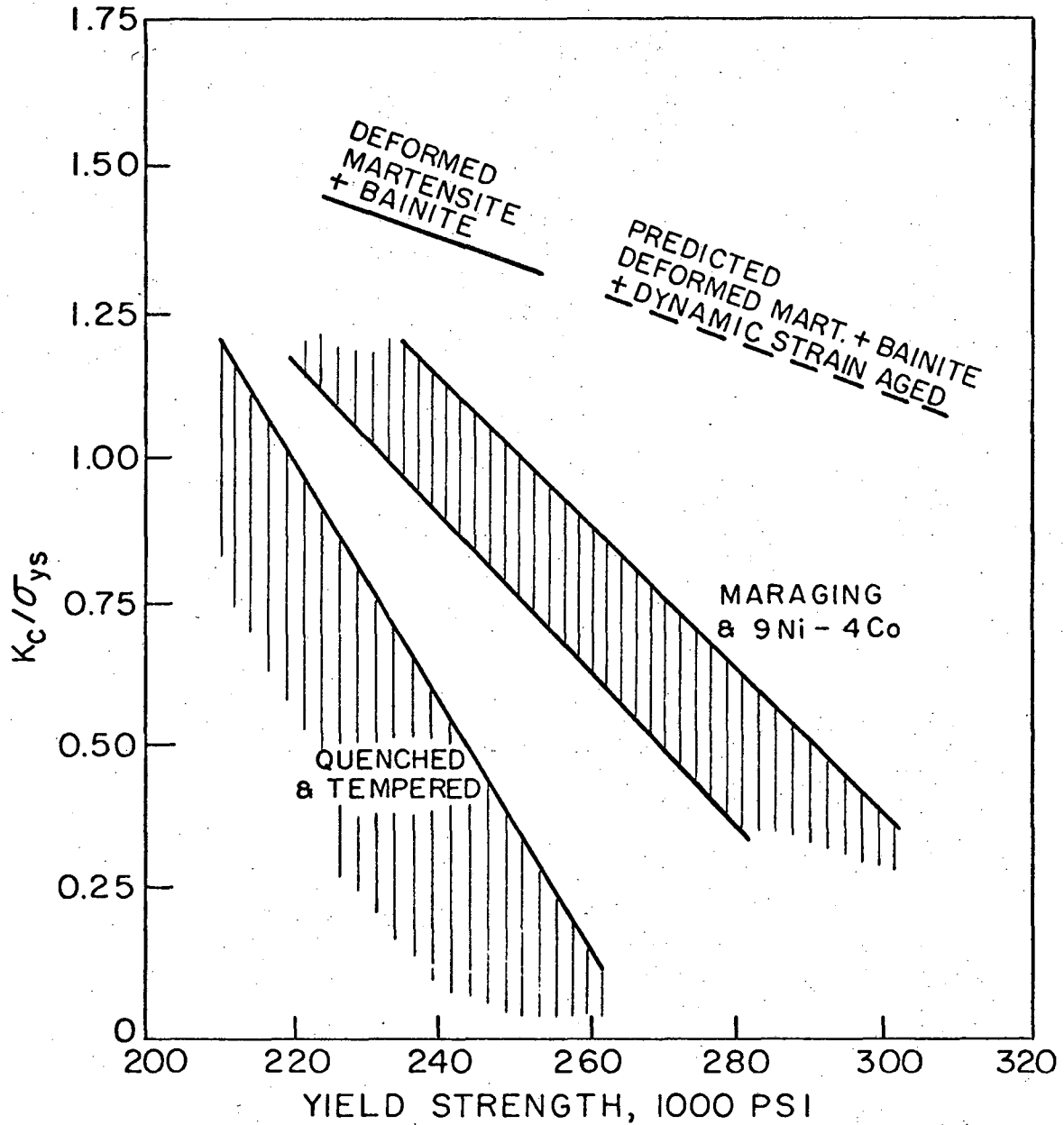
Fig. 12 The incremental gain in tensile strength ( $\Delta TS$ ) with percent deformation for austempered steel and a thermomechanically processed austenite-bainite mixture of the same steel





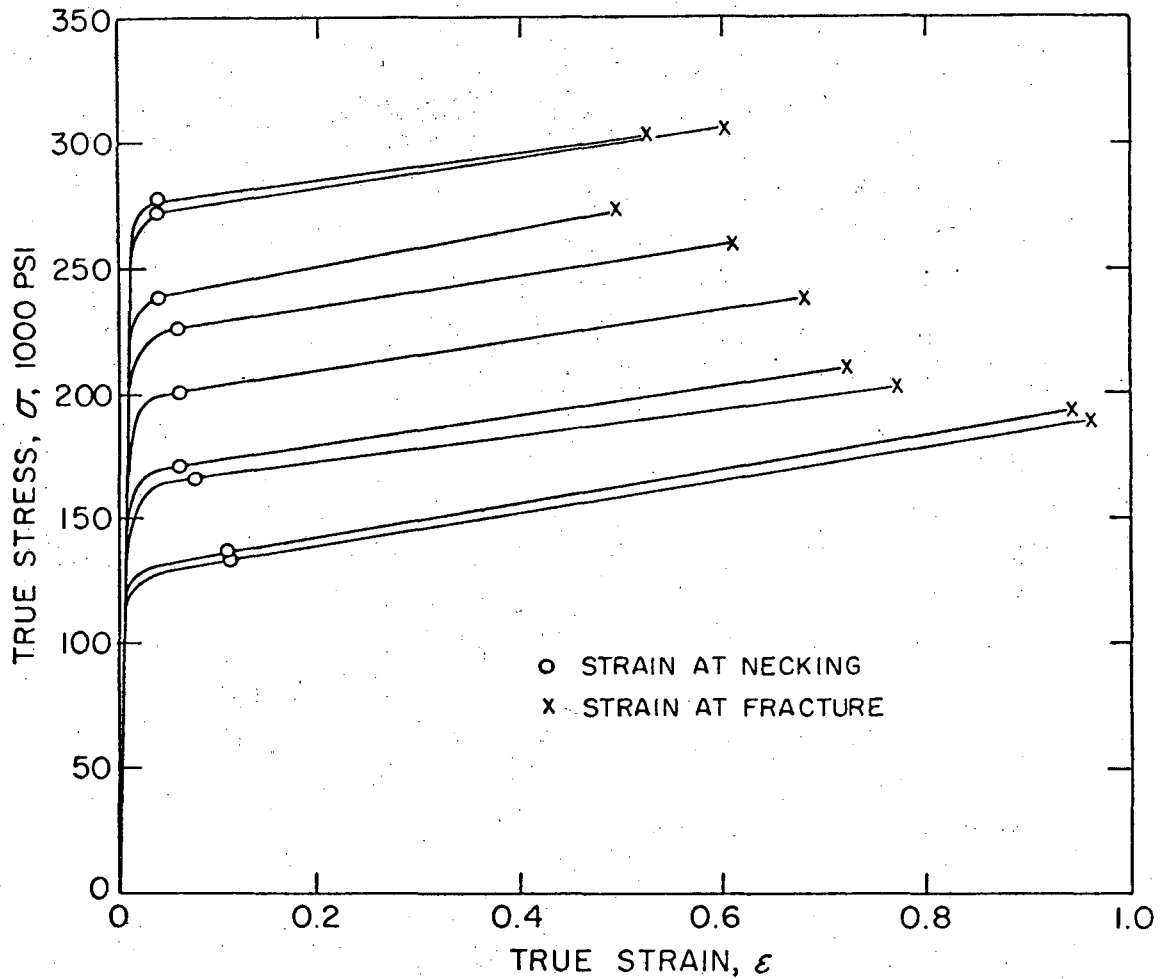
XBL 6812-6443

Fig. 13 The variation of the ratio,  $K_c/\sigma_{y.s.}$ , with yield strength,  $\sigma_{y.s.}$ , of a low alloy steel (Ladish D6aC) given both conventional and thermomechanical processing. Data taken from the work of Gerberich et al. (10)



XBL 6812-6441

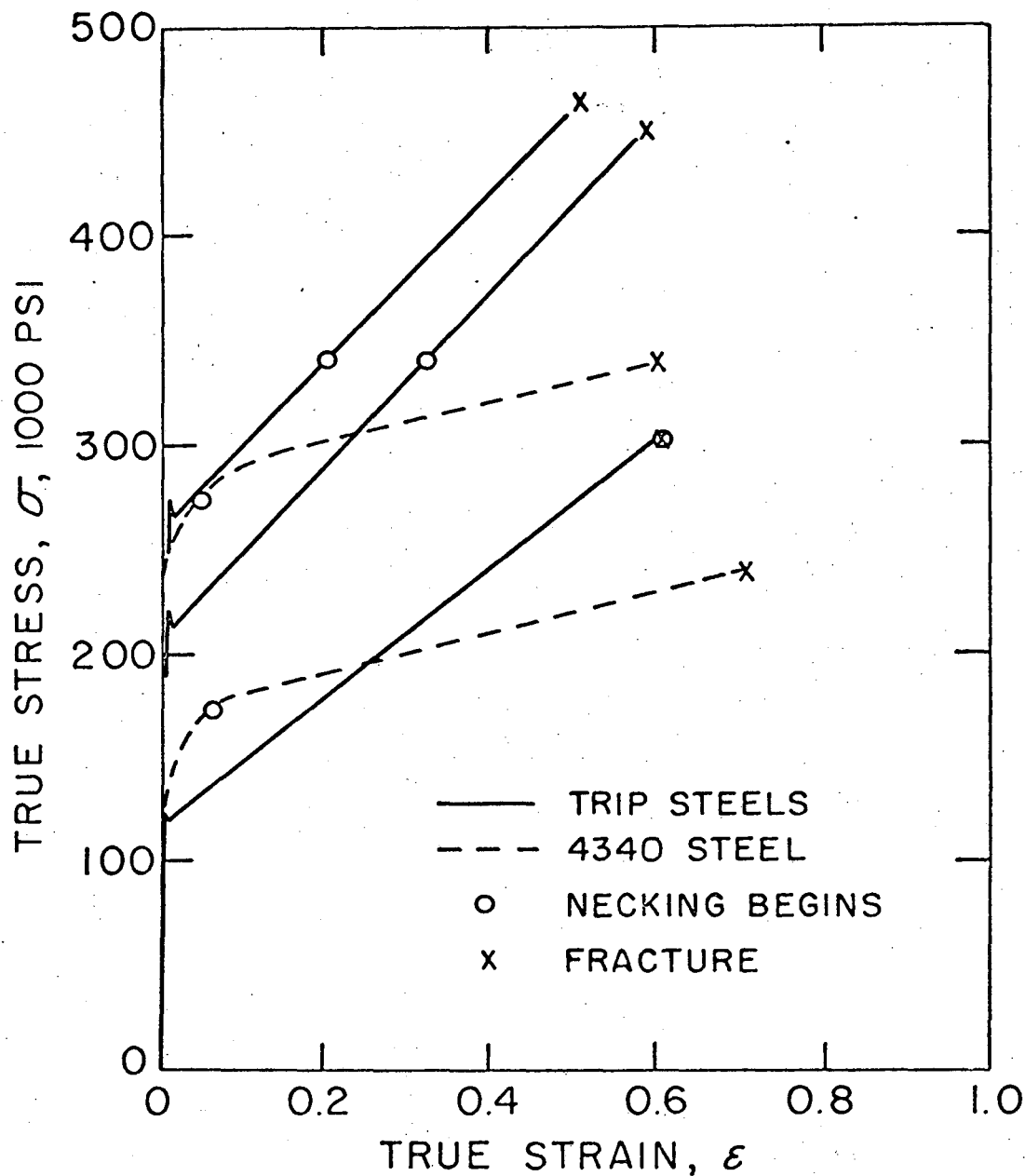
Fig. 14 The variation of the ratio,  $K_c/\sigma_{ys}$ , with yield strength of quenched and tempered, maraging and 9Ni-4Co steels. The predicted relationship of  $K_c/\sigma_{ys}$  vs  $\sigma_{ys}$  is shown as a dashed line for a steel subjected to a combination of thermo-mechanical processes.



XBL 670-5027-A

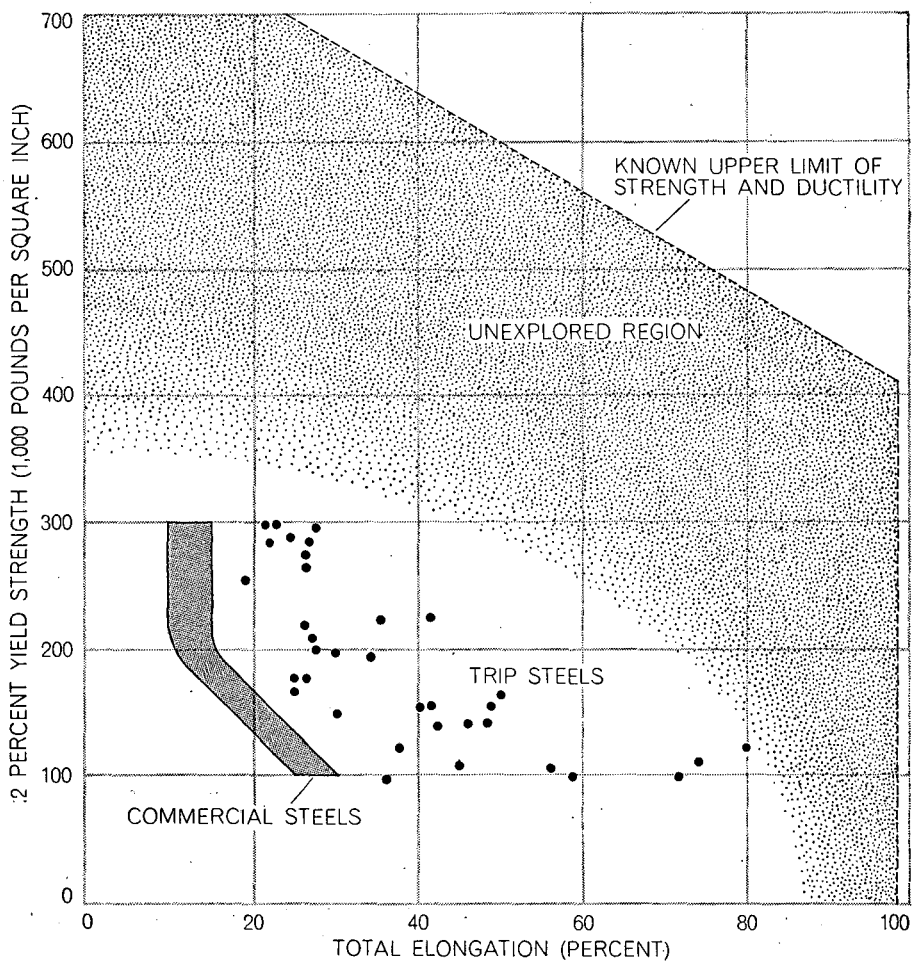
Fig. 15 The true-stress-true strain curves of a quenched and tempered steel (A.I.S.I. 4340) heat treated to produce several yield strengths. Taken from the work of Larson and Nunes. (Ref. 16)





XBL 670-5028-A

Fig. 17 True stress-true strain curves of TRIP steels and of a quenched and tempered steel (A.I.S.I. 4340) at comparable yield strengths.



XBL 6812-6444

Fig. 18 The relation between yield strength and elongation for low alloy high strength steels and for TRIP steels. The known upper limit of strength and ductility is shown as a dotted line in the upper half of the figure. Taken from the work of Parker et al. (Ref. 19)

LEGAL NOTICE

*This report was prepared as an account of Government sponsored work. Neither the United States, nor the Commission, nor any person acting on behalf of the Commission:*

- A. Makes any warranty or representation, expressed or implied, with respect to the accuracy, completeness, or usefulness of the information contained in this report, or that the use of any information, apparatus, method, or process disclosed in this report may not infringe privately owned rights; or*
- B. Assumes any liabilities with respect to the use of, or for damages resulting from the use of any information, apparatus, method, or process disclosed in this report.*

*As used in the above, "person acting on behalf of the Commission" includes any employee or contractor of the Commission, or employee of such contractor, to the extent that such employee or contractor of the Commission, or employee of such contractor prepares, disseminates, or provides access to, any information pursuant to his employment or contract with the Commission, or his employment with such contractor.*

TECHNICAL INFORMATION DIVISION  
LAWRENCE RADIATION LABORATORY  
UNIVERSITY OF CALIFORNIA  
BERKELEY, CALIFORNIA 94720