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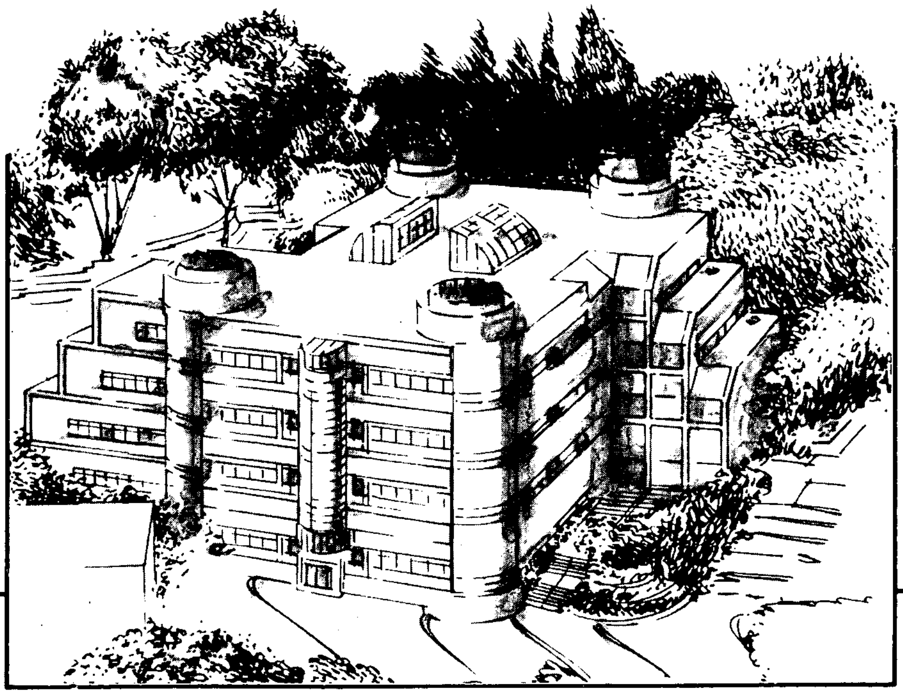

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THE SCIENCE OF THERMOMECHANICAL PROCESSING

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ABSTRACT

This paper provides a brief overview of thermomechanical processing: treatments that combine heat and mechanical work to achieve microstructures that impart useful engineering properties. Thermomechanical processes can be catagorized on the basis of the primary microstructural element they affect, as is done below.

1. INTRODUCTION

The term *thermomechanical processing* describes materials processing treatments that combine thermal exposure and mechanical work. There are literally hundreds of such treatments in everyday use in the processing of engineering alloys. The thermomechanical processing of low alloy steels is treated in detail in some detail in the recent book by Tamura, Ouchi, Tanaka and Sekine(1), which is a very good introduction to the subject as a whole. Descriptions of thermomechanical processes of other classes of materials are scattered through the literature.

Given the wide variety in both the nature and objectives of the thermomechanical processing treatments used in modern industry, there is no possibility of describing or even summarizing them in this brief paper. What I have instead tried to do is to lay out a simple organizational framework in which many of the common thermomechanical processing techniques can be understood in terms of their metallurgical objectives. The scheme given here is only one of several that are useful. Some alternatives are discussed in the book by Tamura, et al.(1).

2. THE NATURE OF PROCESSING

The essence of Materials Science is contained in two sentences: (1) The properties of a material are determined by its composition and its microstructure. (2) The microstructure of a material is determined by its composition and by the processing it has received. While one processes a material to achieve a set of engineering properties, the relation between processing and properties is indirect. The direct effect of processing is to change the microstructure, so it is useful to analyze and classify processing techniques in terms of the microstructural changes they bring about.

A given thermomechanical process may be used to control very different sets of properties in different materials, since the dominant effect of a given microstructural change on the engineering properties of a material depends on both the nature of the material and how it is used. For example, recrystallization is often used to achieve a fine, equiaxed grain structure in an engineering alloy. But a fine, equiaxed microstructure is needed for different reasons in different materials. In low-carbon steel this microstructure imparts high strength and mechanical isotropy. In alloy steel plate it is used to lower the ductile-brittle transition. In Pb, Al and Ti alloys, among others, a fine, equiaxed grain structure leads to superplastic behavior at intermediate temperature and facilitates forming. In each case the same process accomplishes essentially the same microstructural change, but with very different consequences for the important engineering properties. The microstructure-processing relation controls the microstructural change; the microstructure-property relation for the particular material controls the associated change in properties.

3. MICROSTRUCTURE

The most important elements of the microstructure of an engineering alloy are its crystal structure, its grain structure, the distribution of second-phase precipitates or inclusions, the dislocation density and distribution, and the nature and distribution of any chemical heterogeneities within nominally single-phase regions.

The *crystal structure* is fixed by the phase of the material. If the alloy has only one crystalline phase, as, for example, aluminum does, then the matrix crystal structure is beyond the influence of processing. However, many important engineering alloys, such as steel and titanium, have multiple crystal structures whose appearance and fraction are controlled by a combination of composition and processing. Many important alloys, such as eutectic solders, contain two or more phases in significant volume fraction. The fraction, shape and distribution of these can be controlled.

Almost all engineering alloys are polygranular, and their properties are strongly influenced by details of the *grain structure*. The important features of the grain structure include not only the grain size, but also the grain shape and the crystallographic *texture*, or preferential orientation of the crystal axes of the individual grains.

Most engineering alloys contain minority second-phase particles, which include unwanted voids or *inclusions* that intrude during solidification and solid-state *precipitates* that are intentionally introduced. The size and distribution of these strongly influence the properties, and are often controlled by thermomechanical processing.

All engineering alloys contain *dislocations* which strongly influence their strength, ductility and toughness, and often affect their chemical stability. Both the density and distribution of dislocations depend on the thermomechanical history; deformation introduces dislocations, exposure to high temperature permits their elimination through recovery or recrystallization.

Finally, many engineering alloys contain *chemical heterogeneities* in the distribution of alloying or impurity species within nominally single-phase regions. Non-equilibrium solidification phenomena result in chemical heterogeneities in almost all as-cast materials. Phenomena such as grain-boundary segregation can create heterogeneities in homogenized material during processing or service.

The purpose of thermomechanical processing is to manipulate these microstructural elements into a morphology that imparts desirable engineering properties. The simplest and most common of the thermomechanical processes are intended to control the grain structure. We consider these first.

4. THE GRAIN STRUCTURE

The most familiar thermomechanical processes are used to control the grain structure. The *grain size* can be adjusted through recrystallization treatments, in which an alloy is mechanically worked at a relatively high temperature (or subsequently heated) so that new, defect-free grains form and grow to release the free energy stored during mechanical deformation. The new grains ordinarily nucleate at prior grain boundaries, although they may also form at deformation bands or severely worked regions in the grain interior. Since there are usually multiple nucleation events in each prior grain the recrystallized grain size is much finer than that of the parent structure. Increasing the extent of deformation ordinarily helps to refine the grain size. Plastic deformation "pancakes" the grains, increasing the area of grain boundary, and also increases the nucleation rate by providing preferential deformation sites at boundary or internal regions of severe deformation. It is often useful or necessary to cool the alloy rapidly after recrystallization to preserve a fine grain size since recrystallized grains coarsen rapidly at high temperature.

In most commercial processes recrystallization is accomplished continuously by rolling or forging at a temperature high enough to induce recrystallization. The fine grain size can be preserved by using a water table or air blast to quench the material on-line as soon as recrystallization is complete.

The fine, equiaxed grains that are produced by recrystallization are useful for many different purposes in different alloys. Since yield strength is inversely proportional to grain size, alloys such as low-carbon steels and stainless steels are recrystallized to control strength. The grain size also controls the ductile-brittle transition temperature in BCC materials, such as ferritic steels, that fracture in a transgranular mode below T_B; these alloys are recrystallized to suppress the brittle transition. Other materials, such as Pb, Al and Ti alloys, can be formed superplastically if the grain boundary area is large enough to permit rapid creep by grain boundary sliding. These materials are recrystallized to create a sufficiently fine grain size.(2)

The *grain shape* is also controllable by thermomechanical processing. Recrystallization produces equiaxed grains. Rolling below the recrystallization temperature deforms the grains into flat, pancake-shaped figures in the plane of the plate or sheet, while drawing creates fiber-shaped grains along the axis of the bar or wire. Since the ease and degree of deformation that can be introduced in practice increases with the temperature, grain shaping treatments are usually done at the highest practical temperature below the recrystallization temperature. (In ferritic steels the two-phase $\alpha+\gamma$ region also influences the choice of warm-working temperature.)

Grain shaping treatments are particularly useful in materials that have relatively weak grain boundaries, and are used to control failure by intergranular fracture. The intent is sometimes to inhibit intergranular fracture, and sometimes to promote it. In advanced aerospace aluminum alloys, such as the Al-Li alloys that are now coming into use, the grains are severely pancaked so that the intergranular crack path perpendicular to a plate or sheet is as tortuous as possible, increasing toughness for loading in the longitudinal and long-transverse directions(3). In some pipeline steels the grains are pancaked to promote delamination in the plane of the plate when the alloy is subjected to a fracture load. This treatment ordinarily lowers the upper-shelf toughness of the material, but also lowers the ductile-brittle transition temperature since transverse delamination decreases the triaxiality of loading at a crack tip. Similar treatments are used to improve the fatigue resistance of aluminum alloys and high-temperature superalloys, since growing fatigue cracks preferentially follow the weak, planar grain boundaries and are deflected out of the plane of maximum stress.

Finally, the *grain texture*, or crystallographic alignment between adjacent grains, is controllable by thermomechanical processing. Texture is controllable in several different ways. A preferential texture invariably develops during deformation, with a type and degree that depend on the symmetry and temperature of the deformation as well as on the composition of the alloy. A different preferential texture often appears after recrystallization or annealing treatments. By combining selected deformation treatments with recrystallization or annealing steps it is often possible to fine-tune the texture to preselected values.

Crystallographic texture strongly influences the anisotropy of material properties, including both mechanical and electromagnetic properties. Texture control is, hence, particularly important in the processing of formable sheet and electromagnetic materials such as transformer steels. In the case of alloys that are intended for deep drawing, such as aluminum can stock(4), deformation texture introduces a plastic anisotropy that results in "earing" during drawing. This texture can be compensated by the distinct recrystallization texture to create a balanced material that draws uniformly. In transformer steels such as Fe-Si grades, the material is textured by a combination of deformation and annealing to orient the easy directions for magnitization and minimize eddy current losses.

5. THE PRECIPITATE STRUCTURE

The second most common use of thermomechanical processing is to control the precipitate or inclusion structure. In the most usual case deformation is used before the precipitation reaction to improve the *precipitate distribution.* Plastic deformation produces a dense distribution of dislocations that introduce preferential nucleation sites into the alloy, and facilitate the formation of a homogeneous distribution of fine precipitates that is conducive to hardening. Prior deformation is particularly useful to ensure the uniformity of the precipitate field, particularly in the immediate vicinity of grain boundaries. In the absence of effective heterogeneous nucleation sites in the matrix, preferential nucleation on the boundary itself may lead to a denuded, *precipitate-free zone* along the boundary which is harmful to properties. The most common mechanical treatments that precede precipitation are hot rolling or forging. In aluminum alloys precipitation is often best conditioned by a cold stretch of the alloy(5). Prior plastic deformation may also improve the kinetics of precipitation if the deformation-induced defects increase the effective diffusivity. The improved kinetics may permit aging at lower temperature, which minimizes the risk of unwanted changes in the microstructure.

A fine distribution of strengthening precipitates optimizes alloy strength. A homogeneous distribution eliminates precipitate-free zones along the grain boundaries, which maximizes toughness and may improve other properties, such as resistance to stress-corrosion cracking.

An important variant of this thermomechanical processing sequence is used in high-strength, low-alloy steels, particularly those which are alloyed with niobium. As the alloy is cooled during or after hot-rolling the phase transforms from γ (FCC) to α (BCC), predominantly by a "ledge" mechanism in which the α phase grows by adding sub-micron ledges to its surface. As carbon is rejected from the α phase, in which it is less soluble, niobium carbides nucleate at the interface to form a dense distribution of fine precipitates in planar sheets. By controlling the rolling deformation of the steel prior to and during the transformation it is possible to achieve engineering control over both the grain structure and precipitate distribution. Given the commercial importance of this class of steels the technology of thermomechanical processing is well developed, and many variations of the basic treatment have been developed.

In other thermomechanical treatments the precipitation reaction precedes plastic deformation. Straightforward but important examples include the use of mechanical work to break up inclusions in as-cast material before final processing, and the use of hot isostatic pressing (hip) to seal voids in superplastically formed sheet and drawn multifilamentary superconducting wire. The intent is to improve toughness by refining inclusions and eliminating pre-existing voids that might otherwise act as crack or void nucleation sites. In the case of superconducting wire the voids are mechanically sealed to improve both mechanical properties and critical current characteristics.

More sophisticated techniques are exploited, for example, in the processing of superplastic aluminum alloys, where a dense distribution of thermally stable precipitates is introduced before deformation to preserve a fine grain size during superplastic forming. In eutectic alloys deformation is used to accelerate break-up of the eutectic lamellae. Deformation followed by recrystallization is used to achieve the fine, stable two-phase grain structure that is characteristic of many of the best superplastic materials. Still another sophisticated use of thermomechanical processing is in the treatment of ductile, ultra-high carbon steels, which are alternately deformed in the one-phase γ region of the phase diagram and cooled into the two-phase α + carbide field to achieve a very fine-grained α structure with a dense intermixture of fine carbide grains. While the treatment seems modern and complex, its developers believe that it underlay the excellent properties of the Damascus steels that were used for weapons in medieval times.(6)

In these cases the intent is to achieve a very fine grain size that is retained during high-temperature deformation, so that the material can be formed in the superplastic condition without excessive grain growth that would cause a loss of superplastic properties. In the case of the high-carbon steel the intent is to utilize the strength imparted by the very high carbon level while retaining useful toughness.

6. DISLOCATION STRUCTURE

Thermomechanical treatments are also used to control the *dislocation structure* within and alloy. An important simple example is the use of alternate drawing and annealing steps in the manufacture of high-strength wire. The mechanical deformation introduced during drawing hardens the wire. However, the wire must be softened periodically by a recovery anneal so that it can be drawn to the requisite fineness. The ultimate strength of the wire is controlled by adjusting the degree of deformation in the final pass.

The distribution of dislocations within a material is often sensitive to both the temperature and degree of deformation. In most alloys high-temperature deformation produces an ordered distribution in which the dislocations lie in well-defined cells, while low-temperature deformation creates a more random and homogeneous distribution. Thermomechanical sequences can thus be designed to control the dislocation distribution, for example, to provide an optimal template for subsequent precipitation.

Exceptionally high dislocation densities, and hence exceptionally high strength, can be obtained by the rapid deformation of materials that have controlled distributions of precipitates to act as barriers to dislocation flow. An example is the very high, homogeneous density of dislocations that can be attained by explosive forming of precipitation-hardened materials.

7. CHEMICAL DISTRIBUTION

Thermomechanical treatments can also be used to facilitate homogenization of single-phase materials that contain chemical heterogeneities, for example, from non-equilibrium segregation during solidification. As-solidified castings are often forged or rolled prior to homogenization treatments. The mechanical deformation helps to break up and disperse regions of strong chemical segregation, and also provides a distribution of residual defects that may accelerate homogenization by increasing the rate of diffusion.

Thermomechanical processing can also help reduce embrittlement due to grain boundary segregation in materials that contain deleterious impurities that segregate to grain boundaries. Among the useful treatments are recrystallization and deformation treatments that create grains with serrated grain boundaries that are difficult to fracture even when weakened by impurities, and deformation treatments that form plate-like grain with high aspect ratio, and offer no continuous intergranular fracture path perpendicular to the plane of the plate.

8. CRYSTAL STRUCTURE

Finally, thermomechanical treatments can be used to control the crystal structure or distribution of structure in an alloy that has more than one possible phase. The classic example is the use of deformation to control the martensite transformation in steel. Since the martensite transformation involves significant mechanical strain, it couples strongly to deformation and to the defect structure within the material. The martensitic transformation is initiated on cooling at the martensite start temperature, M_s. However, the martensite transformation is triggered by plastic deformation at any temperature below the higher temperature, M_d, which may lie several hundred degrees above M_s. Moreover, both M_s and M_d are affected (and usually lowered) by prior deformation above M_d. Hence thermomechanical treatments can be designed to introduce martensite in alloys with M_s below ambient temperature, suppress martensite in alloys with M_s above room temperature, and control the tendency for martensite to appear in mechanical deformation during service. Since the presence of martensite increases the strength of an alloy, and its formation during mechanical deformation influences both work hardening and toughness, the control of the martensite transformation makes it possible to influence alloy properties.

A particular use of deformation to control the martensitic transformation is the adaptation of intercritical rolling to produce *dual-phase* steels that contain fine admixtures of martensite and ferrite. Mechanically deforming a steel within the two-phase ($\alpha+\gamma$) intercritical region leads to fine grains of ferrite (α) that form at preferential nucleation sites in the heavily deformed γ. At the same time, deformation and chemical segregation of the γ phase stabilizes the phase so that it eventually transforms martensitically at a much lower temperature. The result is a dual-phase mixture of relatively soft ferrite and relative hard, fresh martensite, that has a high ultimate strength and excellent ductility.

A final example of the use of thermomechanical processing to control the phase transformation in steel concerns the grain refinement of steels that are intended for cryogenic service. To have an exceptionally low ductile-brittle transition temperature the alloy should have a fine effective grain size. While there are a number of ways of achieving ultrafine grain size through thermal cycling treatments, one of the most efficient approaches is to mechanically work the alloy in the α state, then heat it into the two-phase $\alpha + \gamma$ region. The deformation structure within the α produces nucleation sites for the γ phase, which loses its crystallographic registry with the surrounding α. When the material is re-cooled the γ reverts to α, creating an ultrafine microstructure with excellent cryogenic properties.

9. CONCLUSION

The above are a few examples of the many ways in which thermomechanical treatments are used to control the microstructure and, consequently, the properties of engineering alloys.

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REFERENCES

1. I. Tamura, C. Ouchi, T. Tanaka, H. Sekine, *Thermomechanical Processing of High Strength Low Alloy Steel*, Butterworths, London 1988
2. F.A. Mohamed, M. Mahmet, T.G. Langdon, Met. Trans., 8, 933 (1977)
3. J. Glazer, S. Verzasconi, E. Dalder, W. Yu, R. Emigh, R. Ritchie, J.W. Morris, Jr., Adv. Cryo. Eng., 32, 397 (1986)
4. R. E. Sanders, F.A. Baumann, H.S. Stumpf, in *Aluminum Alloys, Physican and Mechanical Properties*, E.A. Starke and T.H. Sanders, eds., EMAS, Warley, U.K., Vol. III, p. 1441 (1986)
5. R.J. Rioja, P.E. Bretz, R.R. Sawtell, W.H. Hunt and W. Ludwiczak, *ibid*, p. 1781
6. O.D. Sherby, T.Yama, D.W. Kum, B. Walser, J. Wadsworth, J. Metals, 11, 50 (1986)

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