

Thermo Mechanical Treatment

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A paper by Lips and Zulian¹ in 1964 was the forerunner of a new route - that of thermo mechanical treatment of steels. Today industrially adopted thermo mechanical treatment of steels is actually a departure in many ways from the original classical methods. An attempt will be made to throw some light on the conventional processes; following which a brief overview of the treatments given in the present day will be made. In the latter portion attention will be paid to thermo-mechanical control processing (TMCP) that comprises both controlled rolling as well as combined with accelerated cooling.

1.0 CONVENTIONAL THERMO-MECHANICAL TREATMENT (TMT) OF STEELS

In thermo mechanical treatment of steels, one would have to start with the concept of austenite decomposition as a function of time and temperature i.e. the isothermal transformation (IT). On the basis of such concepts a classification may be attempted as given in Table I.

In classification Ia, austenite is deformed in a temperature range where it is stable, just above A_{r3} (Fig.1); or additions can be made to the steels that inhibit re-crystallisation of austenite. Such alloying elements could be V, Nb or Ti so that rolling could be done at a higher temperature without re-crystallisation. The transformation takes place in deformed, unrecrystallised austenite. Investigations have shown that if radical changes in properties are needed, deformation must be severe. After transformation in such a situation, the properties are directional, and there is a pronounced texture in the main product, i.e. martensite. Some

of the prominent textures in original austenite and in martensite formed through such measures of treatments are given below :

In Austenite, Copper Texture $\longrightarrow \{124\}\langle 112 \rangle$

In Martensite $\longrightarrow (112) + (111)$.

The presence of 112 texture in the quenched and tempered steels used in armoured plates can increase the ballistic limit by about 15%. The ballistic limit describes the maximum impact velocity of a standard projectile that a plate can withstand without penetration. The improvement due to the texture is explained with the help of a high modulus of elasticity in a direction normal to the plate surface and to an increased yield strength in compression in the through-thickness direction².

In classification 1b, the austenite re-crystallises to a fine, equiaxed structure. The grain size is smaller than that is obtained in conventional austenising, quenching and tempering. The mechanical properties are mostly isotropic after transformation.

The flow stress of the material after either 1a or 1b treatments is raised without any impairment to ductility this is attributed mostly to the refining in austenite grain size.

In treatment II the steel is deformed in the two-phase ferrite-austenite region. The process therefore is limited to hypo-eutectoid steels. Such deformation followed by quenching yields a structure of martensite in ferrite. Further, the properties are mostly directional. In some of the high strength low alloy (HSLA) steels, rolling in the two phase regime results in a splitting fracture due to enhanced banding and development of a strong (100)[100] texture in ferrite.

In the scheme of treatment III the thermo-mechanical treatment (TMT) is given below A_{r1} and therefore it is termed sub-critical TMT. It is necessary that the steel transforms slowly at the deformation temperature. Several medium carbon grade steels containing Cr are found to be suitable as they tend to have a "long bay" between the pearlite and bainite noses of the I-T diagram. In this "ausforming process" the yield and tensile strengths of the quenched and tempered martensite are proportional to the strain imparted to austenite. Strengthening is usually in the range of 5-10 MPa for each 1% of deformation. It is also found that

higher the initial yield, the greater is the strengthening. It is found that carbon levels should be between 0.05-0.10%, greater additions produce little effect. The presence of strong carbide forming elements promote increased strength.

There are several mechanisms that have been forwarded for explaining the strengthening in ausforming. Some of the broad changes in the martensite structure due to prior plastic deformation in the unstable austenite are :

- i) Refinement of martensite platelets.
- ii) Changes in the size, amount and distribution of carbides.
- iii) Possible changes in dislocation density
- iv) Development of textures.

The first mechanism is bound to take place with deformation of austenite. The second mechanism becomes prominent only in the presence of strong carbide formers such as Mo. The strengthening due to inheritance of higher number defects from austenite is open to some debate and in any case, the contributions may not be very high. There are also reports of a ductility improvement in the quenched plus tempered conditions. This is partly explained by the depletion of the matrix of carbon due to strain-induced carbide precipitation in the un-transformed austenite. Ausforming also is reported to make the steel resistant to tempering compared to conventionally treated steels.

In the scheme of treatment IIIb, steel is deformed during transformation to pearlite or bainite, as given in Fig.2. This is sometimes called, "isoforming" processes. The properties of the product (pearlite/bainite) are highly anisotropic. The process has been applied to stainless steels such as 301 and 304 varieties where straining is done at a temperature where martensite forms.

The process IIIc can be applied to pearlitic, bainitic or martensitic structures. There is a considerable static or dynamic strain ageing. The yield and tensile strengths increase with plastic strain; the amount of strain being low. The penalty is the low ductility and also decrease of uniform strain. Greater deformation (upto 10%) has been given by cold drawing rather than by uniaxial tension/compression.

Extremely high levels of strengths can be obtained by a combination of ausforming strain aging and Table 2 shows the same.

Treatment classified as IV is a contrasting process, where there is a sharp reduction of strength. Alloy steels are sometimes difficult to anneal when they contain substantial amounts of Mn or Ni that reduce AC_1 temperatures. One can also adopt a process to produce a dispersion of spheroidal carbides in a matrix of ferrites⁴.

1.1 Summary of the Classical TMT

These have not become popular⁵ by the industries except in the case of armoured plates. Some of the reasons are:

- i) Heavy deformation (greater than 50%) is necessary, therefore limiting most of the TMTs to smaller cross sections.
- ii) The mill load can be extremely high in some of the TMT processes.
- iii) Machining problems are there
- iv) Joining is difficult
- v) Anisotropy is encountered.
- vi) Cannot compete in cost in many cases.

2.0 THERMO-MECHANICAL CONTROL PROCESSING (TMCP)

Such processes have been in use for quite sometime now primarily to improve the strength and ductility in the high strength low alloy (HSLA) steels. TMCP consists of controlled rolling alone or control rolling and subsequent accelerated cooling⁶. The essence of controlled rolling lies in deformation of austenite in the unrecrystallized regime thereby producing increased ferrite "nucleation sites". The significance of accelerated cooling on the other hand lies in super cooling of the deformed austenite and thereby increasing ferrite "nucleation rate". The combination of controlled rolling and interrupted accelerated cooling is called thermo mechanical controlled processing (TMCP). Enhanced ferrite transformation at high temperature region and bainitic or martensitic transformation at low temperature region during TMCP gives a homogeneous fine grained structure. In Japan and other advanced countries, major plate mills have installed in-line accelerated cooling devices and are commercially producing TMCP steel plates. Such plates exhibit excellent low temperature toughness and superior weldability in terms of resistance to weld cracking and toughness of the heat affected

zone (HAZ). TMCP steels have been applied to ship hull structures, offshore structures and large diameter line pipes.

2.1 Basics of Phase Transformation During Controlled Rolling

Figure 3a shows various thermo mechanical processes superimposed on the CCT diagrams⁷. One can discern 3 stages in controlled rolling :

- i) Formation of Coarse Austenite grains;
- ii) Deformation in Non-Recrystallised Region;
- iii) Deformation in the 2-phase region.

Figure 3b shows the various stages of controlled rolling processes and changes in resultant micro structure. Broadly, the nucleation sites for ferrites are the crystalline defects. The effective austenite grain boundary area S_v has been related to the various defects in the structure. Figure 4 shows the different nucleation sites for the ferrite and the resultant ferrite grain structure in the hot rolled and heat treated steels, while Fig.5 shows the effect of micro alloying conditions on the recrystallisation stop temperature. It is also easier to conceive the influence of controlled rolling in terms of recrystallisation -temperature -time diagrams with precipitation-temperature time diagrams. This will demonstrate the efficacy of the carbides in preventing the recrystallisation.

2.2 Basic Aspects of Accelerated Cooling :

The controlled rolling process can usher in fine grain structure. However, it has its own disadvantages such as limitation in achieving grain refining, formation of mixed grain structure and anisotropy in properties. Accelerated cooling has been introduced in conjunction with controlled rolling in order to achieve further improvement in the ferrite grain structure. In a way it inherits the characteristic features of controlled rolling and exploits the advantages to the maximum.

In terms of industrial importance there are three processing variables : finish rolling temperature, finish cooling temperature and cooling rate. Fig.6 shows the influence of finish-cooling temperature on strength and brittle transition, the micro structural changes are quite wide and have been studied in great detail. As shown by solid line, yield strength increases gradually with decreasing temperature. The second phase changes from pearlite (P) to degenerated pearlite (DP) to lower bainite

(B). Broken lines show abrupt changes in yield strength by the formation of martensite. Preferred micro structure is ferrite interspersed with bainite islands. As shown in Fig.7 optimum strength-toughness balance is obtained when finish rolling temperature almost coincides with start-cooling temperature, i.e. A_{r3} . One of the major problems studies is the centre line segregation of alloying elements such as Mn, C, P and S during continuous casting. Plates inherit such segregation from the continuously cast slabs and finally lead to detrimental effects particularly of ductility and toughness in through-thickness direction. The degree of centre line segregation can be reduced by - (i) accelerated cooling, (ii) clean steel, (iii) reduction in slab thickness in continuous casting, (iv) combination of these.

Accelerated cooling exhibits more diffused segregation zones with lower carbon concentration at mid-thickness than controlled rolled steels as shown in Fig.8. Such steels eliminate the presence of pearlite band and coarse bainitic formation and enhances ferrite formation. Resistance to hydrogen induced cracking (HIC) is also improved.

3.0 CONCLUDING REMARKS

The basic idea of thermo mechanically controlled processing (TMCP) incorporating controlled rolling and accelerated cooling have proved beneficial in the case of high strength low alloy steel plates. Such processing are now being extended to wires and rods as well. When combined with other improvements in technologies e.g. cleaner steels & sulphide-shape control, TMCP technology can blossom into a very effective measure in improving strength and ductility as well as weldability.

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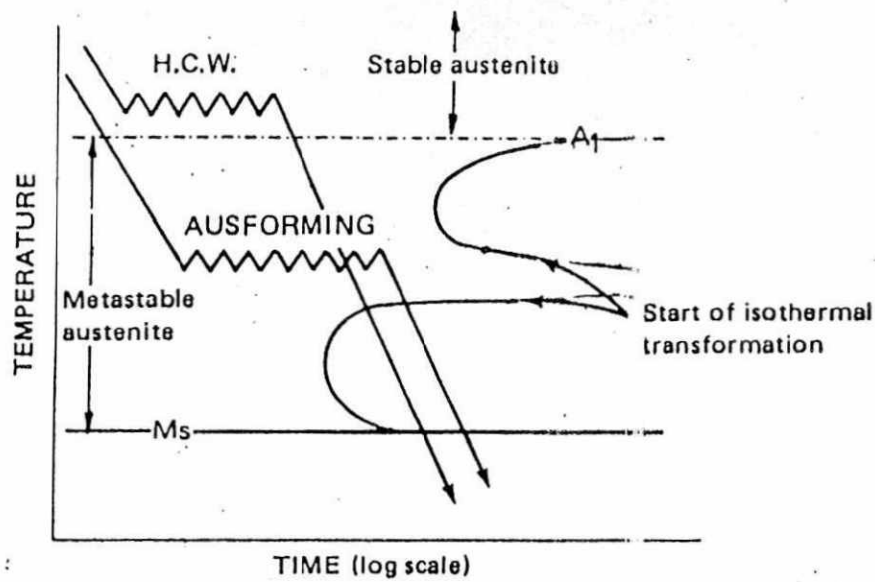


Figure 1. Schematic isothermal transformation diagram with thermal cycles for hot-cold working and ausforming operations. (V.F. Zachary, *J. Iron Steel Inst.*, 207:894 (1969),

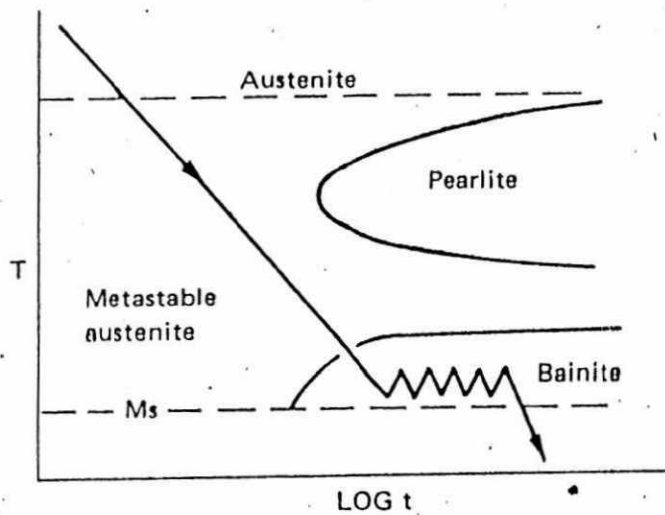


Figure 2. Schematic isothermal transformation diagram with thermal cycle for the isoforming process.

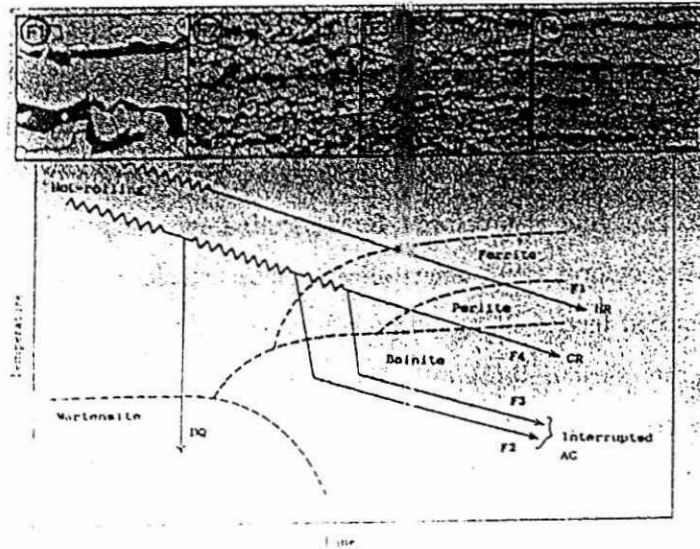


Figure 3(a) Various thermomechanical processings are superimposed on the CCT-diagram, where IR, CR, AC and DQ represent conventional hot rolling, controlled rolling, accelerated cooling and direct quenching, respectively. F1 shows microstructure in conventionally hot-rolled steel, F4 represents microstructure in controlled rolled steel, and F2 and F3 show microstructures in controlled rolled and subsequently accelerated cooled steel.

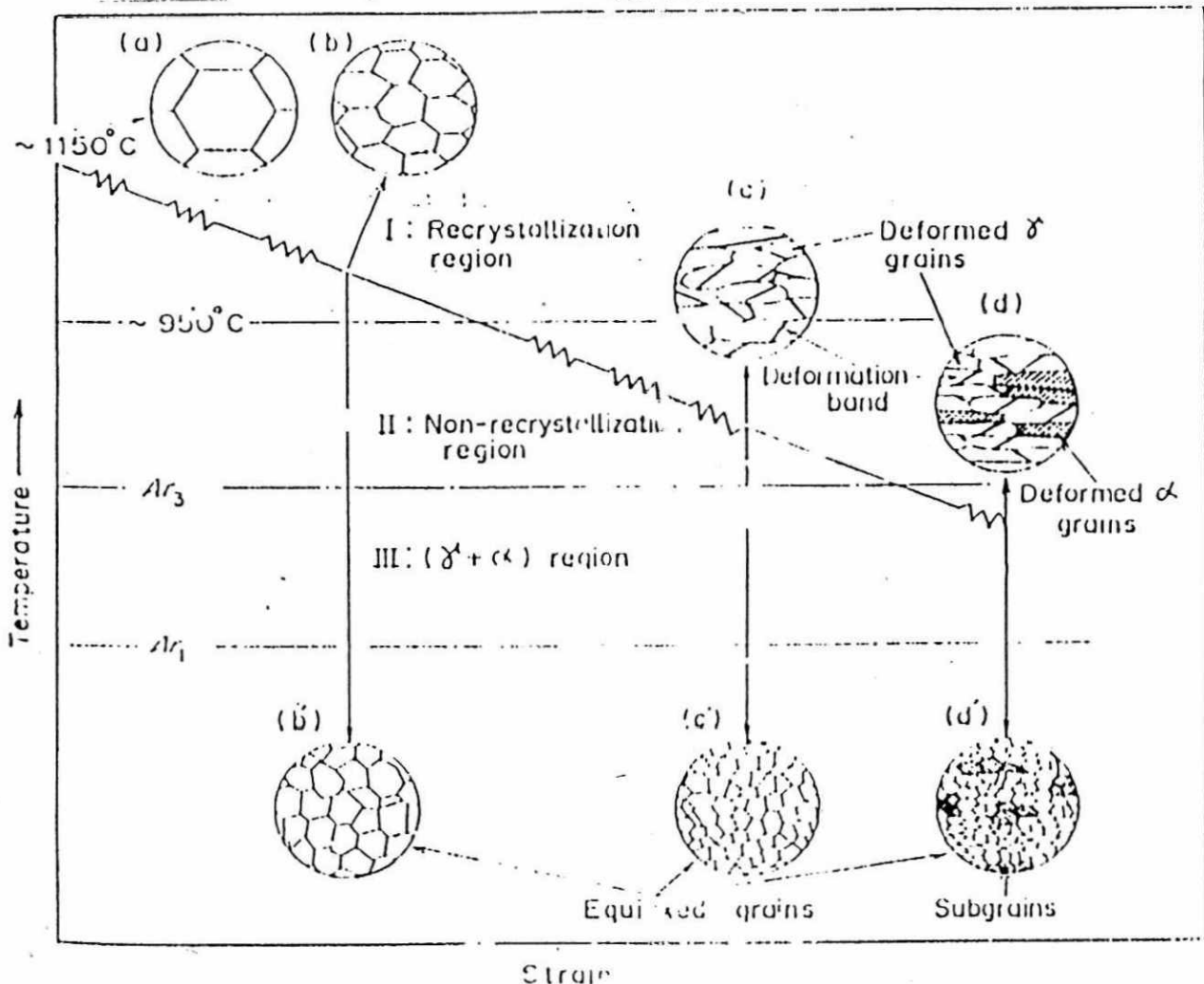


Figure 3(b) Schematic illustration of three stages of controlled rolling process and change in

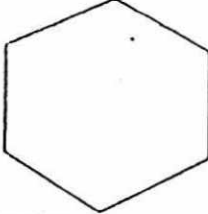
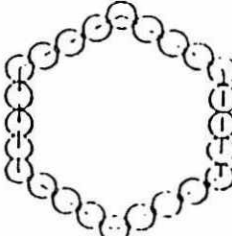
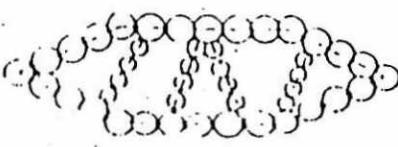
	Conventional hot-rolling	Controlled rolling	Normalizing	Quenching
γ grain structure		 Deformation band		
Nucleation of α grain				 Lath
α grain structure				 Cementite (Tempering)

Figure 4. . Nucleation sites for α grains and resulting α grain structures in hot-rolled and heat-treated steels. (After Tanaka)

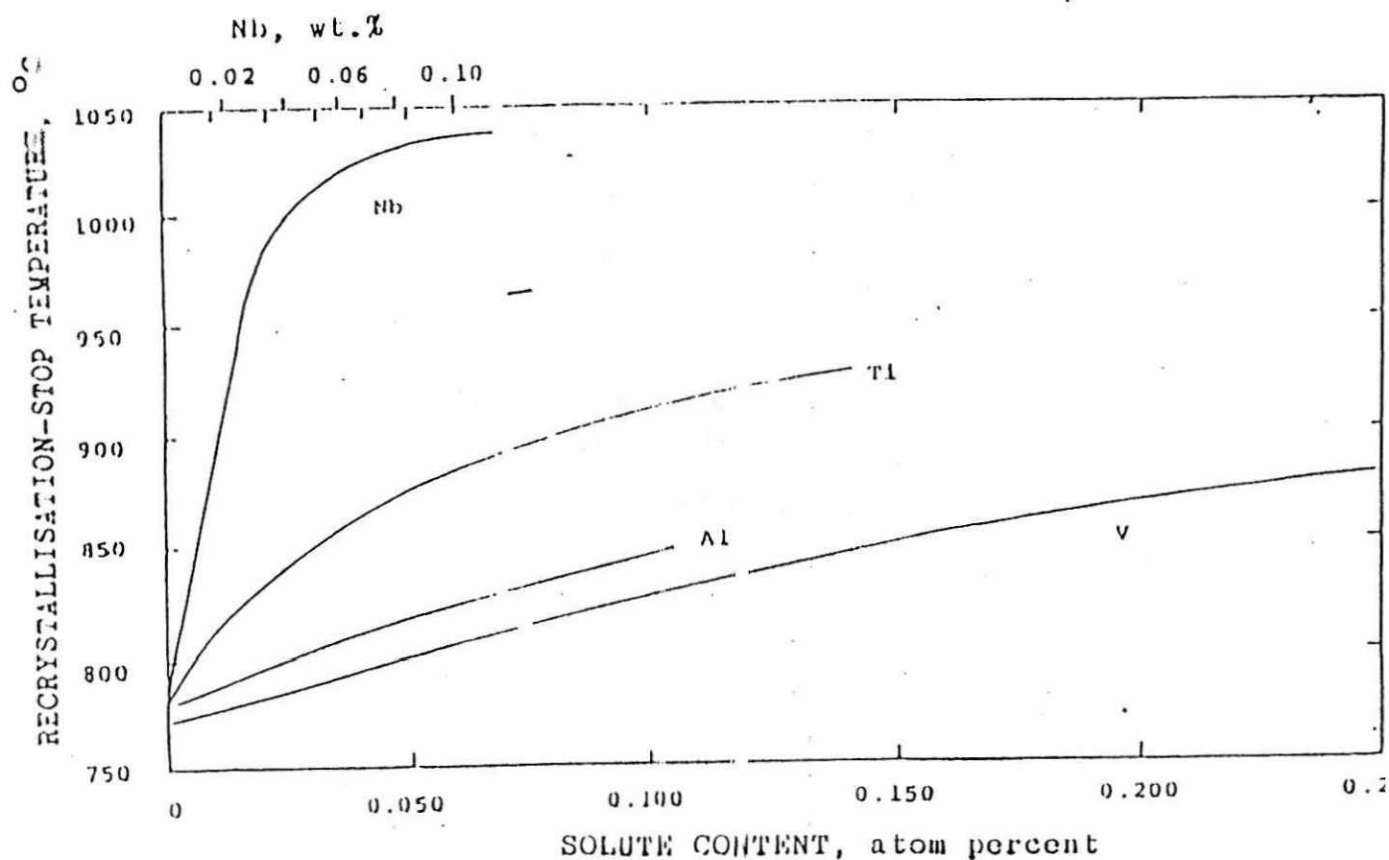


FIG. 5 EFFECT OF TYPE AND CONCENTRATION OF VARIOUS MICROALLOY ADDITIONS ON THE RECRYSTALLISATION-STOP TEMPERATURES (INTERPASS TIME:10 SECONDS).

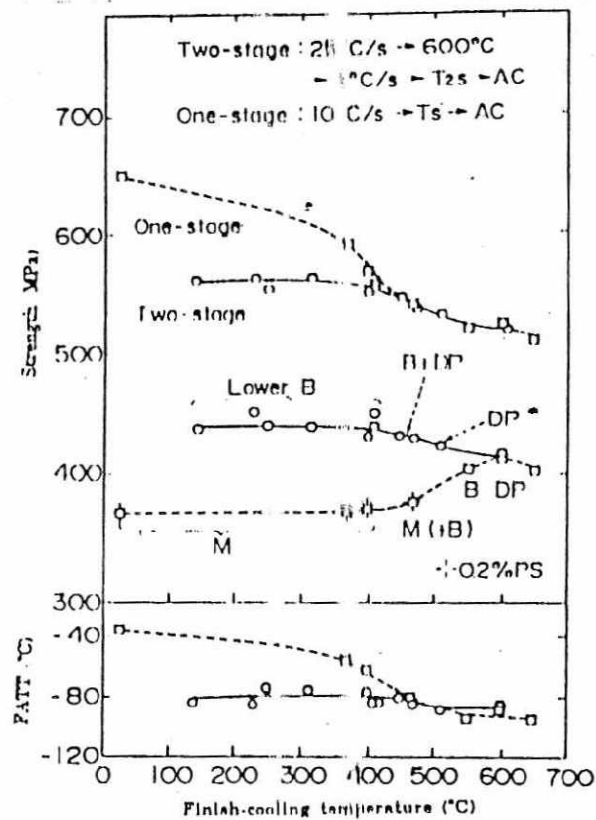


Figure 6. Strength and transition temperature are plotted versus finish-cooling temperature : two cooling methods were employed

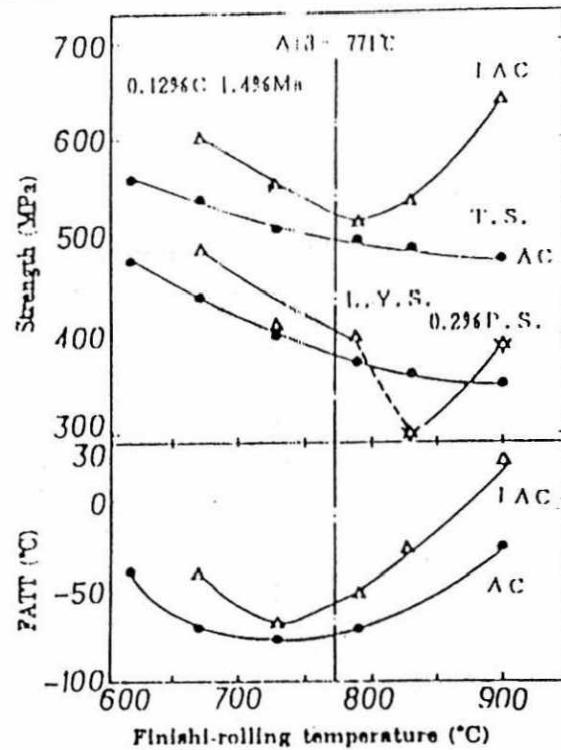


Figure 7: Strengths and transition temperature plotted against finish-rolling temperature in 0.12% C-1.4% Mn steel, which was air-cooled or accelerated cooled after hot-rolling; 0.2% proof stress instead of lower yield point is adopted in steel exhibiting round stress strain curve

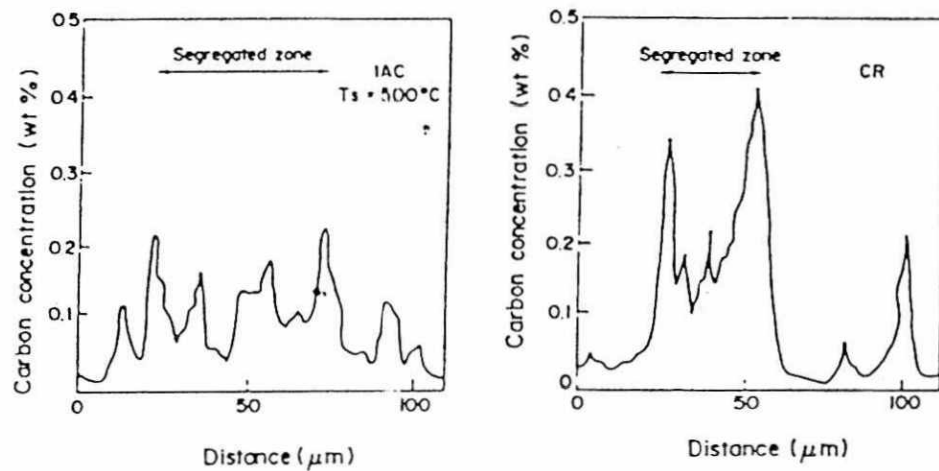


Figure 8: Distribution of carbon concentration in segregated zone at midthickness of 0.08% C-1.3% Mn steel plate revealed by ion mass analyser: (a) accelerated cooled with stop-cooling temperature of 500°C, and (b) controlled-rolled

Table 1 Classification of thermomechanical treatments

I.	Supercritical TMT (above A_{c1})
a.	Without recrystallization (hot-cold work, high-temperature TMT)
b.	With recrystallization (controlled hot rolling, high-temperature TMT)
II.	Intercritical TMT (between A_{c1} and A_{c2})
III.	Subcritical TMT (below A_{c1})
a.	Prior to transformation (ausforming, ausworking, ausrolling, low-temperature TMT)
b.	During transformation (isoforming)
c.	After transformation
IV.	Thermomechanical annealing

**Table 2 Effects of combined thermomechanical treatments¹
(0.6%C-5%Ni)**

Treatment	0.2% Offset yield strength (MPa)	Tensile strength (MPa)
1. Conventional, quenched, tempered 120°C	1800	2280
2. Hot-cold worked, quenched, tempered 120°C	2720	3070
3. 1 + 3% strain, aged 120°C	2450	2520
4. Hot-cold worked, quenched, tempered strain 3%, aged 120°C	3590	3630