THERMOMECHANICAL PROCESSING OF METALS AND ALLOYS

S. Ghosh Chowdhury and V. Rajinikanth
National Metallurgical Laboratory, Jamshedpur 831007
e-mail : sgc@nmlindia.org

For commercial products in any industry, their external shapes are the result of hot deformation i.e. hot rolling. The necessary mechanical properties are deduced from the alloy design and through heat treatment after hot-deformation. Thermomechanical processing (TMP) is a technique designed to improve the mechanical properties of materials by controlling the hot-deformation processes, which originally were designed to produce the required external final shape of the product. The first introduction of TMP for commercial production was controlled rolling of C-Mn steel plates of 40kgf/mm^2 grade for ship-building in the 1950s. During the World War II, a number of transport ships, so-called 'Liberty' ships suffered from the occurrence of brittle fractures initiated at welded joints. This incident stimulated the concept of toughness, which is different from the concept of ductility, and notch toughness became a requirement for ship-building and other structural steel plates. At that time, the concept of ductile-brittle transition temperature through grain refinement was introduced. It was reported that an improvement of about 10-15°C in the 20J transition temperature could be possible through controlled low temperature hot-rolling process.

Research on precipitation hardening in the as-rolled or normalized condition, and in controlled-rolled Nb- or V-containing steels was carried out in the 1960s. A remarkable strengthening by Nb or V additions was caused by either precipitation of fine planar Nb_{CN} or V_N coherent with the a matrix. The precipitates were formed on <100> planes of ferrite matrix during and after transformations.

The role of controlled rolling is to introduce a high density of nucleation sites for a grains in the g matrix during transformation by controlling the hot-rolling conditions. This is in order to refine the structure of the steel after transformation. The most critical factor in rolling conditions to have a controlled austenite structure is the hot deformation temperature. Normal rolling, which does not involve any control of the rolling conditions, usually finishes at 900-1000°C according

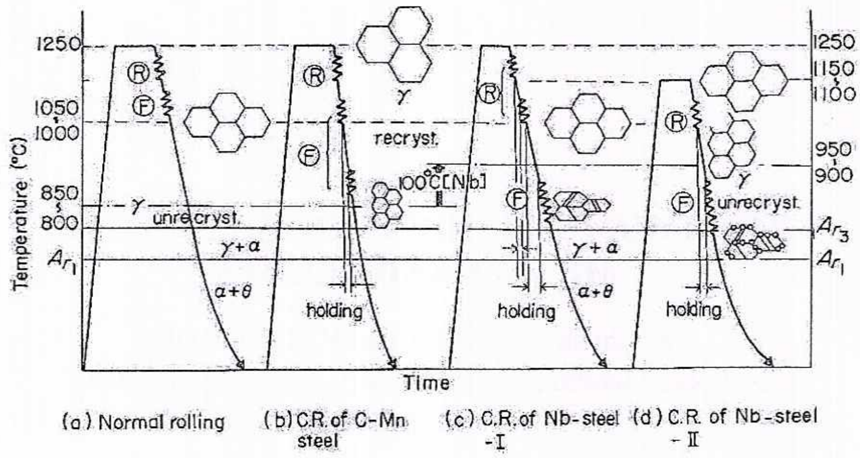

Fig.1 : Development of controlled rolling (a) normal rolling; (b) controlled-rolling of C - Mn steels; (c) controlled-rolling of Nb steels; (d) controlled-rolling of Nb steels (II)

to the plate thickness, as shown in Fig. 1(a). In the controlled rolling of simple C-Mn steels which do not contain any element retarding the recrystallization of γ, recrystallized γ grains are refined by performing several hot deformations in the final stage of rolling at the lowest temperature (800-950°C) in the range where recrystallization of γ grains can occur. The refinement of the a grains is achieved by the transformation from the fine grained γ structure (Fig. 1(b)). The addition of Nb raises the recrystallization temperature by about 100°C. The types of a nucleation sites other than γ grain boundaries, which are introduced by reductions in the non-recrystallization temperature range are activated twin boundaries and the deformation bands. The density of these interfaces and their activity as a nucleation sites including elongated γ-grain boundaries are increased by increasing the total reduction in the non-recrystallization temperature range. In the controlled rolling of Nb bearing steels, a certain amount of the γ-grain refinement by recrystallization can occur during the reductions in the temperature range above 950°-1000°C and after the holding period further reductions are applied in the temperature range below 900-950°C where no recrystallization can occur (Fig. 1(c) and Fig. 1(d)). The α grain refinement in controlled-rolled C-Mn steels is achieved by transformation from the unrecrystallized and elongated γ grains. Larger deformation should be carried out in this temperature range where improved notch toughness is required. The controlled rolling practices for Si-Mn steels and Nb containing steels are apparently similar; however, the metallurgical phenomena occurring during the low temperature finish rolling are intrinsically different.

In both the cases lowering the reheating temperature of the slabs (Fig. 1(d)) is effective in increasing the rolling productivity by shortening the holding time and this can also improve the DBTT and crack arrestability; however, that decreases through thickness properties and the Charpy self energy in the transverse direction.

It is well known that mechanical properties of rolled products can be improved when they are rolled to low finishing temperatures. When thinner plates are normally hot rolled, the reductions are extended to lower temperatures and therefore, the finish rolling temperatures are also reduced. With the reduced plate thickness, the α grains become finer and the yield strength and consequently toughness are further improved.

In controlled rolled steels the microstructures range from a recrystallized ferrite to a fully cellular dislocation substructure while strengthening and toughening mechanisms are different, depending on the microstructure. Steels finish rolled in the recrystallized austenite region gives recrystallized ferrite grain structure, in which the yield stress follows the Hall-Petch relation :

$$\sigma_y = \sigma_o + k_y d^{-1/2}$$

where σ_0 is the frictional stress, d is the grain size and k is a constant.

There is usually a conflict between the grain size which can be produced in a material, the amount or the dimensions of the material which can be so processed and the cost of processing. For structural applications thermomechanical processing of alloys is usually considered to be the optimum method for producing fine-grained alloys. Fine grained structure can be produced by the discontinuous recrystallization of a cold worked material. A small grain size is promoted by a large stored energy resulting from deformation and a large density of sites for nucleating recrystallization. The smallest grain sizes in aluminium are typically achieved by deformation to large strain of alloys containing second-phase particles larger than ~ 1μm and subsequent annealing to stimulate recrystallization. Ferrite has a high stacking fault energy, so that recovery processes preceed and accompany recrystallization of cold rolled ferrite and it is difficult to obtain grain sizes less than about 10μm in ferritic steels. It has been shown recently that cold rolling and annealing of steel with a pre-defined grain size of ~3μm resulted in a recrystallized grain size of less than 1mm. This is attributed to the large number of recrystallization nucleation sites available at pre-existing grain boundaries.

If a material is given a large strain at intermediate or high temperatures, a microstructure containing predominantly high angle grain boundaries may evolve with little or no further annealing. Such a microstructure is virtually indistinguishable from the one, which has been conventionally recrystallized, but because it has evolved gradually and uniformly throughout the material, this is generally known as continuous recrystallization. The production of micron-grained alloys by conventional thermomechanical processing is limited by the achievable strains i.e. typically ~3 - 4 if the resultant material is to have a minimum thickness of ~1 μm. Several new processing routes are being developed which allow larger strains to be imparted on the material. Equal Channel Angular Pressing (ECAP) developed in the former Soviet Union is one such method by which it is possible to impart large strains. During ECAP the sample is pressed

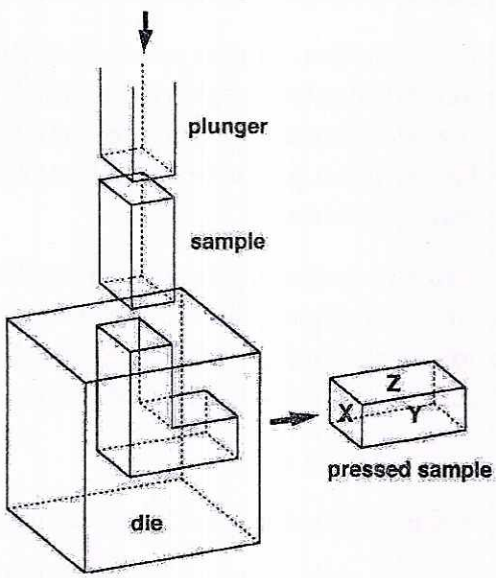

Fig. 2 : Schematic illustration of equal channel angular pressing (ECAP)

through a closed die which has two intersecting channels of equal size offset at an angle of 90° (Fig. 2). The die angle is an important factor in ECAP as it not only determines the strain per pass but also affects the geometry of deformation.

Another technique for increasing the applied strain is Accumulative Roll Bonding (ARB) in which the material is rolled, stacked and re-rolled in such a way that it maintains the initial sample thickness with a total strain upto 8 resulting into sub-micron grain sizes. Critical factors for successful ARB are surface preparation and cleaning, deformation temperature and the amount of strain.

Apart from that, deformation during the α-γ transformation will affect the phase transformation and may also result in dynamic or static recrystallization of the austenite and ferrite. This is termed as deformation-induced ferrite transformation.