The CAPL and Its Metallurgy

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1. Introduction

The continuous annealing and processing line, CAPL at NSC's Kimitsu Works has been operating since October, 1972. The Kimitsu CAPL is the world's first continuous annealing line for producing drawing quality cold rolled steel sheets, combining a number of processes following cold rolling into a single process. This has made it possible to ensure improved, uniform product quality and drastic savings in both energy and cost.

The Kimitsu CAPL is operating smoothly, and has produced more than 2.3 million tons of cold rolled sheets to date. No. 2 CAPL will be put into operation at NSC's Yawata Works in February, 1979 and a similar process is expected to be completed in CSN, Brazil by 1981.

The essential technical points of the CAPL process are equipment techniques to combine a multiplicity of conventional processes into a single line and metallurgical techniques for providing a high degree of adaptability for the production of various types of cold rolled steel sheets.

2. Equipment and Operation of CAPL

The conventional production process of cold rolled steel sheets entails five steps after cold rolling, i.e., electrolytic cleaning, batch annealing, coil cooling, temper rolling and inspection and recoiling. As shown in Fig. 1, CAPL combines these processes into a single line. Needless to say, this offers a number of advantages in cost, quality and operation.

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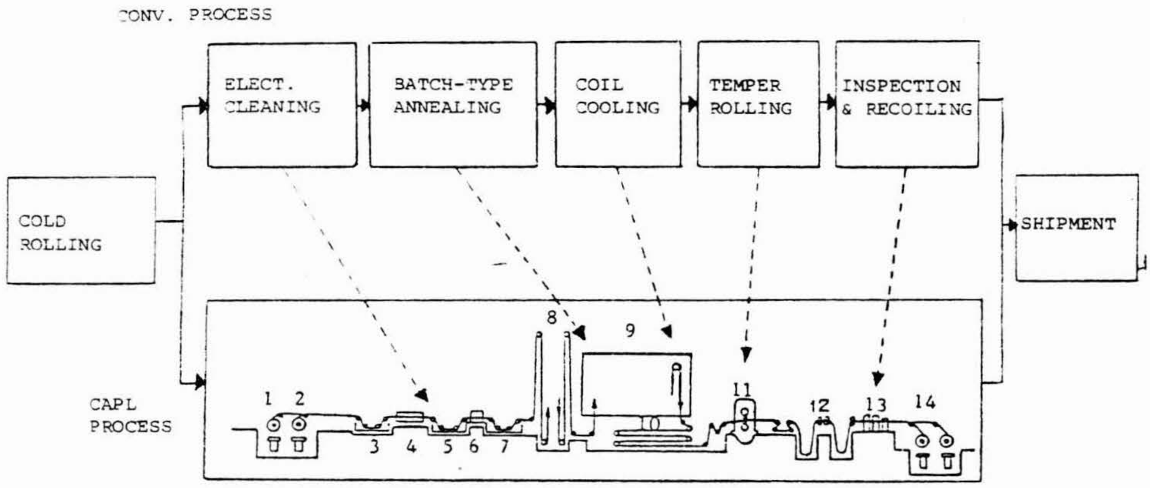


1. No. 1 pay-off reel
2. No. 2 pay-off reel
3. Hot caustic tank
4. No. 1 brush scrubber
5. Electrolytic cleaning tank
6. No. 2 brush scrubber
7. Hot rinse tank
8. Entry strand looper
9. Furnace
10. Exit loop car
11. Temper mill
12. Side trimmer
13. Oiler
14. No. 1 and No. 2 tension reels

Fig. 1. COMPARISON OF CAPL AND CONVENTIONAL PROCESS EQUIPMENT

Fig. 1 shows also the line arrangement of CAPL. Major equipment such as pay-off reels, welder, electrolytic cleaning section, annealing section, temper mill, inspection table and tension reel are connected in series, and loopers are installed on the entry and delivery ends of the annealing section to permit uninterrupted travel of the strip in the furnace section.

The construction of the cleaning section is similar to that of a conventional cleaning line, but it was confirmed from test results that the cleaning capacity of CAPL can be as small as half of the conventional line because of high gas cleaning capacity in the furnace.

Fig. 2 shows a typical annealing cycle. In addition to radiant tube heating used in the heating section, a preheater of the jet impinging type is installed on the entry side of the furnace to make effective use of high temperature waste combustion gas collected in the plenum chamber. In the Kimitsu CAPL, fuel efficiency has been improved by approximately 6% by installing the preheater.

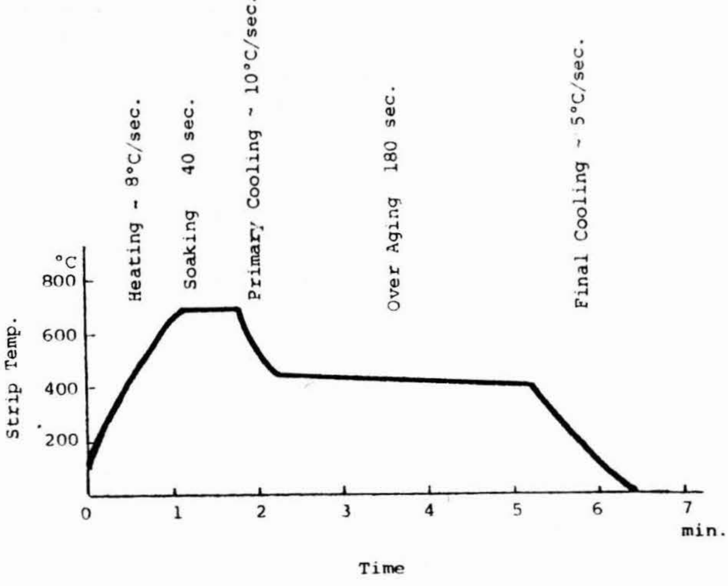


Fig. 2 TYPICAL ANNEALING CYCLE OF THE CAPL

Primary cooling following the soaking section is a metallurgically critical process. NSC has adopted gas-jet cooling as primary cooling from the viewpoints of metallurgical requirements and operating efficiency, as will be discussed later. Gas-jet cooling is a system which cools inert gas in the furnace with a heat exchanger and jets the cooled gas onto the strip.

The time required for over-aging is as short as 3 minutes in gas-jet cooling, depending on the primary cooling rate. An important factor in over-aging is selection of an appropriate hearth roll diameter. The strip is subject to bending stress every time it is bent by the hearth roll. Excessive bending stress may cause quality deterioration (stress aging) due to over-aging. Fig. 3 illustrates changes in yield strength and elongation during over-aging while applying these bending stresses. The proper range of stress is

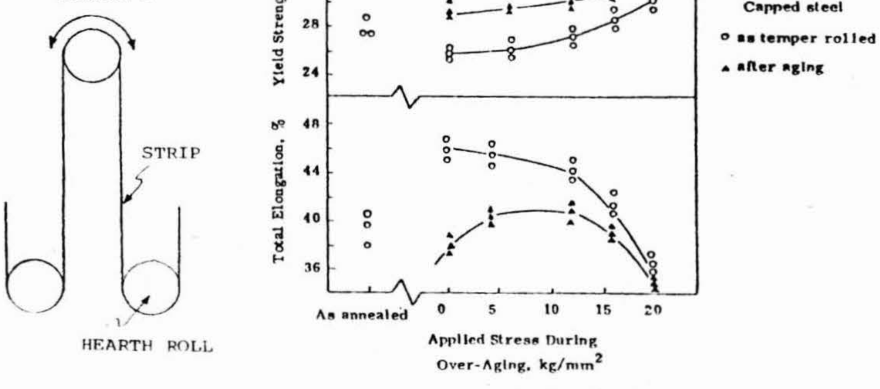


Fig. 3 Effects of applied stress during

approximately 5 kg/mm^2 minimum in terms of carbon precipitation and approximately 15 kg/mm^2 maximum in terms of stress aging. In other words, the hearth roll diameter should be properly determined according to the strip thickness so that the bending stress applied to the strip can be held within 15 kg/mm^2.

For secondary cooling, any means capable of cooling the strip as rapidly as possible can be used. In the Kimitsu CAPL, gas-jet cooling is employed. Although water-quenching is one of the most commonly used methods of increasing the cooling rate, this method requires not only quenching from the temperature at which surface oxidation of the strip does not occur but also provision of a drying means taking into consideration rolling temperatures (preferably under 40°C) in the succeeding temper mill.

The most critical point in realizing the in-line temper mill was the development of a new work roll changing system. This involved two prerequisites. First, the strip must not be cut off during roll changing, and second, the rolls must be changed as rapidly as possible. NSC has developed a push-out type changing system, which satisfies the above requirements. Fig. 4 is a schematic diagram of the system, in which a new set of work rolls placed beforehand on the mill drive side is pushed into the mill with a hydraulic cylinder while used work rolls are pushed out to the work side. Since the upper and lower rolls at this moment are separated at their chocks with a rail and spacer, it is not necessary to cut the strip. This system reduces total changing time to less than two minutes.

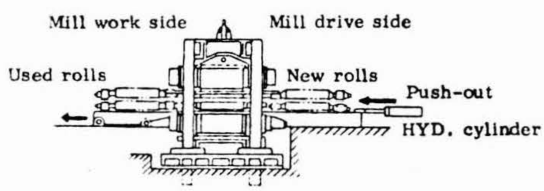


Fig. 4. Schematic diagram of push-out type roll changing device

In recent years, process control computers have been increasingly used in various types of processing lines. An instance in the Kimitsu CAPL is shown in the following. Kimitsu Works features a central computer for production control, organically connected with process control computers. Fig. 5 is a function block diagram, centering on the process computer of the CAPL. As can be seen in the figure, main functions of the process control computer include tracking, automatic pre-setting, data logging, automatic operation and annealing cycle control.

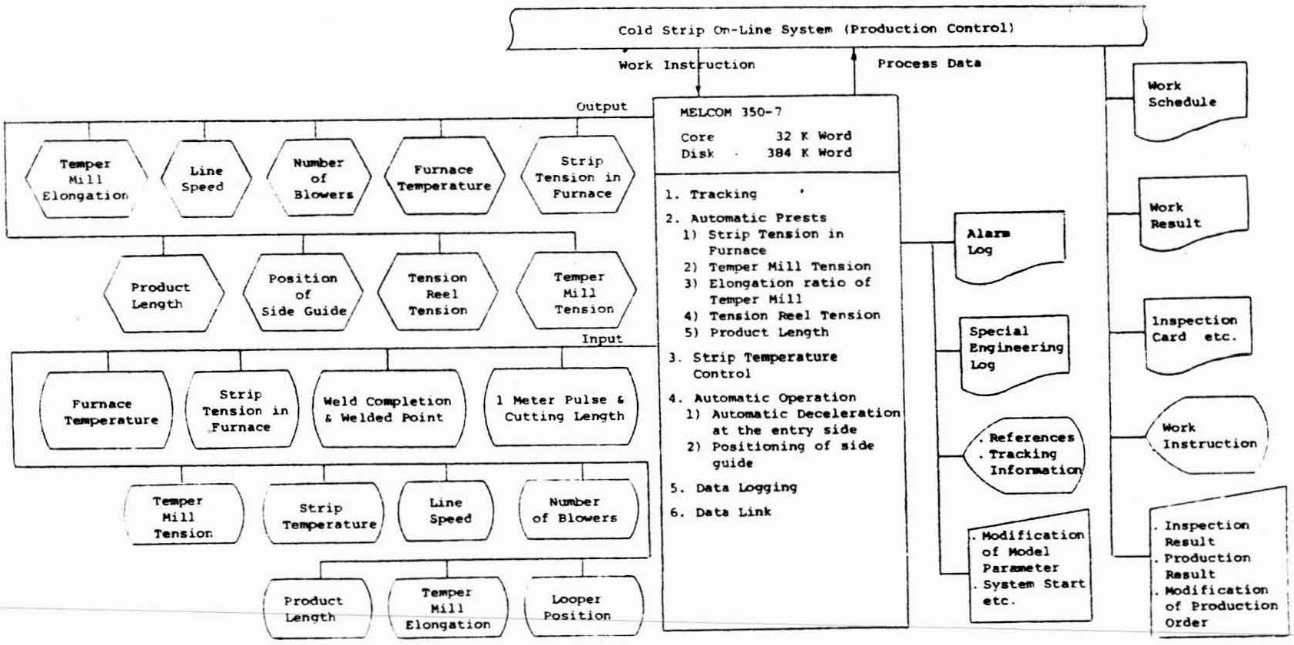


Fig. 5 On-Line Production Control System and Process Control Computer System

The Kimitsu CAPL has been in smooth, full-scale production for about six years, and has produced more than 2.3 million tons of cold rolled sheets. Recent operating data are given in Table 1.

Table 1. ACTIVE OPERATING DATA

Amount of Production		35,800 T/M	PRODUCT MIX.
Rated Production		57.7 T/H	CQ 61% DQ 29%
Working Rate		98.0%	DDQ 7%
Energy	Fuel Gas	171,840 Kcal/T	HSLA 1% ENAMEL 2%
	Power	60.6 KWH/T	etc.
	Steam	29.3 Kg/T	

3. Metallurgy of the CAPL

Metallurgically most important part in the continuous annealing cycle is primary cooling rate. There are two typical practices of the primary cooling. One of these is gas-jet cooling which is moderate rapid cooling rate of 10 degrees C per second. And the other one is water-quenching which results in drastic rapid cooling rate of several hundred degrees C per second.

The difference between gas-jet cooling and water-quenching in the primary cooling procedure results in a significant difference in mechanical properties of the products, of one method compared with the other. Now we elaborate this problem for drawing quality and high strength low alloy steels (HSLA).

As mentioned already, we have adopted the gas-jet cooling at the CAPL from standpoint of operation and metallurgy.

Influence of primary cooling practices on drawing quality steel

Table 2 indicates the influence of primary cooling practices on the mechanical properties of drawing- and deep-drawing-quality steel sheets. The products made by the gas-jet cooling process are characterized by their lower yield strength and higher elongation.

Table 2 INFLUENCE OF PRIMARY COOLING PRACTICE ON MECHANICAL PROPERTIES OF DQ AND DDQ SHEETS

STEEL	COOLING PRACTICE	YIELD STRENGTH kg/mm^2	TENSILE STRENGTH kg/mm^2	ELONGATION %	HARDNESS H_{RB}	ERICHSEN VALUE mm	LANKFORD VALUE
DQ	GAS JET COOLING	20.3	34.8	42.0	46.0	10.9	1.28
	WATER QUENCHING	22.5	35.3	40.3	46.7	10.3	1.24
DDQ	GAS JET COOLING	18.0	33.0	44.8	41.6	11.0	1.75
	WATER QUENCHING	19.7	35.7	42.3	45.0	10.8	1.71

Gauge: 0.8 mm

The effects of cooling rate on the mechanical properties of the products are associated with the precipitation behavior of carbon, which is manifested in the morphology of carbides. In the water-quenched products carbides are finely dispersed in grain interior as shown in Photo 1.

x500

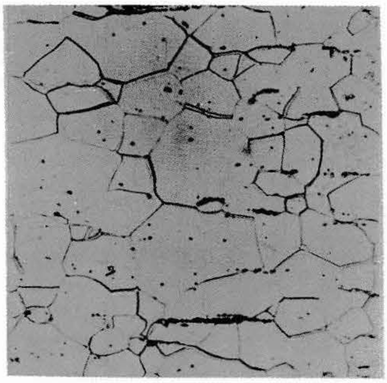
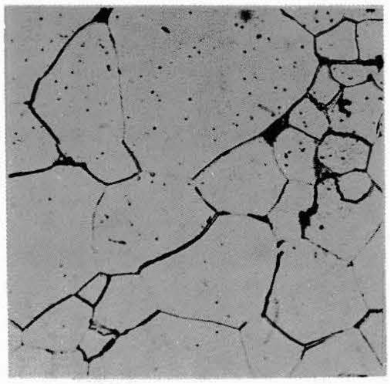
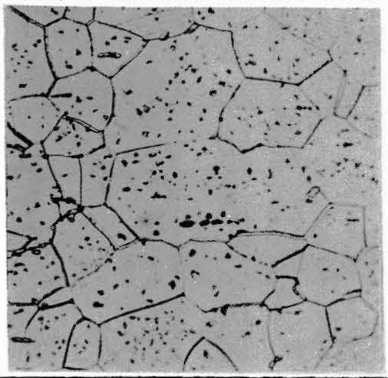
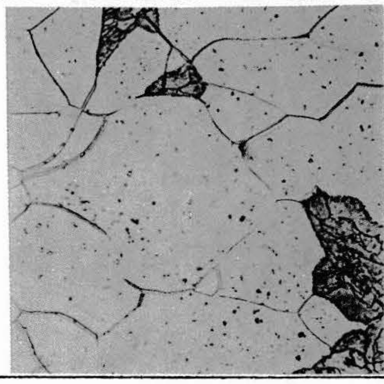
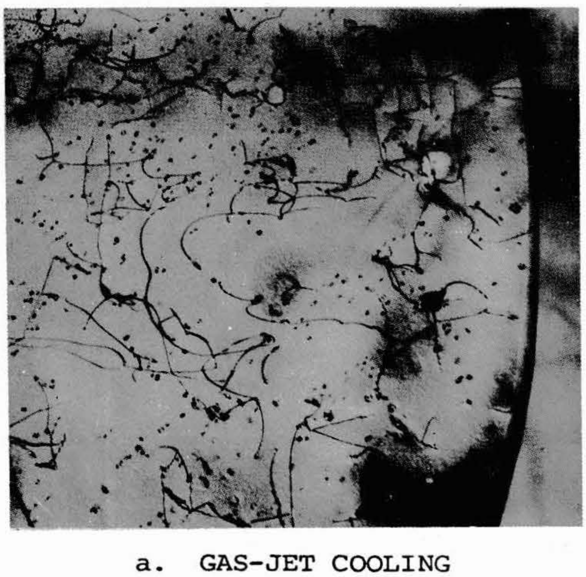
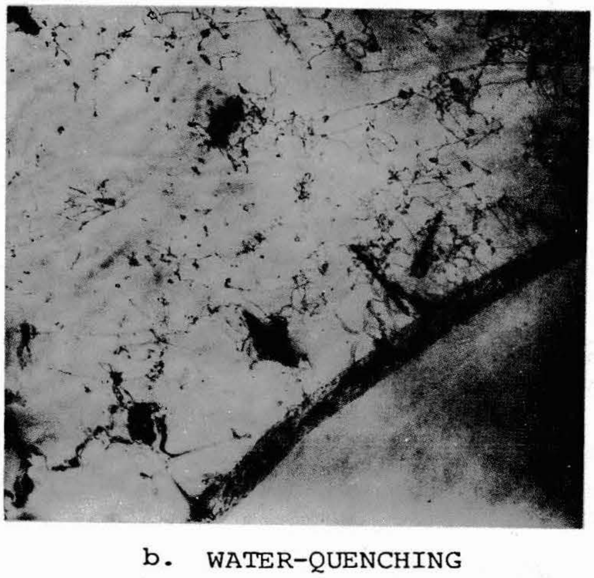
Cooling Practice	DQ	DDQ
Gas-Jet Cooling		
Water-Quenching		

Photo 1. CARBIDE MORPHOLOGY OF DQ AND DDQ SHEETS

Observation by high voltage electron microscope suggests how the difference of carbide morphology gives rise a substantial difference in ductility. Photo 2 a and b shows microstructures after skin pass rolling of the samples annealed by following the gas-jet cooling and the water-quenching cycle, respectively. The material was a cold

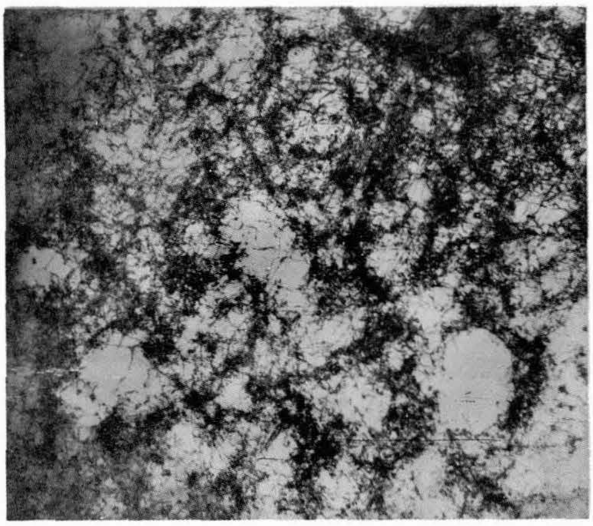


a. GAS-JET COOLING

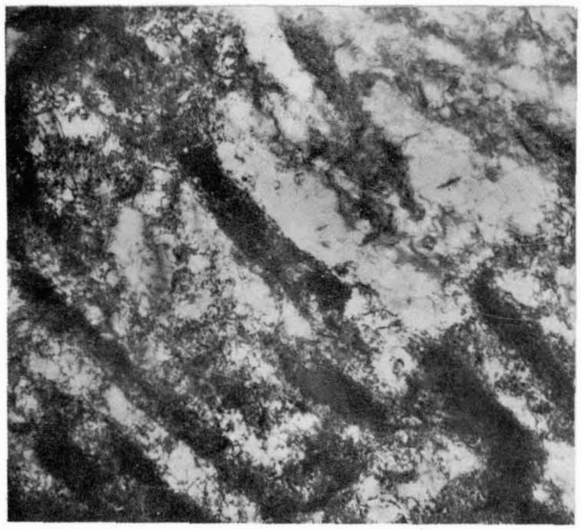


b. WATER-QUENCHING

Photo 2. MICROSTRUCTURES, AS SKIN PASS ROLL (1.0%) (x10000) rolled aluminum killed low carbon steel. In the water-quenched specimen dislocations are in cluster around the carbides which are in the shape of needle. In the gas-jet cooled specimen grain interior is free from carbides and dislocations are distributed uniformly. Photo 3 gives deformation structures after tensile deformation of 4%. In the water-quenched product more dislocations are trapped by the carbides with



GAS-JET COOLING



WATER-QUENCHING

Photo 3. MICROSTRUCTURES, TENSILE DEFORMATION (4%) (x10000)

progress in tensile deformation. Thus the carbides in grain interior lead to high rate of dislocation storage and inhomogeneous distribution of dislocations.

In order to obtain high elongation and good ductility, rate of work hardening must be kept high during plastic deformation. If there arise local variations of work hardening because of inhomogeneities of deformation, localization of plastic deformation occurs and results in the generation of necking, which leads to fracture. As manifested in the electron micrographs, the difference in the carbide morphology is closely related to the variation in the mode of deformation, and the carbides in grain interior promote the concentration of local deformation. Therefore lack of ductility is inevitable in the water-quenching process.

Influence of primary cooling practices on HSLA steels

Strengthening mechanisms of HSLA are solid-solution- and precipitation-hardening. These mechanisms require the addition of alloying elements which increases cost. Continuous-annealing process has introduced "dual-phase hardening" as a new material strengthening method. Increased attention is directed towards the dual-phase steels as an attractive answer to the problem of poor stretchability and shape-fixability (spring-back), which have been major drawbacks in the cold forming of HSLA steels. The dual-phase steels are characterized by their lower yield strength, higher work hardening rate, and improved elongation over the conventional HSLA steels. The dual-phase steels are based on plain carbon-manganese-silicon steels, without addition of carbo-nitride forming elements and produced by treating the materials in the two phase region of ferrite and austenite, followed by rapid cooling. The dual-phase microstructure consists of low temperature decomposition products from austenite, dispersed in polygonal ferrite. The presence of a small volume-fraction of the second hard phase, in the ferrite matrix, accounts for continuous yielding, rapid work hardening, high tensile strength, and improved elongation over the conventional HSLA steels.

The difference in the primary cooling practices leads to a significant difference in mechanical properties of the dual-phase steels. Fig. 6 shows the relationship between tensile strength and

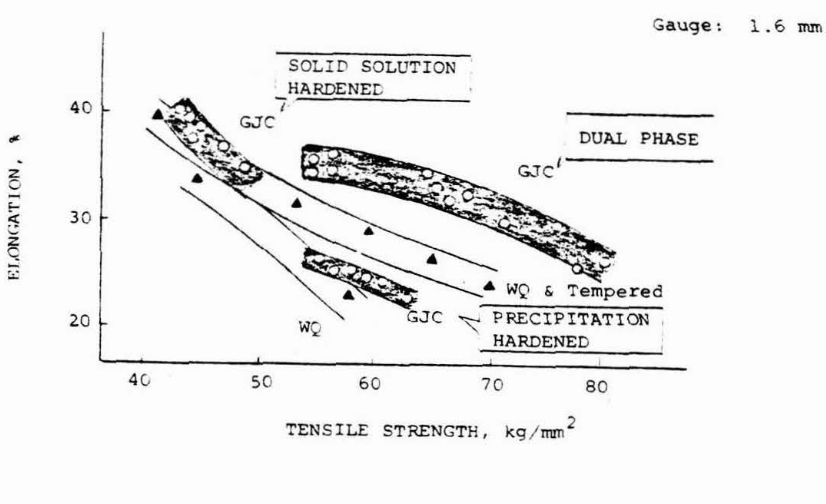


Fig. 6 STRENGTH AND DUCTILITY OF HSLA SHEETS

total elongation for the dual-phase steels. It is seen that elongation of the gas-jet cooled dual-phase group is superior to any others, including the water-quenched group, at any given strength level.

Fig. 7 shows variances of mechanical properties due to the variation of cooling rate after soaking at the alpha-gamma temperatures. Loss of ductility is evident when the cooling rate exceeds 20 degrees C per second.

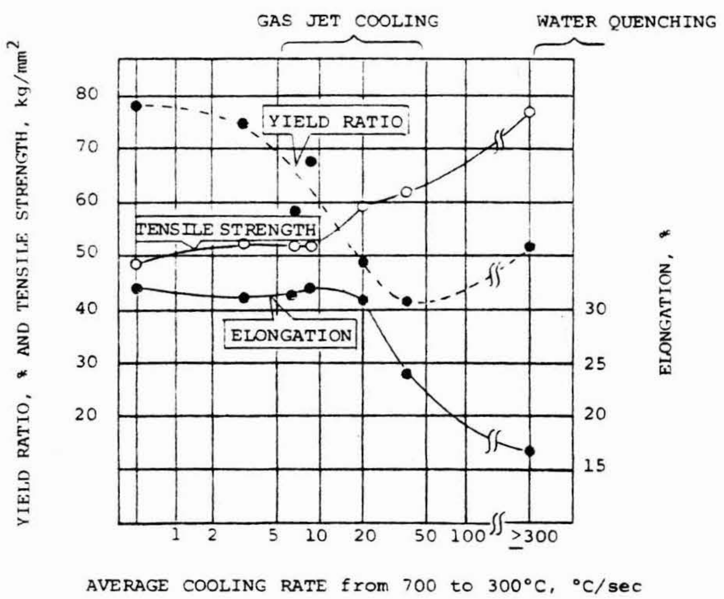


Fig. 7 INFLUENCE OF COOLING RATE ON MECHANICAL PROPERTIES OF HSLA STEELS

Poor ductility of the water-quenched material is additionally evident under work hardening characteristics shown in Fig. 8, for

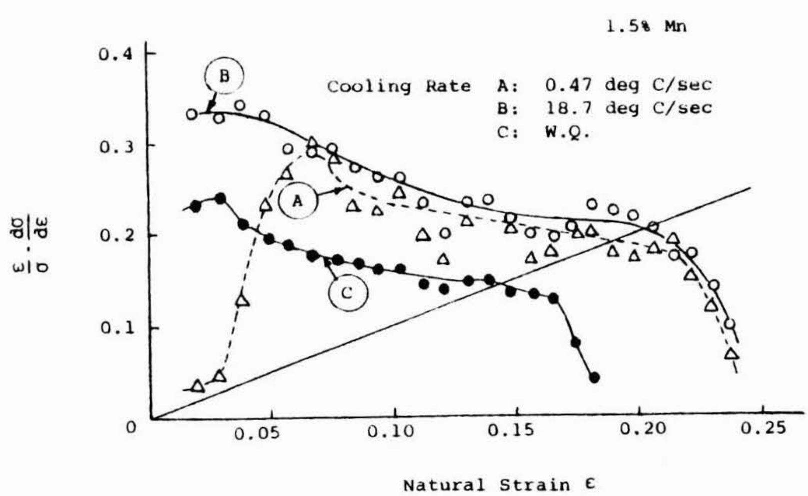


Fig. 8 INFLUENCE OF COOLING RATE ON WORK HARDENING PROPERTY

which the work hardening rate is plotted at various levels of strains up to fracture. The gas-jet cooled dual-phase steel is the highest in uniform elongation. The water-quenched material gives the lowest level of the work hardening rate, and the poorest uniform elongation. The dual-phase steels show a very high work hardening rate at small strains; and do not follow the "power law"; the work hardening coefficient, "n", is not constant at a wide range of strain.

The effects of cooling rate on the mechanical properties of the products are associated with the phase transformation behavior during the primary cooling process. The second phase particles vary in accordance with the cooling rate after intercritical annealing. The phase transformation product in the water-quenched material is martensite, while a part of austenite is retained in the gas-jet cooled material. Mössbauer spectral analysis shows a retention of austenite in the gas-jet cooled dual-phase steel to the amount of several percent in volume. The austenite cannot be transformed into martensite by a subzero treatment, cooling the steel down to the liquid nitrogen temperature. However, the austenite is susceptible to undergo strain-induced-phase-transformation and a substantial amount of the austenite diminishes during the progress of tensile deformation up to 10 percent, by which a very high rate of work hardening is obtained. The strain-induced-phase-transformation is accompanied by a dimensional change of the second phase particles and exerts a compressive stress around them. Consequently, compatibility between the ferrite matrix and the second phase particles can be restored. The extraordinary ductility of the gas-jet cooled dual-phase steel may be somewhat analogous to the superplasticity induced by the martensite transformation during plastic deformation of TRIP (transformation induced plasticity) steels.

Furthermore the ferrite matrix of the gas-jet cooled material is characterized by nearly complete removal of carbon from solution.

The zero carbon ferrite in the gas-jet cooled material is soft and ductile, which results in the high ductility of the material. Thus a good combination of the soft ferrite matrix and the dispersed austenite particles contributes to the excellent ductility in the gas-jet cooled dual-phase steels.

4. Conclusion

The CAPL process is the most rational process ever developed for production of cold rolled steel sheets in terms of both operating techniques and metallurgy. This process is expected to receive increasing attention throughout the world in the future.

To achieve higher operating efficiency, it will be necessary to improve the equipment, and an attempt of such improvements will be considered on the Yawata CAPL.

We have already established the CAPL production system not only for drawing quality and HSLA steel sheets but also for various types of cold rolled steel sheets such as super deep drawing, porcelain enameling, electrical grade and blue sheets. We are determined to continue our research efforts to further diversify the product mix.