Technology of Continuously Annealed Cold-Rolled Sheet Steel

Edited by

R. Pradhan

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Proceedings of a symposium sponsored by the Heat Treatment and Ferrous Metallurgy Committees of The Metallurgical Society of AIME and held at the TMS-AIME Fall Meeting in Detroit, Michigan, September 17-18, 1984.

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Preface

The international symposium, held at the TMS-AIME Fall Meeting in Detroit, Michigan, (September 17-18, 1984) and sponsored by the Ferrous Metallurgy and Heat Treatment Committees, represents the third such conference on the subject of continuous annealing of cold-rolled sheet steels. The previous two were the TMS-AIME symposium on the Metallurgy of Continuous-Annealed Sheet Steels (Dallas, Texas, February 15-16, 1982) and the International Symposium on Continuous Annealing of Steel (Stockholm, Sweden, June 18-20, 1984).

The papers presented at this symposium indicate that the primary focus of research is currently in the area of drawing and deep-drawing quality steels. The first three papers in this section deal with the fundamentals of nucleation and growth of carbides during continuous annealing, and the relations between carbide morphology and the tensile and aging properties. Other papers involve the optimization of processing parameters and the addition of alloying elements (Ti, B and Zr) to facilitate production of the DQ and DDQ grades. The section on high-strength steels encompasses both HSLA (Nb-and V-microalloyed) and dual-phase steels; the papers on dual-phase steels discuss the effects of pertinent processing parameters and the consistency of tensile properties. For the first time, the production of tin plate on modern continuous annealing lines is addressed. Additionally, several papers deal with the progress in the areas of increased in-line operations and process developments aimed at improving product quality.

Thanks are due to K. Matsudo, K. Osawa, K. Kurihara (all of Nippon Kokan K.K.) and H. Katoh, H. Takechi, N. Takahashi, M. Abe (all of Nippon Steel) who presented excellent state-of-the-art review papers. The willingness of I. Gupta (Inland Steel), R. Stevenson (General Motors) and S.R. Goodman (U.S. Steel) to serve as Session Chairmen is gratefully acknowledged.

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January, 1985

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PROCESS DEVELOPMENT

Invited Papers

METALLURGICAL ASPECTS OF THE DEVELOPMENT OF CONTINUOUS ANNEALING TECHNOLOGY AT NIPPON KOKAN

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A feasibility study on the production of formable cold-rolled sheet steel by continuous annealing (CA) was started in 1963 at Nippon Kokan K.K.(NKK). It was found out that CQ grade is attainable by a combination of in-line overaging and high temperature hot-coiling, which leads not only to softening, but also improvement in the drawability ($\bar{r}$-value) of steel. Thus, the development of CA process was carried out. The water-quenching method was adopted for primary cooling to minimize the overaging time. The roll-quenching method has also been developed to meet energy saving demands since the oil crisis. Products covering a wide range of strength levels, from EDDQ to ultra-high strength (TS: 150 kg/mm^2) steels, have been realized by controlling chemistry and CA operation. Further investigations have been performed to optimize the manufacturing conditions.

The situation and background for starting the research and development of CAL at NKK are reviewed. Then, processing and metallurgical factors for production of low-strength deep-drawing sheet by CA are described with regard to coiling temperature after hot rolling and cooling and overaging after recrystallization annealing. The metallurgy of high-strength cold-rolled sheet steel with various performances is explained in terms of microstructure. Finally, future vision of the technology is discussed.

Introduction

The first application of continuous annealing (CA) technology for steel strip was started at Armco Steel Corporation, for production of hot-dip galvanized sheet in 1936.[1] Then, various facilities for production of aluminized sheet, tin plate, stainless steel, and non-oriented silicon steel were made one after another. Continuous annealing is characterized by the following features: (1) good uniformity of mechanical properties of products, (2) good flatness of sheet, and (3) short operation time. A great deal of effort[2-4] was made in applying CA sheet steel towards automotive and appliance usage, which accounts for a large part of sheet steel production. Although sheet steel people desired the application for a long time, it was not realized until 1970. At that time, as a result of detailed metallurgical research and investigation, Blickwede[3] declared that CA was feasible under the following conditions: (i) large ferrite grain size of starting material (hot band) accomplished by low temperature finishing and high temperature coiling in the hot rolling process and (ii) precipitation of carbon in solid solution by heat treatment for two or three minutes at 370°C. Furthermore he proposed that the application of CA for the production of cold-rolled (CR) sheet steel was economically possible, by incorporating a CA furnace, skin-pass rolling mill, and other devices. The sheet steel produced by CA, however, was not widely rated as deep-drawing sheet because of its poor mechanical properties.[5,6]

The first CA facility for deep-drawing sheet started commercial operation at Kimitsu Works of Nippon Steel in 1972. The previous year, at Fukuyama Works of Nippon Kokan (NKK), a continuous annealing line (CAL) made by modification of a tin CAL had been utilized for development and production of steel of the same grade.[7] Since those years, CAL's with various features[8-11] came into appearance at the steel works. In 1973, the first oil crisis increased the demand for high strength sheet steel, which is necessary for reducing vehicle weight, and hence, CA technology became of greater interest than before. Now fourteen facilities for CA are operating throughout the world, and several facilities are to be constructed in the next couple of years.

The success of CA technology is attributed, of course, to the metallurgical study of researchers, and furthermore, to managers who tended to be of one accord in promoting contemporary trends: enlargement, acceleration, and continuation of steel processing lines. As a result of this success, the steelmaking technology has improved along with CA operation. Furthermore, CA technology has brought about progress in metallurgy and operation for producing high-strength cold-rolled (HSCR) sheet steel.[12]

First, the situation and background for starting the research and development of CAL at NKK are reviewed. Then, processing and metallurgical factors for production of low strength deep-drawing sheet by CA are described with regard to hot-mill coiling temperature and cooling and overaging treatments after recrystallization annealing. Metallurgy of HSCR sheet steel with various properties is explained in terms of microstructure. Finally, future vision of the technology is discussed.

Brief History of the Development of CA Technology at Nippon Kokan

Nearly a quarter century has passed since NKK's first encounter with a CAL for steel strip. The steps taken are briefly reviewed in chronological order.

A tin CAL started operation at Mizue Works (now, Keihin Works) in 1962.

Its annealing capability was found to be much greater than the tin plating capability. To increase the operating time of the tin CAL, the possibility of producing sheet steel for drawing use was considered. Investigations of overaging after primary cooling with a gas-jet device were made, and the results were applied to the production of CQ grade sheet by adopting overaging with box annealing after CA treatment.[13] These investigations encouraged the production of drawing quality sheet by CAL alone.

Another tin CAL, planned for Fukuyama Works, was equipped with a water-quenching device for primary cooling,[14] in order to reduce the overaging time due to restrictions of the capacity of apparatus and yard. A method for arresting the strip temperature at the overaging temperature during the course of rapid cooling was also tried. It failed, however, due to restriction of cooling technique and time limit for development. The annealed sheet was harder than the box annealed sheet and poorer in $\bar{r}$-value. This shortcoming was resolved by changing the manufacturing conditions of steels to be fed into CAL: the adoption of high temperature finishing and coiling method in hot rolling process,[15,16] which had been found to be effective for box annealing to increase $\bar{r}$-value.[17] As a result, feasibility of producing CQ grade sheet by CAL was confirmed, and fortunately, the product was found to be of higher $\bar{r}$-value than box annealed one. Thus, following improvement of descaling technique for hot band coiled at high temperatures, shape control of water-quenched steel strip,[18] and some subsidiary investigations, it was decided to construct CAL for both tinplate and cold-rolled sheet.

The first CAL started operation at Fukuyama Works in 1971, and the researchers were immediately confronted with problems of abnormal ferrite grain growth of hot band and non-uniformity of mechanical property along the coil length (i.e., degradation at the head and tail of the annealed coil). Both these problems stemmed from the high temperature coiling after hot rolling. The former problem was moderated by controlling the period of time before water cooling at the run-out table.[19] The latter was mitigated by optimizing the cooling pattern, and was completely alleviated in 1980 by reducing the carbon content to nearly 0.02%.[20] With these techniques, production of CQ grade sheet from low-carbon capped steel was made possible. At the same time, a study on sheet production from continuously cast steel was started, because of a prediction that the steel for cold rolling would be replaced by this method. The second CAL was planned for construction at Fukuyama Works, which was to produce cold-rolled sheet steel alone.

At that time, an investigation of producing DQ and DDQ grade sheet and HSCR sheet steel was conducted, using the first CAL and laboratory simulator. For example, the effect on sheet property of chemistry such as C[20] and Mn[21] in low C steel and of Ti and Zr[22] in ultra-low C steel was examined for low strength products, and metallurgy of dual phase steel and bake-hardenability were studied for high strength steels.[23-26] In 1976 the second CAL equipped with a water-quenching device[27] started operation at Fukuyama Works, after a slight prolongation by the first oil crisis.

In the move toward energy saving due to the first oil crisis, CAL energy requirements of electric power and steam were reduced, whereas fuel required for reheating the strip after water-quenching still remained a problem. To meet this demand, roll-contact cooling (RQ) was devised and developed.[28] A full scale examination of the roll-contact cooling method was carried out in Fukuyama Works.[29] In 1982 the roll-contact cooling device was installed in the second CAL at Fukuyama Works, and both WQ and RQ methods were available in one line.

By means of combination blowing in steel making, it became possible to steadily reduce carbon content to 0.02%. Furthermore, using RH degassing technique, research on DQ and DDQ grade sheet production was elaborated. Since then, ultra-low C steel with C content lower than 0.003% has been stably cast. Now, CQ, DQ, and DDQ grades of low strength sheet and various products of high strength steel with 35 to 150 kg/mm^2 in tensile strength can be manufactured utilizing either the WQ or RQ method, accomplishing energy and resourse savings along with high yield.[8]

Metallurgy of Low-Strength, Deep-Drawing Sheet Steel Production by Continuous Annealing

The usual tin CAL is characterized by a heat cycle of rapid heating, short time soaking, and rapid cooling. As a result, the annealed sheet is rather hard, with several shortcomings: low drawability and poor anti-aging property due to a large amount of remaining solute carbon. These deficiencies were removed by the adoption of both high-temperature coiling after hot rolling and a heat cycle which combines rapid cooling after soaking and overaging. By optimizing the chemistry based on this technology, sufficiently soft sheet with superior deep-drawability and anti-aging properties was developed.

It is necessary for deep-drawing soft sheet to possess low yield stress, high elongation, high n-value, and high $\bar{r}$-value. Furthermore, it requires sufficient anti-aging property. Ferrite grain size influences yield stress, ductility (represented by the elongation) and n-value. The development of {111} texture improves the $\bar{r}$-value. The remaining solute C and finely dispersed carbide affects the ductility; the former exerts strong effect on the anti-aging property at room temperature.

Deep-drawing, soft sheet steel is produced by controlling these metallurgical factors and optimizing the processes of steelmaking, hot rolling, cold rolling, continuous annealing, and skinpass rolling. The effect of each processing condition on sheet property is described below.

Coiling Temperature after Hot Rolling

Figure 1 shows the effect of coiling temperature after hot rolling on the mechanical properties of continuous-annealed low C capped steel sheet.[30] For coiling temperature higher than 670°C, a significant decrease in yield stress and an improvement in $\bar{r}$-value are achieved. Figure 2 shows micrographs of hot bands coiled at 600 and 700°C; the higher temperature coiling leads to the coarsening of carbide and the growth of ferrite grain. The large grain size of the hot band aids the grain growth after cold rolling and annealing. The coarsening of precipitates (mainly carbide, as well as, AlN in Al-killed steel) was found to contribute greatly to the grain growth by weakening the dragging effect of the precipitates.

Figure 3 shows the heating rate dependence of the $\bar{r}$-value of annealed sheet of cold-rolled low C capped steel, coiled at different temperatures after hot rolling.[31] The $\bar{r}$-value is higher for the high coiling temperature, and increases with increasing heating rate, while it decreases for the low coiling temperature. This is due to the coarsening of carbide into massive cementite, as described later. Figure 4 exhibits the {200} pole figure of rapidly heated cold-rolled sheets from hot bands coiled at either low or high temperature after hot rolling.[32] The latter is higher in density of {111} component than the former. Softening and improvement in deep-drawability, which are related to grain growth and development in {111} recrystallization texture, are attributed to carbide coarsening and ferrite grain growth in hot band.[33] Therefore, high temperature coiled hot bands have been generally fed into CAL.

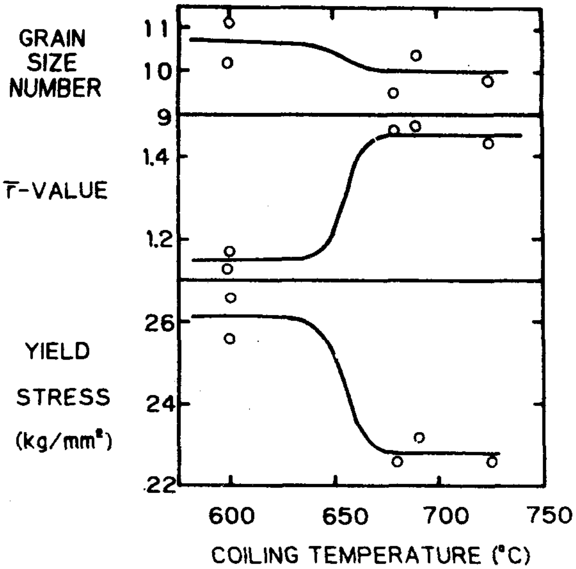

Fig. 1. Effect of coiling temperature on cold-rolled sheet properties.

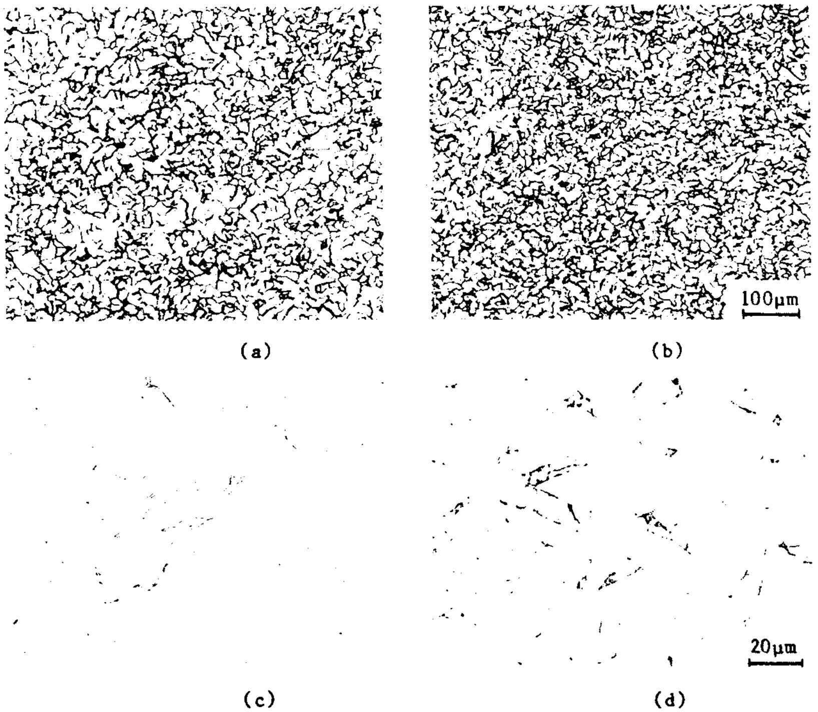

Fig. 2. Microstructure of hot band coiled at (a,c) high temperature and (b,d) low temperature.

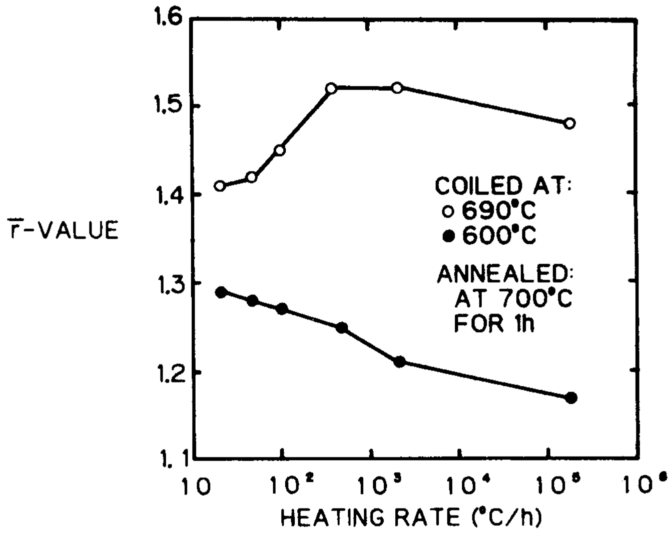

Fig. 3 Dependence of r̄-value on heating rate during annealing.

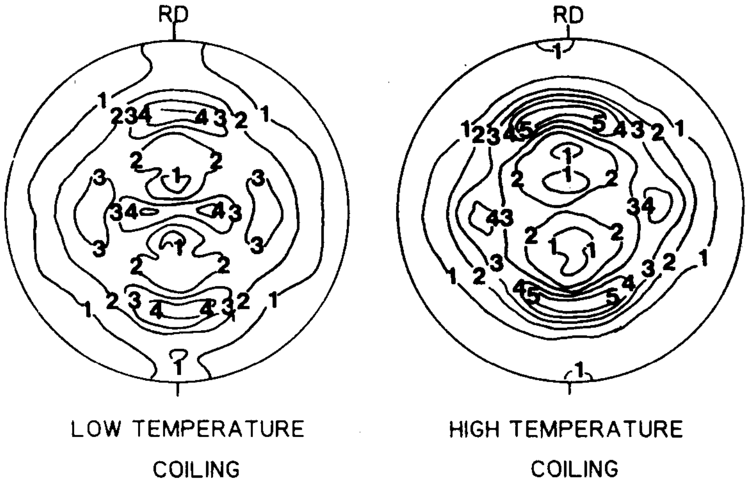

Fig. 4. Difference in annealing textures of cold-rolled sheet from low and high temperature coiled hot bands.

In Al-killed steel, AlN distribution changes with the coiling temperature, and together with carbide morphology exerts an effect on the properties of annealed sheet. Figure 5 shows the change in the properties of continuously annealed, Al-killed steel that result from changes in the morphologies of AlN and carbides in the hot band.[34]

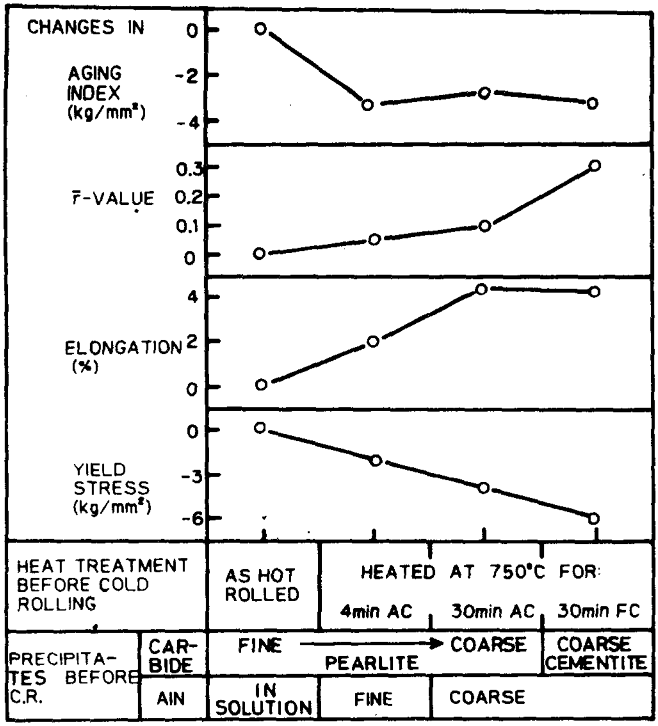

Fig. 5. Changes in sheet properties with coiling temperature simulation of hot band.

In CA, Al-killed steel can impart improved anti-aging property, low yield stress, and high ductility, by the AlN precipitation and coarsening achieved by the high temperature coiling. The contribution of AlN to sheet property is different between BA and CA: In BA, AlN is kept in solid solution by low temperature coiling at hot rolling and is precipitated during recovery and recrystallization at a time favorable to the development of the {111} recrystallization texture, (being effective on texture control). In CA, however, AlN is not effective in texture improvement, but deleterious to grain growth. It is advantageous to precipitate AlN before annealing in order to optimize mechanical properties and eliminate solute N, which is not stabilized during short time annealing (CA) at low temperatures. Thus, Al-killed steel hot bands for CA treatment should be of the above-mentioned microstructure with both coarse carbide and precipitated and coarsened AlN.

Several mechanisms were reported [35,36] for the improvement of {111} texture development during rapid heating of cold-rolled sheet from high-temperature coiled hot band. From the authors' research the following two mechanisms were proposed:[37] (i) A decrease in the area in the vicinity of carbides, where recrystallization grains with random orientation are apt to nucleate, and (ii) the retardation of carbide dissolution due to coarse morphology, enabling recovery and recrystallization to occur in the presence of a small amount of solute carbon.

A recent study has made further progress in the interpretation of the latter phenomenon, by offering a more detailed mechanism:[38] The recrystallization texture is affected by an interaction between solute C and Mn, which is unfavorable for {111} texture formation. Thus, recovery and recrystallization under low solute C content suffers little effect from the interaction, promoting orientation selectivity of recrystallized nuclei to develop {111} texture. Figure 6 shows the effect of Mn content on the $\bar{r}$-value of annealed sheets of steels with various C content.[38] For ultra-low C steel the effect of Mn is indistinct, and as the C content increases, the effect becomes obvious: The $\bar{r}$-value is lowered. The figure demonstrates that the interaction between solute C and Mn has a great effect on $\bar{r}$-value.

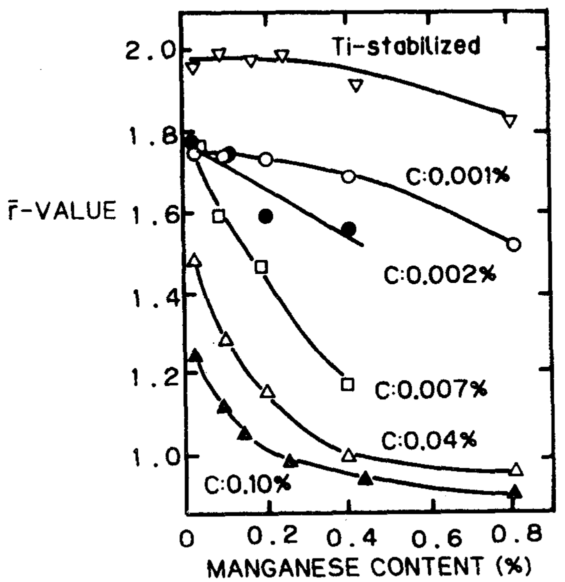

Fig. 6. Effect of manganese on $\bar{r}$-value of steels with various carbon content.

Despite the high temperature coiling, the head and tail of the coil length are cooled rapidly and both the carbide coarsening and the AlN precipitation and coarsening are not sufficiently performed. This tends to cause degradation of the annealed sheet properties. Al-killed steel is less effective than capped steel in maintaining the uniformity of various properties of sheet from high-temperature coiled hot band. The non-uniformity of sheet properties along the position in coil can be alleviated by controlling the chemistry and hot rolling conditions.

For control of hot rolling conditions, it is effective to raise the temperature in the head and tail of the coil in order to promote the carbide coarsening and AlN precipitation and coarsening.

As for chemistry control, the amount of C or Mn is reduced in order to decrease the number of carbides or to accelerate carbide coarsening, which is easier in low Mn steel; N is lowered to decrease the amount of AlN, for the purpose of lessening the detrimental effect of the precipitate.