I. Introduction—Brief History of Continuous Annealing

Continuous annealing is spreading in pace with concatenation of other processes, not only in the iron and steel industry but also in the aluminum and copper industries. In this Nishiyama Memorial Seminar, I wish to examine the backgrounds and situations in which the continuous annealing was promoted then to discuss those continuous annealing or heat treating processes that are currently popular mainly from the viewpoints of heating and cooling technology.

In my career of over a quarter century as a furnace designer specializing in the continuous annealing, I have encountered many memorable events, of which I like to mention six today. The first was when I first discovered in 1956 A. F. Mohri’s paper; the heat cycle he established on his metallurgical studies has been adopted by almost all the subsequent Tin-CALs, among which we have today large lines with a line speed of over 2 000 fpm.2) The second was the U.S. Steel’s famous patent of 1958 on rapid cooling followed by overaging of strip, which they called the Shelf Annealing as may be understood by Fig. 1.3~ The metallurgical common knowledge at that time was that aging should bring about hardening by precipitation of carbides, so that this work of the U.S. Steel researchers’ that proved the opposite came as a great surprise. Of course, today everybody knows how the dislocation theory can explain this phenomenon of age-softening by overaging beautifully.5~

The third was in 1962 when the floater type continuous annealing furnace was introduced to the aluminum industry under a very imaginative name of the “Magic Carpet”.6) This method, in which aluminum strip is floated on air-cushion and annealed as floating in air, literally enchanted the people of aluminum industry.

The fourth was the commissioning of a large vertical type continuous annealer of 70 m high at the Chase Brass. I heard that the tall building which housed this furnace in became quite an attraction to local journalism.

The fifth was when in Japan the first length-wise unified catenary type stainless steel continuous annealing furnace was built: the development of special heat resisting rolls7~ had made the unification of old divided shell structure possible,8~ so that the furnace length was greatly reduced and the thermal efficiency greatly improved. This was in early 1970s.

The sixth and the most recent one was the “realization of long dream of Sheet-CAL”9) of 1971 to 76 in the form first of Nippon Steel’s (NSC) CAPL,10~ then of Nippon Kokan’s (NKK) NKK-CAL,11~13~ and following those two processes Kawasaki Steel’s (KSC) KM-CAL14~ was developed in 1980.

Of the great advances that our metal industries achieved despite the two Oil Crises, those Sheet-CAL technologies are rightfully of our own, and as of 1982, the proportion of continuous annealing practice is already over 50 % at the Nippon Steel,15~ working towards 80 % level, which will be attained in the near future. Besides this, not only at home both the Sumitomo Metals and the Kobe Steel have installed CAL, but this technology has been exported to the USA, Sweden, Belgium, Brasil, and USSR.

Why, then, is this popularity? Firstly, sandwitched between the already concatenated continuous casting, reheating, hot strip rolling, pickling, and cold strip rolling lines in the front, and also well automated finishing process in the rear, the annealing remaining batch process presented an obvious neck in the overall system streamlining.

Secondly, though less salient, the need of handling larger and heavier coils for cutting down on the handling time to improve the productivity has become acute. Contrary to the intent, however, this means that fast and uniform heating is difficult for any batch process by nature, a shortcoming that had to be overcome by annealing longer or by providing more powerful fan to intensify the forced convection. Of
course, the loosening up the coil is effective, but this means more additional work steps and coil handling, where the coil is apt to getting scratched, a liability that cannot be tolerated often, particularly for aluminum. Further, there are many grades such as, for example, that call for partial annealing for which the time difference between the outer layers and the core of a coil to attain the same temperature may become critical.

This may be seen in Fig. 2, which is a result of computer simulation study conducted for a powerful convection type aluminum batch annealer. It will be seen that the greater the coil, the longer becomes the heating time and the larger becomes the temperature difference between the surface and core of coil. With a far smaller heat conductivity, it is easy to see how the situation is severer for steel. This means simply that larger coils and more efficient annealing are mutually incompatible, a single great reason why American and Japanese aluminum firms have installed the floater continuous annealer, some of which are capable of handling strips of over 200 mm wide.

The third is the need of saving energy and manpower. A furnace thermal efficiency reaching to 80 to 90%, or even over 100%, by recovering the heat released from the cooling strip to preheat the incoming strip, as well as automation and computer control of the line can only be achieved by CAL.

In the fourth, the conventional batch annealing has become not good enough to satisfy customer's varying needs for higher quality and faster delivery. In fact, in a poll conducted for American aluminum industry, 430 out of a total of 1526 returns cited the precise delivery as the greatest merit of continuous annealing.

Lastly, continuous annealing promises not only reduction of the running cost but a substantial saving in the initial cost and the space. Those merits become all the more apparent when annealing is concatenated with the lines of cold strip rolling, pickling, temper mill, and surface treatment into the so-called integrated line.

Before closing this chapter, however, I must add a word of caution by quoting an interesting German report, according to which an experiment conducted so as to trace the NSC-CAPL and NKK-CAL processes by faithfully following the respective annealing cycles failed to reproduce the quality those two firms claimed. This means that the steel to be put to continuous annealing must be adequate for CAL process: insufficient degassing and chemistry adjustment at steelmaking and improper hot coiling temperature at rolling can totally defeat the very idea of Sheet-CAL.

II. Heating Technology for Steel Sheet-CAL

Typical Sheet-CAL is illustrated in Photo. 1, while

![Photo. 1. A Sheet-CAL furnace.](image)

![Fig. 2. Heating practices and coil core-surface temperature difference in aluminum coil annealer.](image)
basic structure and heat cycle are schematically shown in Figs. 3 and 4. Typically, the heating technique applied to the already existed Sheet-CALs is essentially the same as developed for the Tin-CAL, and therefore is of the type of, the indirect heating mainly using the radiant tubes (RT). The shortcoming with this method is that in order to ensure a reasonably long service life for the RT, the surface heat load of each tube must be held low, so that in the end the furnace length must necessarily be designed long. Further, RT itself is rather expensive both in the initial and in maintenance, and its heat momentum is rather large, making the response to temperature control sluggish.

In this chapter, I wish to discuss first the RT heating techniques, particularly for the energy saving measures developed, then other newer methods being developed to overcome the shortcomings of the RT heating method.

1. The Radiant Tube (RT) Heating Methods

1. The Radiant Tubes

The RTs that are being used in the Sheet-CAL come in two types of U shape and W shape as shown in Fig. 5 and with a diameter of 5, 6, or 7 in.; they are to be selected in accordance with the maximum width of strip and the corresponding furnace heating capacity. The material can be various, such as ACI HF, HH-2, HK, or HL with 1.5 Mo, but from the cost performance viewpoint HH-2 is recommendable. The highest heating temperature of RT should preferably be below 1 000 °C. This is to prevent high temperature deformation of tube, but simple specification of maximum temperature is not enough to ensure uniform heating of work and a reasonably long service life for the RT.

Therefore, when a great number of RTs are to be equipped, the surface temperature distribution must most carefully be checked a priori in conjunction with the burners so that no hot spot may occur to bring the local temperature to over 1 000 °C, and that the temperature profile be a gentle slope along the length of a tube with the peak temperature held as low as possible. An example of temperature profile is shown in Fig. 6 for an RT in a test furnace for Sheet-CAL.

To avoid the deformation of RT, methods of attaching and supporting so as to leave enough freedom for thermal expansion and contraction must be taken. In fact, failure of an RT is due more often to cracking or deformation resulting from improper attachment and supporting than to expending of its inherent life resulting from high temperature oxidation.

2. The RT Burners

The properties that are required of an RT burner may be summarized as follows:
1) not to produce hot spots, and the peak temperature be low;
2) stable combustion even for low excess air rates, and not to make small explosions with soot accumulated on repeated on-off or by backfiring;
3) be able to operate under a tube pressure that is lower than the furnace pressure so that the combustion gas may not leak out into the furnace through cracks;
4) the air-fuel ratio be stably maintained throughout all of the combustion turndown, the flame be stable, and no abnormality to appear in the tube surface temperature distribution;
5) the combustion air be preheated sufficiently by the recuperator provided individually to each burner, preferably to over 400 °C;
6) the NOx be below 80 ppm;
7) the burner noise be below 70 dB (A); and
8) the surface temperature of burner and of burner
attachment be kept to lower than 100 °C.

As not all the burners that are equipped to conventional Tin-CALs satisfy all of those requisites sufficiently well, many are being replaced with new ones.

Now, the currently practised RT combustion methods may be classified into the pull type (with either an educator or an exhauster), the push type, and the push-pull type. Those are schematically depicted in Figs. 7 to 9. However, the push type can hardly be used in a CAL because the RT internal pressure will greatly exceed that of the furnace.

Of the remaining two, the push-pull type is superior to the conventional pull type in many ways as may be understood in Table 1. Among those merits of the push-pull method, the most interesting is the ease of control. That is to say, for a group of a great number of burners, while the variation in the air-to-fuel ratio \( m \) is as much as \( m=1.2 \sim 1.5 \) for the pull type, that for the push-pull is only \( m=1.05 \sim 1.15 \).

For another, according to Okada and Kitamura,\(^{23}\) in the push-pull method the flame length can be controlled simply by changing the swirl number of the combustion air; they have shown that the relative position of the peak in the RT surface temperature profile and the concentration of NO\(_x\) may both be presented in a function of the swirl number. This
is shown in Figs. 10 and 11, out of which an RT burner system design computer program has been developed.

3. Fuel Saving in the RT Heating

As mentioned earlier, the conventional heat recovery method for the RT exhaust gas has been to preheat the combustion air by means of a single stage recuperator provided for individual burners.\(^{24}\) In this case, however, because of restrictions in the space available at each burner and the pressure drops allowable for combustion air and combustion products at the recuperator, a preheating of air to 400 °C has been the reasonable limit. This means that the exhaust gas temperature is yet as high as about 600 °C at the recuperator outlet, and today, economy demands this heat be recovered much more until the exhaust temperature become 200 °C or even lower. Some of the devises that have been found effective are:

1) the use of a common recuperator on top of the individualized recuperators to make it the double recuperation;

| Table 1. Comparison between pull type and push-pull type for radiant tube heating system. |
|---------------------------------|-----------------|-----------------|
| Items                          | Types           |
|                                | Pull*           | Push-Pull**     |
| Temperature control            | High-low-off    | PID-off         |
| Precision                      | Not very good   | Very good       |
| Air-to-fuel ratio              | Complex         | Easy            |
| Control                        | Complex         | Easy            |
| Regulation                     | Not very good   | Good            |
| Reproducibility                |                 |                 |
| Combustion air flow rate       | Not possible    | Possible        |
| On-line measurement            |                 |                 |
| Feedback                       | Not possible    | Possible        |
| Combustion gas flow rate       | Possible        | Possible        |
| On-line measurement            |                 |                 |
| Feedback                       | Not possible    | Possible        |
| Tolerance to changes in fuel  | Almost none     | Great           |
| calorific value                |                 |                 |
| Capacity of exhaust fan motor  | Large           | Small           |
| Combusion air blower           | Unnecessary     | Necessary       |
| Maintenance                    | Difficult       | Easy            |
| System reliability             | Not very high   | High            |

* Exhaust fan type  
** Air gas flow rate control type

Fig. 10. Relation between the strength of swirl and the position of temperature peak along an RT.
2) the use of the stack recuperator equipped in the collective flue;
3) the use of exhaust gas to preheat the strip;
4) the use of exhaust gas to preheat the furnace atmosphere to indirectly preheat the strip;
5) the use of exhaust gas to preheat fuel gas having relatively low calorific value;
6) the use of a heating medium in the roll heating to preheat the strip;
7) generation of either steam or hot water by means of waste heat boiler or water heater; and
8) the use of a porous gas-permeable solid either at the outlet end of RT or in the recuperator to raise the thermal efficiency.25)

It has been shown that the final exhaust gas temperature can be brought down to lower than 200 °C by combining those methods.

Moreover, thanks to the recent progress in the recuperator technology, it is now quite common that a temperature recovery rate of over 70 %, namely, for an exhaust of 900 °C, a combustion air preheated to at least 900 °C × 0.70 = 630 °C should readily be obtainable. So much so that, unless the temperature recovery rate exceeds 70 %, one does not today consider that recuperator as "high efficiency".26) Indeed, this, coupled with extensive energy saving exemplified above, has elevated the level of overall thermal efficiency of RT heating method very close to that of the direct fired (DF) heating method to be discussed next; at present, theoretically or practically, the limiting thermal efficiency is considered to be the same for either.

It is conceivable, further, that a 90 to 100 % efficiency may be attained by utilizing the heat the strip releases away on cooling. In fact, the NKK-CAL that was installed at the Swedish Steel AB is equipped with a system in which the heat released by strip cooling from 700 to 560 °C is recovered as a hot water of 120 °C, which is used for heating shops in the winter time or sold to neighboring town as general purpose hot water.27) This kind of idea itself is old,28) but this is a classical example of an idea taking quite a while and needing a host of supporting technologies for it to materialize.

2. The Direct Fired (DF) Heating Methods

One method of heating that my supercede the RT method is the direct fired (DF) heating. For application to Tin-CAL, this method has a long history: the Selas Corp. has built one for the Inland Steel in 194929) and four for the Bethlehem Steel in 1956.30) But, subsequent years saw more application of it to the continuous galvanizing line (CGL), and for Tin-CAL, then for Sheet-CAL, RT heating to become predominant. In more recent years, however, from the mounting need of making as compact as possible the line that is tended to become ever larger with attending increase in the number of pass, the DF is on the verge of revitalization.

Thus, a large DF heating type Sheet-CAL will be developed by the Nippon Steel in the near future,31) but the following problems will have to be solved;
1) development of a direct fired heating burner and combustion system that ensures a stable non-oxidizing flame;
2) development of a system that ensures the strip to be heated unoxidized to as high a temperature as possible;
3) development of strip temperature control system that ensures an precise following-up of heating rate tuned to the slowing down or speeding up of the line speed;
4) for the above purposes, development of light furnace lining structure having a small time constant;
5) establishment of a method of preventing overheating and oxidization of the strip upon slowing down or stopping of the line; and
6) establishment of an effective preventive measure for picking-up by the hearth rolls down-stream to the DF heating zone.

Besides the obvious need of integrating all those new techniques and devices into an operational technology, comparative study of the radiative direct fired (RDF) heating method, which is the one that is currently common, and the convective direct fired (CDF) method, which is often used in the copper and aluminum industries, for their possible advantages as a system element will have to be done carefully.

1. The Radiative Direct Fired (RDF) Heating Method

The RDF method, which has been found effective to reduce the furnace size as mentioned earlier, may be applied to a Sheet-CAL any time, provided that a slight oxidation of the strip is tolerated then counteracted by conducting either the atmospheric reduction or the post anneal pickling.

The cares to be exercised to perform the non-oxidation heating with the RDF method are:
(1) the furnace temperature should be raised as much as the desired rise of strip temperature;
(2) at the same time, the air-to-fuel ratio should...
be made gas rich so as to provide more of the combustible CO + H₂ in the combustion gas; and

(3) for thicker strips that need longer residence time, the rise of furnace temperature and enrichment of fuel should be done that much more.

This means generally that the highest furnace temperature will become 1200 to 1350 °C and an m value of 0.9-0.95. In view of energy saving, this definitely calls for a certain heat recovery measure, for which a system that has for some time been practiced in the CGL or stainless steel catenary type furnace will be adequate.

This system is shown in Fig. 12 schematically. As may be seen in the figure, the heat of the exhaust gas is utilized to preheat the strip in two steps: while gas is still hot, the heat transfer is in the RWP (Radiative Waste-gas Preheating) mode, say from 1200-1350 °C down to 700-800 °C, and when the gas becomes cooler, it is in the CWP (Convective Waste-gas Preheating) mode, say from 700-800 °C to 200-300 °C. A clever combination of RWP and CWP promises a compact plant for greatest heat utilization.

All in all, the most important single equipment in any RDF heating is the direct fired burner, particularly the burner nozzle. Inasmuch as no “ultimate” burner is commercially available, the selection must be done in consideration of materials and structure of nozzle against dimensional stability and length of service life. As for the question of which one of the nozzle mixing type or the premixing type should be taken, on the other hand, this is no longer much of a problem today, for reliable burners of either kind are readily available.

2. Theory and Practice in the Oxidation-Reduction in the RDF Heating

According to the theory of equilibrium between steel and combustion gas, the steel is oxidized by CO₂ and H₂O and reduced by CO and H₂. The balance of oxidation and reduction between CO and CO₂ on one hand, and between H₂ and H₂O on the other, is shown in Fig. 13 as a function of steel temperature.

It will be seen that to heat steel from 20 °C to, say, 700 °C perfectly non-oxidizingly throughout, the gas composition must be CO/CO₂ > 1.5, and H₂/H₂O > 4.0, for which the RDF burner combustion need be at an air-to-fuel ratio m ≤ 0.5. This kind of combustion condition is actually realized in some heating furnace of the pipemaking line.

From those theoretical viewpoints, such RDF heating furnaces like today’s CGLs that operate at an m of 0.9 or so should not be called the NOF (Non-oxidizing Furnace) but rightly MOF (Minimum Oxidation Furnace). This is important for a DF heating continuous annealer because every stoppage of line will immediately mean a badly stained strip at the best and burning and breaking through of the strip inside the furnace at the worst.

Therefore, special preventive measures are being provided for a DF furnace such as:

1) to produce atmosphere having m ≤ 0.5 quickly by blowing raw gas into the furnace;
2) to blow methanol into the furnace so as to cool the strip and at the same time to produce a reducing atmosphere through pyrolysis of CH₃OH → CO + 2H₂;
3) to blow a great quantity of N₂ gas into the furnace to purge CO₂ and H₂O out and at the same time to cool the strip;
4) to separate the strip from the furnace by retracting the furnace body so as not to overheat but to let the strip cool in air; and
5) to introduce a water jacket or other cooling means into the furnace to rapidly cool the strip.

The reality is that without those emergency measures no DF heating system can be a commercial one.
another reason why it should be called the MOF, not the NOF.

How, then, is it that what the theory predicts as will fail can be accomplished in practice? My answer to this is that it is a matter of time and quantity of reaction. That is, the time the steel stays in the heating zone is about 25 sec at most in a continuous annealer, whereas it is 7 hr or more for batch annealing, really a ratio of about 1 to 1000; in this very short period of time, even when the steel does get oxidized in the weakly oxidizing atmosphere, the amount of oxide formed can be held to a commercially tolerable small quantity.

The results of DF heating experiment due to M. B. Pierson, shown in Fig. 14, substantiate this explanation. As may be seen in the figure, what is important for non-oxidizing heating is the combination of $m$ value, furnace temperature, and residence time of the work. Here, his observation that the steel was reduced first, but, in the same atmosphere, it became to be oxidized after a certain period of time does not stand to reason: probably, this was simply that the steel looked to him as if reduced in an atmosphere which had been slightly oxidizing from the start, because oxidation was so minimal in the time span employed.

It is well known, on the other hand, that reduction can actually be achieved in the Selas furnace that features direct impingement of the fuel gas onto the steel. This is shown in Fig. 15. The question is how we do understand this. For that, I might invoke a Soviet research. According to this report, a dynamic analysis of combustion of methane gas revealed that at a certain stage of combustion process formaldehyde ($\text{H}_2\text{CHO}$) is formed in a great quantity. This may mean that the residual oxygen existing in the mixture gas of air and fuel is caught by this formaldehyde resulting an oxygen deficient situation, and that thereafter combustion proceeds by reaction between oxygen and formaldehyde. This state of affairs

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**Fig. 14.** Oxidation–Reduction behavior of steel upon direct fired heating.

**Fig. 15.** Oxidation–Reduction diagram of steel due to Selas Corp.
would be observed as combustion of mixture gas in an oxygen deficient condition, hence successful completion of the non-oxidizing heating.

Indeed, this theory is rather convincing, and if it is right, we can see importance of such factors as burner capacity, shape and length of flames, and distance from burner to strip in designing a DF heating furnace. On the other hand, however, even if creation of reducing atmosphere through combustion by impingement of burner flame is proved by the dynamism, it remains to be a matter of local occurrence, and in between two adjacent burners, oxidation dictated by equilibrium should prevail. Therefore, if the non-oxidation anneal is to realize as a whole, it must be a consequence of repetition of reduction at the burner and oxidation in between as the steel moves through the heating zone.

Moreover, from the reaction rate theory it may well be that the balance between oxidation and reduction given in the final and high temperature range of strip heating does control the entire process. This notion would appear to give some credence to the assertion that provision of a strongly reducing zone immediately after completion of heating will relax those stringent requirements for heating of strip greatly.

3. The Convective Direct Fired (CDF) Heating Method

In the convective direct fired (CDF) heating, the combustion gas that has been created by burning fuel in a direct flame mode is led to the heating chamber pressurized by a recirculation fan, then blown onto the strip surface through nozzles. Namely, the CDF heating is a form of forced recirculatory direct fired heating of gas impingement type.

This is being applied to continuous annealing of aluminum, copper, and their alloys as a well established technology. In the continuous bright annealing furnace for copper strip, for instance, combustion is gas-rich with an m of about 0.9 so that the combustion gas will contain combustible CO + H₂ from 3 to 4%. Then, to make the residual O₂ less than 50 ppm, swirl is given to the flame on one hand, while the chamber is designed longish so as to secure temperature and time necessary for reaction on the other, and after adjusting the gas composition to be equivalent to the DX gas (wet) let it impinge upon the metal. By equipping with an automatic m value controller working on either a CO meter or an H₂ meter to enrich the fuel gas, further, the atmosphere can be held stably to bright annealing condition in a wide firing range. Thus, the copper strip bright annealing, which used to rely traditionally on the RT heating with protective atmosphere, is now almost always of the CDF heating type.

The merit of CDF method as compared with RT or RDF method are:

1. thanks to the forced convection, fast and uniform heating is ensured irrespect of metal surface emmissivity (ε);
2. thanks to the large convective heat transference (hc), the furnace, or the gas temperature can be greatly reduced for a given furnace length, making uniform heating easier and improving the furnace heat efficiency;
3. even though for a material with a particularly small ε, as its effective radiative heat transference ε·hrBB is also small, deficiency in the capacity must be countered to either by raising the furnace temperature or by lengthening the furnace, but then since hc does not depend on ε, it is quite possible to make hc ≈ ε·hrBB, so that the furnace length may be shortened quite a bit (Fig. 16);
4. because the heating rate can be regulated not by changing the furnace temperature but by changing the nozzle gas velocity, hence the hc itself, a very fast response is had, so that the temperature control and changing of line speed or strip thickness is greatly improved;
5. on changing of setting of the heating temperature, since the response of the gas temperature is faster than that of furnace temperature, the time needed to execute the cycle change is shortened;
6. no overheating of the strip upon line stoppage, hence no troubles like strip breakage at all; and
7. as only a very small number of burners are needed in comparison with the cases of RT or RDF heating, both operation and maintenance are much easier.

The point No. 3 above merits further explanation: suppose in an existing Sheet-CAL, one wishes to replace the current RT heating with a CDF having an hc of 57 kcal/°C·m²·h, then for heating the strip to 700 °C, the furnace length can be shortened to some 60% of the original even while lowering the furnace temperature from 900 to 800 °C. Or, if the furnace 

![Fig. 16. Shortening of RT heating furnace length by adopting forced convective heating for radiative heating.](image-url)
length is to remain the same, the furnace temperature can be lowered to as low as 720 °C. This means that now the thermal head is only 20 °C, a figure which not only makes a very precise heating control quite possible, but entirely eliminates any danger of overheating on changing the line speed or the strip thickness.

Thus, application of CDF heating to Sheet-CAL is worth a close study. For the problem of keeping the oxidation to below the tolerable limit, which will have to be solved before it is realized, a safer way, that of forced convection using RT combustion heating (CRT) will come as a transient. This method is to be actually adopted by some of American Sheet-CALs, and the furnace length is expected to be cut to about 60 % of that for conventional radiative RT (RRT) furnace.

3. Other Heating Methods

Other than the RT and the DF heating, methods using electric resister, induction, ohmic resistance, electron beam, roll, or salt bath appear to hold some prospects in the future. Since the RDF, CDF and CRT methods are all able to achieve a 30 ~ 60 % reduction in furnace length from that of conventional RRT furnace, however, any new comer will have to promise an even greater reduction. In this respect, the elctic resister heating method will not become very popular because the furnace length will remain the same as or even longer than RRT furnace.

On the other hand, according to recent studies made by Iguchi and his co-workers for ultra-high rate heating of steel of 10⁶ to 10⁷ °C/sec, achieved by methods like ohmic resistance, plasma jet, capacitor discharging, or irradiation by laser, following very interesting observations have been made:

1) while the normal isothermal transformation diagram generally holds good for austenitic transformation under such fast heating, for more exact study, TTA (Temperature–Time–Austenitization) curves will have to be prepared;
2) quenching after such fast heating produces a structure which is even tougher than that due to ordinary quenching—since this phenomenon appeared to them the quenching function was augmented by the fast heating, they called it the “upper-quenching”;
3) the structure obtained through ultra-high rate heating and quenching is one in which only the pearlite gets austenitized then transformed into martensite upon subsequent quenching, with ferrite left intact—a peculiar structure which they called the “martenoferrite”; and
4) by combining the fast heating and thermomechanical treatment, therefore, an original rapid heating superplasticity heat treatment method may be had, out of which a novel material is expected to develop.

This technology may or may not apply to the cases at hand as such, but the importance of rapid heating is clear enough. It is for this reason that I regard the methods of induction, electron beam, salt bath and roll heating as highly promising for future Sheet-CAL application.

1. The Induction Heating Method

The induction heating has been tried on a Tin-CAL by the Westinghouse for a part of the heating zone, but with dubious results. The difficulty was apprently that the temperature difference over the strip width was as much as 10 % of the strip temperature due to eddy current generated at the edges. This may prove to be fatal for realization of sole induction heating.

On the other hand, however, Yamazaki and his associates have successfully developed an induction heating method for drying the surface coating of silicon steel sheets. In view of their success, which is undoubtedly due to the fact that temperatures needed for drying is only 250 °C or so, at which the unevenness of temperature should not be much of a problem. This suggests for possible application to Sheet-CAL the partial heating for a raise of 200~300 °C at the final stage of heating zone. This usage would be effective not only to reduce the furnace length but to improve the strip temperature control.

To heat a thin strip by induction in the longitudinal flux mode, namely to align the magnetic flux parallel to strip, the frequency need be very high to maintain the efficiency reasonably high. Therefore, the transverse flux mode, in which the magnetic flux is through the strip thickness, will have to be taken for additional advantage of the use of low frequencies and better efficiency. In either case, cooling of the in-furnace coil or electrode will pose another difficult problem.

2. The Electron Beam (EB) Heating Method

The electron beam (EB) heating method is being tried on the paint drying line, the vacuum deposition of zinc or aluminum, and the stainless steel bright annealing line. The merits to be exploited are:
1) the ease of control of heating output and the very fast response of less than 1/100 sec, so that overheating of stock can be readily avoided even for a sudden change in the line speed or line stoppage;
2) the simplification of equipment in that loopers and bridles can be eliminated;
3) the greatly reduced furnace length, hence saving of space;
4) the yet better grade of bright annealing than conventional gas atmosphere method thanks to the vacuum environment; and
5) the cleaning or descaling effect of bombardment by electron or ion beam.

For those advantages, the U.S. Steel has started commercial production of aluminized steels by means of an EB continuous vacuum deposition method since 1966. It looks as though application to Sheet-CAL is not too far. An example of operating EB continuous aluminizing line is illustrated in Fig. 17.
in which molten sodium is used as the thermal medium. It is claimed on the basis of pilot plant tests that the furnace length can be only 1/70 of conventional RT heating type ones, that fuel consumption is no more than 15 %, that no loopers are needed, and that the precision of temperature control is very good. Besides those, it was in this process that the epoch-making idea of utilizing the heat the strip releases upon cooling as an important process heat source by using it for preheating the strip was first put to practice.

The second is BISRA’s invention. The features reported are about the same as above, and it was reported that by performing the overaging treatment on the coil following annealing, a good quality tin gage steel of the TU specification was obtained.

Despite those benefits, no large commercial lines of either type have ever been built. The reason is probably that the handling of salt, particularly removal and recovery of that adhered onto work surface, is not well developed. However, in this age of high energy cost, the very idea of linking the heating and cooling by a single heat medium to achieve fast heating and effective heat recovery should merit a special attention.

4. The Roll Heating Method

Even while the roll cooling has recently been commercialized in a Sheet-CAL, drawing an attention it deserves, the roll heating method, which had been developed in 1960s by a Swedish firm of the Gränges Metal Verken, is still operating in this country for annealing copper strips of as thin as 60 μm.

This appears to suggest an early application of this method to the Sheet-CAL, probably to preheat the strip by utilizing exhaust gas heat through a heat medium.

III. Cooling Technologies for Sheet-CAL

The way that every one of the ten-odd Sheet-CALs that have been built here or in abroad is different from the other attests to the fact that this is an yet developing technology. For example, the methods of primary cooling after the heating and soaking now practiced can be classified into the gas jet (GJ) method, the roll cooling (RC) method, the hot water (HW) method, the cold water (CW) method, the CW/RC switching method, the two-phase (gas phase/liquid phase) method, and the others. The mean cooling rates achievable by the first four method through a range of 600 to 400 °C on cooling a 1.0 mm thick strip from two surfaces as calculated with mean heat transfer rates α that are estimated for each are shown in Table 2. Here, the equation used is:

\[ CR = \alpha \cdot \log(JT)/1.8 \cdot C \cdot \rho \]

where, \( CR \): the cooling rate (°C/sec·mm thickness) 
\( \alpha \): the overall heat transfer coefficient as seen from the strip surface (kcal/m²·h·°C) 
\( C \): the mean specific heat of the strip (kcal/kg·°C) 
\( \rho \): the density of the strip (kg/m³) 
\( \log(JT) \): the logarithmic mean temperature difference (°C).

It is to be noted that for the RC system \( \alpha/2 \) has to be used in the above equation because it is naturally the one side cooling.

As the cooling rate can be regarded as being inversely proportional to the strip thickness, further, for a practical range of, say, 0.4 to 1.6 mm, the actual rates of those methods overlap each other. In this sense, therefore, the rates specified by the patent claims of NSC-CAL, NKK-CAL, and KM-CAL as 5 to 30 °C/sec, 30 to 50 °C/sec, or 50 to 2000 °C/sec, respectively, are not much of a significance. Rather, what is important in assessing any cooling method is to know the greatest rate and the range of heat transfer obtainable as a system.

1. The Gas Jet (GJ) Method

The gas jet (GJ) method was first developed some 20 years ago by the General Electric (GE) and by the Midland-Ross (M-R) for Tin-CAL, primarily to shorten the furnace length by the last cooling zone. At first, both of them met with difficulty of strip flattering and getting scratched, but GE was able to overcome this successfully into commercialization by rearranging the unit coolers and M-R by means of the pressure pad system.

For application to Sheet-CAL, however, many more had to be added to improve the controlling and to ensure a large enough convecting heat transfer.
coefficient \( h_c \). For the latter, in particular, devices like 1) to increase the gas jet velocity as well as gas volume; 2) to make the distance between strip and nozzle variable and to set it as small as possible; 3) to enrich the gas with \( H_2 \); 4) adding an atomized liquid to the gas; and 5) using atomized liquid as the coolant are under testing.

Thus, in the KM-CAL, an average \( h_c \) of as much as 250 kcal/m²·h·°C has been reported realized by combining methods 1) to 3) properly. As this figure is considerably larger than what is considered achievable in commercial lines, their effort is to be commended. As for the method 3), there are more gases besides hydrogen that will increase the \( h_c \). Some of the candidates are shown in Table 3) in comparison with air.

Table 3. Comparison of convective heat transfer rates of various gases with that of air as the base (at 300 °C).

<table>
<thead>
<tr>
<th>Gases</th>
<th>Ratios</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1.00</td>
</tr>
<tr>
<td>Carbonaceous combustion product</td>
<td>1.06</td>
</tr>
<tr>
<td>Water vapor</td>
<td>1.15</td>
</tr>
<tr>
<td>Carbon dioxide (CO₂)</td>
<td>1.38</td>
</tr>
<tr>
<td>Hydrogen (H₂)</td>
<td>1.58</td>
</tr>
<tr>
<td>Coke gas</td>
<td>1.71</td>
</tr>
<tr>
<td>Methane (CH₄)</td>
<td>1.70</td>
</tr>
<tr>
<td>Acetylene (C₂H₂)</td>
<td>1.73</td>
</tr>
<tr>
<td>Ethylene (C₂H₄)</td>
<td>2.16</td>
</tr>
</tbody>
</table>

Now, if we are to plot the GJ data, both heating and cooling, of what actually experienced in operating furnaces in terms of \( h_c \) vs. \( Q \), the gas density, or gas volume per two surfaces of strip m³/min·m², we obtain an arrangement shown in Fig. 18. Further, considering that \( h_c \) should be a function of \( Q \) on the basis of mass transfer, we might expect a relationship \( h_c = k \cdot Q^a \) would be a reasonable presentation. It will be seen in the figure that a \( k \) of 5.5 and an \( a \) of 0.7 give a very good fit. This may mean that the idea of mass transfer as a basic mechanism is an agreeable one on one hand, and on the other hand, that reliable prediction of necessary gas volume to obtain an \( h_c \) value should be possible with this chart.

Other finer points that need be considered when designing a GJ system are the change of \( h_c \) value by the kind of gas to be used, the change of \( h_c \) by the change in gas concentration, the entrainment effect, or the change of \( h_c \) due to dragging-in of the gas around the nozzle jet, effects of nozzle pitch, nozzle shape and size, and distance between nozzle and strip on \( h_c \), the change in the coefficient of vena contracta due to changes of nozzle design, and effects of the gas volume and pressure, namely the mass velocity of the gas, on \( h_c \). It is worth remembering that knowledge of those and a selection of proper combination is essential to design a really efficient gas jet system.

Adding to those, furthermore, means to counter to the differences in the cooling rate across the width i.e., over edge-center-edge, of the strip should be provided for quenching the strip with high velocity gas jet to ensure uniform cooling and to forestall buckling. Also, as fluttering or twisting of strip induced by the pressure difference between the two sides of strip or by the suction effect of the gas escaping around the edges can be an immediate cause of scratching, means of stabilizing the strip is a necessity. For this purpose, the non-contact type pressure pad system shown in Fig. 1969 and the contact type guide roll system illustrated in Fig. 2014 are both known to be effective.

2. The Cold Water (CW) Cooling Method

When quenching by rapid cooling is intended, there is no medium than water that is cheaper and easier to use. It is so with CALs also so that water had been used in Inland Steel's martensitic tin plate annealing line59 and in many aluminum strip solution heat treatment lines.60,61 When a thin and wide strip is water-quenched from a high temperature, however, large deformation is inevitable, so that following-up with a stage of shape correction has been the common practice.

A challenge to this common sense practice was made by Kubodera, Nakaoka, and co-workers, and a very practical strip non-deforming water quenching method was developed.62,63 The key to their success is found in the treatment of the vapor film that adheres onto the strip upon water quenching: as vapor film is formed unevenly over the surface of strip that is running through the water, the strip is subjected to a very fast cooling where there are no vapor films.
present and to a much slower cooling where the vapor film acts as insulator. They traced the deformation of strip to this uneven cooling, and to prevent it, they have devised a practical method to remove the vapor from the strip surface. It was to combine in-air water jetting and in-water water jetting, and it was by the success of this method that the NKK-CAL was commercialized.

Beautiful though their solution was, there are yet some points left to be improved. For example, the cooling rate is too fast to practice the interruptive quenching, so much so that unnecessary overcooling is unavoidable to make commercial quality (CQ), drawing quality (DQ), or deep drawing quality (DDQ) sheets, for which reheating zone for overaging, hence additional fuel, is needed. Because of water quenching, further, oxidation due to water vapor is inevitable, necessitating a pickling unit and bringing up the problems of added installation cost and of treatment of waste acid.

Although those problems can be solved, theoretically at least, in practice other difficulties, such as these coming from the restrictions inherent in the basic requirements of non-deforming water quench system, will become unignorable. For those reasons, the accelerated cooling (AcC), that in the order of 100 °C/sec, will become popular.64 To achieve this, propositions like 1) to counteract the vapor oxidation, the atmosphere at the strip exit of the water tank is enriched with H2 to maintain a large H2/H2O ratio there65; 2) to alleviate the excessively large cooling power, other quenchant than water is either added to water or employed in its place66,67; and 3) as in the NKK-CAL, to conduct the pickling at the furnace end so as to double for the final cooler also, are being made.

3. The Hot Water (HW) Cooling Method

We have seen that uniformization of cooling in the CW method was achieved by removing the vapor film from the strip surface, but here is another process that utilizes a completely reversed idea. It is due to Belgian firm CRM, and they have succeeded in cooling the strip uniformly with boiling water, thus by developing vapor film uniformly over the strip surface.68,69 They have called it the HOWAC process, and have decided to build it in 1984.70

The features of this HOWAC process are claimed to be as follows68:

1) the cooling rate is some 1/20 of CW cooling and considerably faster than GJ cooling;
2) as it is a relatively slow cooling, interruptive quenching is readily possible simply by changing the length of submerged strip;
3) this will be used advantageously for CQ, DQ, and DDQ in that application of interruptive quenching should result in a saving of fuel at the reheating zone, though it does preclude the manufacture of higher grades high strength strip steels because they need be cooled to water temperature; and
4) considering that recovery of strip heat by hot water can be done quite easily, a very good heat efficiency may be had.

There is one uncertainty with this process, however. It is the question if the vapor film can stay stably against fluttering of strip, under higher suddenly raise of line speed, or uneven contact of the strip and the submerged rolls. Any one of those will give rise to local separation of the vapor film, which will in turn cause uneven cooling.

4. The Roll Cooling (RC) Method

The free change of cooling rate and the saving of fuel by interrupted cooling, the two operations that are considered very difficult, if not altogether impossible, for either of CW and HW methods have both been realized in NKK-CAL by means of the RC method.71 The development work of this method was undertaken by Naemura et al.,72 first for the No. 2 CALs of their own, then it was applied in 1981 successfully to Kobe Steel’s Sheet-CAL.
With this method, cooling rates that are between those of the GJ or the CW methods and appropriate for AcO (Accelerated Cooling), such as 100 °C/sec or more, may readily be obtained. Further, by changing the length of contact between the roll and the strip, the cooling rate can also be controlled easily.

Here, however, steady holding of tension so as to ensure a uniform cooling rate over the strip width and the quality and manner of flow of the cooling water are both important. As for the quality of water, as formation of deposits at the inner wall of the roll means a loss of the heat transfer rate, use of pure water is recommended. For the manner of water flow, on the other hand, the one that divides water at the center to make each half flow to the respective roll end, rather than a one-directional flow, appears to be promising. Further, even though the cooling rate can be controlled to a certain degree by changing the water flow rate, decreasing flow rate should be practiced with care for it may accelerate the formation of scale or incur uneven cooling.

Lastly, this RC method has already been applied to the secondary cooling zone, in which it is reported that the fan power was actually halved.

5. The CW/RC Switching Method

The CW/RC combination type Sheet-CAL, in which the CW method is used for manufacturing high strength steels and the RC for making CQ, DQ, and DDQ was commissioned by the Kobe Steel in 1981; it has since been working to expectation.

The most important technical point in this CW/RC method is how to execute the changeover in the shortest possible time. There are a number of proposals for this, but ideally no changing of strip path should be involved. That is to say, rather than bypassing either one of CW and RC, the strip is made to go through the both in series, while either of them is stopped in accordance with the schedule. Needless to say, proper consideration should be given to the one that is on the upstream so as to be able to withstand the heat it must bear during the stoppage yet not to precool the strip by itself.

6. The Two-phase (Gas/Liquid) Method

This method, with its wide range of easily controllable cooling rates, promises fast development of applications, including my own proposal. In fact, it has already been employed in two CAPLs by the Nippon Steel, whose data is expected to be published soon.

The important technical points for this method are that the strip be not oxidized, that the recovery of coolant be sufficiently good, and that a non-polluting coolant be selected. Equally important is the uniform mixing of the gas and the liquid phases. The two possible methods are, like in the case of burners, the nozzle mixing and the premixing. From the uniformity stand point, the premixing is superior, but how to prevent condensation of once atomized liquid is the key point. For the nozzle mixing, it may typically be the parallel flow type or the cross flow type, with any varieties in between, as may be seen in Fig. 21.

Generally speaking, the smaller the atomized liquid particles, and the smaller the proportion of liquid against gas, the smaller the cooling rate, or the easier the uniform cooling. Here, the current arbitrariness in the divisioning of two-phase mixture states by liquid particle size can be detrimental, as pointed out by Kunioka and his co-workers, for furthering the technology. For this purpose, I propose to define the two-phase cooling both by the liquid particle size and by the flow pattern as follows, with provision that the liquid-to-gas ratio be given in specifying the cooling rate, and that this nomenclature be used for the cases of liquid only, this because of the ever present gas entrainment due to liquid jet thrust:

<table>
<thead>
<tr>
<th>Nomenclature</th>
<th>Liquid particle size</th>
<th>Flow pattern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fog cooling</td>
<td>&lt;1 μm</td>
<td>Two-phase</td>
</tr>
<tr>
<td>Mist cooling</td>
<td>1~100 μm</td>
<td>Liquid</td>
</tr>
<tr>
<td>Spray cooling</td>
<td>&gt;100 μm</td>
<td>Laminar flow</td>
</tr>
</tbody>
</table>

It may be noted in Table 4 that this proposition of mine bases itself on the investigation due to the Stanford Research Institute. According to this, mist is defined as made up of particles of 0.01~10 μm and spray 10~2 000 μm, but no definition for fog. Therefore, I corrected for this by adapting the range for smog of 0.01~2 μm and modifying it to read less than 1 μm for the cooling fog. As for the cooling mist, on the other hand, I took the upper limit to be 100 μm in view of the meteorological fog, which is around 100 μm.

In fact, people of the aluminum industry have been using this convention without calling it as such. That is to say, in order to prevent deformation of aluminum alloy strip upon quenching for continuous solution heat treatment, fog cooling is being applied to when the strip is thin and liable to deforming, mist cooling for medium thicknesses, spray cooling for thick plates, and laminar flow cooling for yet thicker stocks that need faster cooling rates.

Besides that the need of defining fog cooling is thus obvious, if simply because it is being used in the USA for solution heat treatment of aluminum alloys, the proposed plan is reasonable, I believe, both in
the overall arrangement of the situations and in the relation to the meteorological conventions.

As for the methods of creating fogs and mists, the general practice is to nozzle mix a high pressure water and a high pressure air, and by regulating the ratio, the desired water particle size is obtained, the two extremes being the air jet cooling, which is attained by decreasing water, and the water spray cooling, this by reducing air.

Those water quenching methods of aluminum strip have been established by the American firms of Kaiser, Reynolds, and Alcoa in the floater type continuous quenching lines for manufacture of aircraft grade sheets. It is well to remember that this technology has been perfected for aircraft materials, which demand an exacting quality, meaning that it should be worth for intensive study for adoption in the Sheet-CAL whose major product is automotive sheet steels.

7. Other Cooling Methods

Besides those discussed so far, there are two methods that are promising. They are the methanol cooling and the press-quenching by salt bath.

Of the two, the methanol cooling, which I have studied intensively, can be said to be near perfection to apply to the Sheet-CAL. That is, in a series of tests conducted with 1.0 mm thick strips, cooling rates of 80~200 °C/sec have been achieved over a range of 700~300 °C obtaining bright finish. Further, liquid nitrogen, liquid ammonium, from gas, and lower hydrocarbons have been proposed for the coolant.

The methods of using salt bath of various kinds for quenching, on the other hand, have been studied as discussed earlier. One famous variety is the continuous isothermal transformation furnace for bainite steels, where lead is used for salt, and, to suppress the transformation deformation, press-quenching, namely quenching by pressing the work against a flat plate, is often employed. Here, the coolant may be lead-bismuth alloy, and the press-quenching can be combined with spray quenching.

Lastly, I wish to call your attention to the quench back. This is a phenomenon that is especially notable with steels of high quench sensitivity, in which the work is precooled, by its own heat conduction and radiation to environment, to below the proper quenching temperature so that effective quenching is no longer possible. This often happens when the line speed is abnormally lowered, so much so that the cooling unit even with a cooling capacity great enough for ordinary purposes cannot follow up. The nomenclature is due to the M-R research staff, and to forestall this trouble, the aluminum industry people have established lower most line speeds for each alloy.

The results of computer simulation of this phenomenon are shown in Fig. 22, in which you will note that the thinner the strip, the greater the temperature drop due to quench back. This will be even greater in the actual cases where the furnace temperature is lower than the work temperature, for then the radiation cooling is superimposed on top of what have been considered in the simulation.

This would mean that precooling could be a problem for manufacturing of high strength steels in Sheet-CAL. One method of countermeasure is to maintain the pre-quenching furnace temperature at a proper level, for which purpose provision of quick heater, either of an induction type or of a plasma jet type, just before quenching to prevent lowering of, or to recover, the strip temperature is effective.

IV. Heating and Cooling Technologies for the Tin-CAL

Photograph 2 shows a Tin-CAL furnace. As mentioned briefly at the outset, the Kawasaki Steel has been successful in developing their own CAL, the KM-CAL. The KM-CAL is noted for its dual duty, namely for the sheet gages and for the tin gages, and it was for this feature that their technology has been exported to West Germany recently.

Now, for a dual-duty line like the KM-CAL, the greatest technical problem that has to be solved is how to move a strip as thin as 0.15 mm at a speed as fast as 600 m/min through various temperature zones without incurring the heat buckling. Naturally, this
calls for a technology of more uniform heating and cooling as well as more delicate temperature control than those for ordinary Tin-CAL. Factually, it has been reported that the following have been the important improvements:

1) that by preheating the rolls, the temperature difference between roll and strip is reduced;

2) that an automatic system that determines the correct emissivity of the strip has been developed and employed; and

3) that for the first cooling zone, in particular, A. extensive H₂ enrichment as much as 50%, B. an automatic controlling of cooling intensities in the strip lateral direction on the basis of direct measurement of temperature profile, and C. the process computer controlling by what they call the “Adjustable Cooling System” to obtain a widely ranged cooling rates, have been done.

Needless to say, in the background of KM-CAL, there lay technologies that had been cultivated in the Tin-CALs to realize a fastest possible motion for the light gage works such as, for example, the improved hearth rollers having a profile and surface roughness that are determined in consideration of initial crown and heat crown, the improved heat curves on recognition of different thermal heads for different thicknesses, and the improved in-furnace tension control to give rise to an optimum balance for the strip being treated.

As may be understood from those, the first cooling zone is now capable of functioning variously in accordance with the metallurgical requirements such as, for example, holding, cooling at a rate of 30~50 °C/sec, or fast cooling. Owing to this versatility, the products range has been expanded to include the high temper tin-plates, the low temper tin-plates, electrical steels, dual phase steels, and cold rolled sheets. The heat cycles for these are shown in Fig. 23.

We may expect that this kind of multiple-purpose furnaces will become popular among comparatively
small-scale steel makers on one hand, and that cases of conventional Tin-CALs being converted to those multiples will increase on the other. For example, the NSC has recently announced that their Tin-CAL can now be made to serve for manufacturing soft tin gages by applying their own over aging cycle to it.15 That is to say, where conventional Tin-CALs were able to deal with only T4, T5, and T6 grades, and batch annealing in a bell type furnace was necessary for T1, T2, and T3 grades, any one of T1 to T6 can now be produced in one single Tin-CAL.

Thus, I feel I can prophesy with confidence that the technology of rapid cooling plus overaging that was first invented by the U.S. Steel3 and was subsequently developed into Sheet-CAL in Japan will find its applications not only in the Tin-CAL but in the CGLs of various kinds. In fact, the Sheet-CAL of the Bethlehem Steel has been so laid out that it will be used as a CGL quite easily, and conversely with their CGL the Sumitomo Metal has been able to produce 100 kgf/mm² class dual phase high strength steels.89 There will be many exciting developments in stock for this technology.

V. Heating and Cooling Technologies in Continuous Annealing of Stainless Steel Strip

The methods of heating and cooling for continuously annealing stainless steel strips can be various in accordance with if the steel is of the JIS SUS 200 series (the ferritic steels of 18 Cr type), the JIS SUS 300 series (the austenitic 18Cr–8Ni type), or the JIS SUS 400 series (the martensitic 13 Cr and 16 Cr types). The heat cycles for those are illustrated schematically in Figs. 24 to 26, respectively.

As for the annealing line, further, two kinds, the annealing-and-pickling line (APL) and the bright annealing line (BAL), should be separately considered. In the APL, in particular, differences existing between the so-called “hot” strip, which is to be subjected to the intermediate anneal for softening, and the “cold” strip, which is for the final annealing before temper rolling, must be recognized, because an APL is generally expected to deal with both. Namely, as may be surmised in Table 5, especially by the ε value, the thermal responses of the two are very much different, so much so that when accepting the “cold” strip, the productivity of the line will be reduced to about one half of that for treating the “hot” strips.

Moreover, where it has been the common practice to do the intermediate annealing of the ferritic and the martensitic steels in a bell type annealer, because those steels need be kept to the temperature for a long time then cooled slowly, it is said that NSC has succeeded in doing this in an APL.90 If pursued to commercialization, this should prove to be a development worth watching.

In the world of BAL, where rigid controlling of atmosphere is the prime requisite to ensure bright finish, on the other hand, recent trend is toward the
muffle type furnace. The vacuum type should also be watched closely.

1. Heating Methods for the APL

The APLs are most commonly of the direct-fired catenary type because of the need of heating the work up to as high as 1200 °C. As for the atmosphere, the popular practice has it to maintain the oxygen concentration at 2 to 3 % on the premise that the work is to be pickled afterwards. This is because as the oxygen content approaches zero, the scale that develops becomes denser, hence harder to pickle. Oxygen sensors that enable this controlling are commercially available today. A typical catenary type APL is shown in Photo. 3.

Actually, the furnace shown in Photo. 3, which is of the unified furnace structure, is a product of fairly recent development; before that, the furnace body of all the large lines had to be composed of several sections in what is known as the split furnace catenary type. This was because of the difficulty of placing the support rolls in the furnace, since rolls that not only could bear up such high temperatures but would not pick up scale particles to damage the strip surface were unknown: they had to be placed outside of the furnace and between two adjacent sections at a very considerable expense of large heat waste occurring at the section junctions, not to mention the necessarily lengthened line.

As it was obvious that the problems of rolls had to be solved before those difficulties were overcome, many proposals have been made toward development of in-furnace service rolls: for example, the asbestos rolls,92 the chromium plated rolls, the copper plated rolls,93 the silica fiber rolls,94 the vermiculite sleeve rolls,95 the carbon sleeve rolls,96 and the ceramic fiber sleeve rolls.97 In the matter of long service life, however, none proved satisfactory.

The breakthrough was achieved by the Chugai Ro Kogyo who undertook to develop the asbestos roll in conjunction with the split furnace type line, though at first for prevention of scale pick-up trouble. Namely, Kitada and his associates have succeeded in unifying the split furnaces into one continuous entity by devising a means, a cooling chamber, that keeps the roll surface temperature down to a level that ensures a long enough service life.98 The unified furnace APL thus produced duly demonstrated its indubitable superiority in the fuel rate, and, aided by the outbreak of the Oil Crises, it has become so popular that all the APLs that were commissioned afterwards are of this design.

Further improvements have been added, and today the most advanced APLs, which are equipped with RWP, CWP, and the collective recuperator system in much the same way as in the MOFs of CGL (Fig. 12), can proudly boast a fuel rate that is a mere one third of what had once been with the split furnace type APLs.99,100 The progress thus achieved is illustrated in Fig. 27.

In the mean time, quite another idea has been developed by the Nippon Steel. It is the "U" type furnace that is depicted in Fig. 28, in which, as the work is hung freely in a upright chamber making a letter U, there is no need for the in-furnace support rolls. Together with other features like the compactness, hence the smallness of surface area for better heat economy, the ease of threading, the possibility of positively utilizing the heat the work gives up on

Unit: fuel consumption
10³ kcal/t at 1120 °C heating

Split furnace

Unified furnace
Roll & roll cooling chamber
Spare roll

Unified furnace + RWP

Fan

Unified furnace + CWP + RWP

Fig. 27. Progress of the catenary type APL furnace.
cooling by making the inlet path the heating zone and the outlet path the cooling zone, and the small fluctuation in the tension thanks to the free loop controlling, this merit appears to promise a good future for it. On passing, however, I might mention a fact that the idea of U type furnace itself is my own, for which a patent has been granted to me in the form of a coatings drying line for silicon steel strip.10 Furthermore, I submit that an "I" type furnace, in which both heating and cooling is conducted consecutively in one single vertical pass, should be considered in earnest. Insofar as a 70 m high continuous annealer is actually working for copper strips as I described in Chapter II, there should be no reasons in the case of stainless steel why an I type furnace would be impossible where U furnace is possible. On the contrary, the merit of having the work coming out of the furnace at low enough temperature, quite possible with an I type disposition if those fast heating, fast cooling technologies of present days are exploited to full, will be held favorably over the U type, in which the work necessarily exits the furnace at a high temperature. Moreover, my long experience tells me that, with an I type design, it will not be too difficult to shorten the furnace length to 60 to 70% of today's APLs.

Lastly, I would like to introduce to you in Fig. 29 a salt bath type continuous annealer that was developed by the Ajax Electric. This one is being used for heat treating beryllium copper and phosphorus bronze, and should be of a technical interest to the iron and steel industry because of its unique arrangement of salt flow.

2. Cooling Methods for the APL

Though cooling of ferritic and martensitic stocks is not much of a problem because they are to be slowly cooled, that for austenitics is much more demanding: after having been held for a certain period of time for austenitization, they have to be cooled at a rate of more than 20 °C/sec through a range of about 900 ~ 600 °C, with the cooling rate accelerated after about 700 °C. The popular practice is to let the work cool down to 900 °C naturally, then apply forced cooling by mist, or, when the gage is light enough, say less than 3 mm, by air jet.

When the work is cooled down to about 600 °C, however, either one of the following two methods should be adopted for further cooling according not only to whether the strip is the hot rolled stock or it is cold rolled one, but to whether the descaling before pickling is to be conducted in the Kolene process103 or in the Ruthner process,104 for the nature of the scale is different. Namely, if the Kolene method of descaling is to be employed, the "cold" strip is air-cooled to 450 °C, let pass through a 450 °C salt bath to crack the scale, then led to the pickling unit, whereas the "hot" strip is cooled to 80 °C, first by air-cooling then by water spray, and shot-blasted before pickling. If the Ruthner method is to be used, on the other hand, the work, whether it is "hot" or "cold", is cooled to 80 °C likewise, namely by air-cooling followed by water spray, then the "hot" strip is passed through a scale breaker before pickling, though the "cold" strip is sent to pickling unit bypassing the scale breaker.

3. Heating Methods for the BAL

The BAL, which was commercialized in the USA in about 1950, was first introduced to this country in 1961. It was Nisshin Steel's Shunan Line, then in 1968 Kawasaki Steel's Nishinomiya Line, depicted in Fig. 30,105 which was designed by the Drever and the Production Machinery was commissioned. Other varieties are shown in Figs. 31 and 32.

The weakness of this kind of BAL lies in the fact...
that the heating zone is made up of refractory and electric resistor elements. Namely, because the refractory is bare, or exposed to furnace atmosphere, attaining a low enough furnace atmosphere dew point is a very time-consuming and maintaining it during operation is not too easy either. Besides, for the service in those high temperature, low dew point atmospheres, the resistor must be the very expensive Mo wires, while the refractory must be the high grade alumina bricks because the silicate component gets reduced to produce H₂O, raising the all important dew point.

For those reasons, the muffle type BALs are being developed intensively. Various types, namely vertical, horizontal, direct-fired, or electric resister heating, are possible with the muffles, and the one that is operating in this country today is of the horizontal, roller hearth type.

Another development worth our attention is the vacuum BAL furnace, particularly that makes use of the electron beam (EB) heating. If and when this type BAL is perfected, the merit will be enormous; the vacuum annealing will dispense with the rather tedious post-anneal skin pass rolling process, which is necessary at present to give rise a proper bright surface finish to the stainless steel strips.

4. Cooling Methods for the BAL

In the vertical BALs, the work is cooled first slowly by a water jacket, then rapidly by means of the gas jet (GJ). For austenitic steels, in particular, high speed GJs of up to 60 to 70 m/sec are used to ensure a cooling rate of at least 15 °C/sec for metallurgical reasons. In any event, as the BALs are to produce the final products, uniform cooling is of the primary importance to prevent deformation associated with rapid cooling.

VI. Conclusions

When I was preparing this lecture to review the development and the future prospects of heating and cooling technologies for Sheet-CAL, I found myself drawing rather heavily on the data gained in the continuous annealing of copper and aluminum. Having been engaged for a long time in designing the continuous annealers both for ferrous and for nonferrous metals, I am firmly convinced, and I hope you will agree with me from what I have described today, that engineers of both fields should intensify the exchange of technologies and experiences, and that through such interchanges both will benefit greatly.
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