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# Modern controlled atmosphere roller hearth furnaces for the heat treatment of ball bearing steel

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The annealing of ball bearing steels is a specialised field of heat treatment technology which has so far received little attention in subject literature. The divergence of opinion in the past on rational annealing techniques for these steels and the necessary equipment can be partly traced to the adoption of batch annealing cycles to the continuous roller hearth furnace. The concepts "retention time above transformation temperature" and "time for equalising temperature differences within the charge" were often not clearly delineated.

Furthermore, the evaluation of temperature differences in their effect on retention time varied widely. In recent years, however, a more unified conception based on extensive experience with modern roller hearth furnaces has been established. This development will be discussed and the latest annealing techniques for ball bearing steels outlined in the following review.

The annealing charge is in wire coil, coiled rod or bar form and the objective of the heat treatment is soft annealing with a change in grain structure. This treatment is a necessary precondition for efficient further processing. Internal stress conditions and work hardening effects are removed at the same time.

The results of the annealing heat treatment are critical for product quality. The most important factor is optimum uniformity of tensile properties, microstructure and surface quality. Even small variations in these properties are difficult to equalise further processing and result in non-uniform product quality.

## Annealing cycle

The ideal heat treatment cycle for soft annealing ball bearing steels with a change in grain structure is as follows (fig. 1): Rapid heat up to about 800 °C, keeping temperature difference in annealing charge extremely small while passing through the critical temperature.

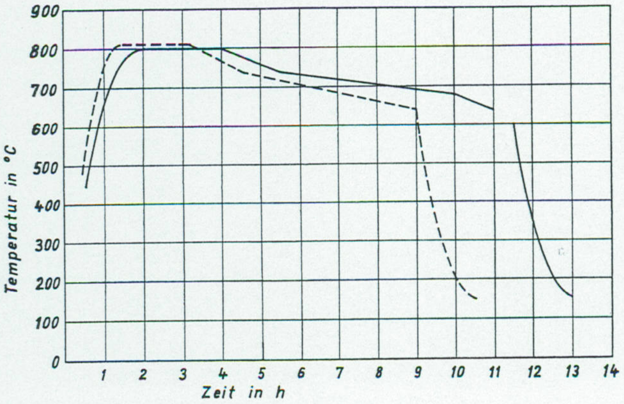

**Fig. 1** **Temperature curve for annealing ball bearing steel**
——— wire coils - - - - - - bars
Temperatur in °C = temperature in °C, Zeit in h = time in hrs

Hold at about 800 °C for about 2 hours for grain structure change.

Drop temperature to 740 °C, keeping heat uniform in charge. Slow cooling from 740 °C to 680 °C at rate of 10 to 15 °C/hour. The cooling rate through the transformation range will determine tensile values.

Cool from 680 ° to 640 °C in about 1 hour, i.e. at a rate of 40 °C/hour. This phase ensures that the whole charge passes through the critical temperature before rapid cooling. Rapid cooling from 640 to about 150 °C. Cooling to this temperature is required to avoid oxidation in air on leaving the furnace.

It is obviously easier to maintain this annealing programme with the material in bar form than in coils, as bars are transported on the roller hearth in a thin layer with uniform heat transfer and practically no temperature gradient across the charge.

Wire coils on the other hand are stacked to a height of up to 1 metre and transported through the furnace on bases.

Stacking is essential for a short furnace and high throughput. In heating and cooling it is important to minimise temperature differences between the outer coils in the stack. Heat transfer to the inner turns of a coil is mainly by gas convection and radiation. The heat flow in the material is poor as the wire is loosely wound.

The heat transfer condition for coiled rod is similar. Coils are transported through the furnace in annealing tubs.

The annealing cycle described can be completed faster with bar material than in coils. The normal overall cycle time including rapid cooling is 10.5 hours for bar and 13 hours for coiled material. The different forms of annealing charge respond to control of temperature with varying speeds as a certain uniformity of temperature must be maintained in the charge. It should also be noted that annealing times are longer for coils of light gauge than for heavy wire.

Holding time can be reduced somewhat with increased charge temperatures. This applies particularly to bar material where temperature control is better. The resulting grain structure remains satisfactory.

## Controlled atmosphere

Annealing of ball bearing steels must be carried out under controlled atmosphere to avoid adverse effects on the material. Heating in unprotected conditions oxidises and decarburises the outer layers of material.

Heating by radiant tube or electric element is therefore required. With the appropriate controlled atmosphere, oxidation and decarburisation are avoided and it is also possible to obtain a given carbon content in the surface layers of the material.

Furnace atmospheres must satisfy the following conditions for satisfactory annealing:

Free oxygen must not enter the furnace or be present in the furnace atmosphere. Oxygen concentrations above

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* Manager – Gas Technology Division,
5800 Hagen, W. Germany

10 ppm are likely to result in oxidation. The oxidation rate falls off with temperature and practically no oxidation occurs below 180° C. Annealing charges are therefore cooled to 150° C under controlled atmosphere conditions before leaving the furnace. Oxygen in combination, present as water vapour and carbon dioxyde in the furnace atmosphere, can also cause oxidation of the charge. The limiting temperature of water vapour oxidation of steel is about 300° C. Above this temperature the protective atmosphere should be reducing to prevent oxidation. If we consider the reaction equilibrium curves of $H_2O/H_2$ mixture with iron oxides (fig. 2), it is evident that the $H_2O$ content at low temperatures is very small. In practice it is not however necessary to dry the furnace atmosphere to equilibrium temperature level, as the gas/metal oxidation rate slows down at lower temperatures. Furthermore, the cooling speed of the annealing charge below 600° C is so fast that no significant oxidation by combined oxygen takes place. It is therefore sufficient for the theoretical gas composition to act reductively on the material at the annealing temperature.

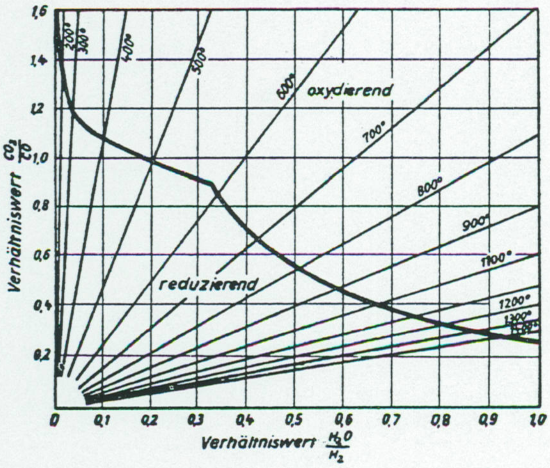

**Fig. 2 Equilibrium for iron-iron oxide reaction in $H_2O/H_2$ and $CO_2/CO$ mixtures**

oxydierend = oxidising; reduzierend = reducing; Verhältniswert = ratio

The carbon containing gas constituents carbon monoxide and methane prevent decarburisation of the charge at temperature. For neutral carburisation characteristics, the furnace atmosphere must be in equilibrium with the surface carbon content of the charge material. Carburisation follows the reaction:

$$3\,Fe + 2\,CO \rightleftharpoons Fe_3C + CO_2$$

The equilibrium curves for the reaction are given in figure 3.

Carburisation in $CH_4$ follows the reaction:

$$3\,Fe + CH_4 \rightleftharpoons Fe_3C + 2\,H_2$$

The appropriate equilibrium curves are shown in figure 4.

The protective atmosphere conditions must be reducing and non-decarburising during the whole heat treatment cycle. This requires carbon and hydrogen containing gases to be present in the furnace atmosphere. The gas mixtures obtained from the starting gases used for atmosphere generation contain $N_2$, $H_2$ and CO as well as small amounts of $CO_2$, $CH_4$ and $H_2O$.

In evaluating the effects of controlled atmospheres individual gas constituents cannot be considered independently, as they react in the mixture in accordance with temperature. The composition of furnace atmosphere varies with temperature up to gas equilibrium conditions. The requirements of the annealing charge in respect of furnace atmosphere will also vary with temperature.

There are generally two principal temperature ranges to be considered in soft annealing ball bearing steels. An atmosphere gas which is non-decarburising at 700° C may cause a certain amount of case decarburisation at 800 °C. The composition of the furnace atmosphere must

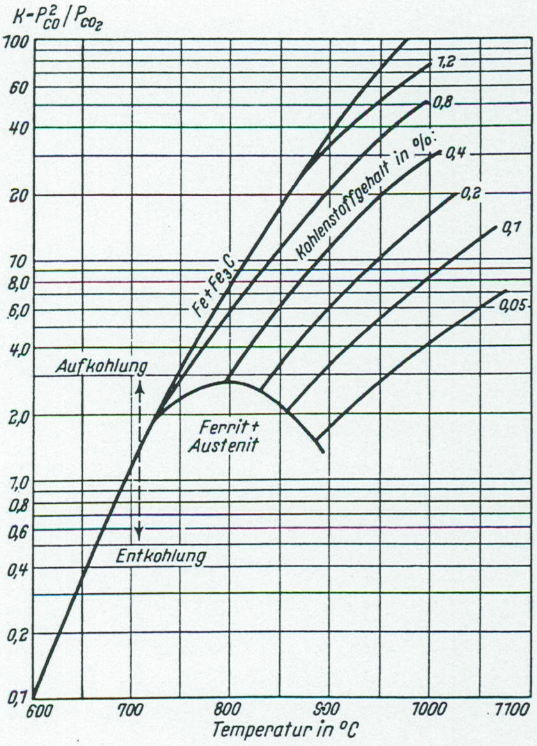

**Fig. 3 Equilibrium curves for reaction 3 Fe + 2 CO $\rightleftharpoons$ $Fe_3C + CO_2$**

Kohlenstoffgehalt = carbon content; Aufkohlung = carburising; Entkohlung = decarburising; Temperatur in °C = temperature in °C

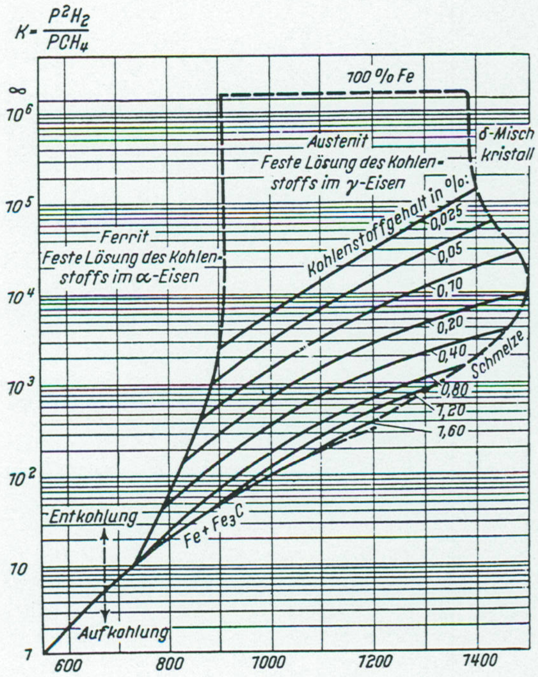

**Fig. 4 Equilibrium curves for reaction 3 Fe + $CH_4$ $\rightleftharpoons$ $Fe_3C + 2\,H_2$**

Austenit feste Lösung des Kohlenstoffs im γ-Eisen = austenite, fixed solution of carbon in γ-iron; Ferrit, feste Lösung des Kohlenstoffs im α-Eisen = ferrite, fixed solution of carbon in α-iron; Mischkristall = mixed crystal; Kohlenstoffgehalt = carbon content; Schmelze = molten; Entkohlung = decarburising; Aufkohlung = carburising therefore be controlled in accordance with the temperature conditions in each of the two zones. For this purpose a gas of low carbon content may be used as a so-called carrier and a gas with a higher carbon content injected in the higher temperature furnace zones.

Gas mixtures obtained from mono-gas generators may be used as carrier or supplementary gas depending on composition, which is widely variable by regulation of the fuel-air ratio (I). Commercial nitrogen from air separation also yields an economic, high quality mono-gas (II) which is readily controlled in composition (fig. 5).

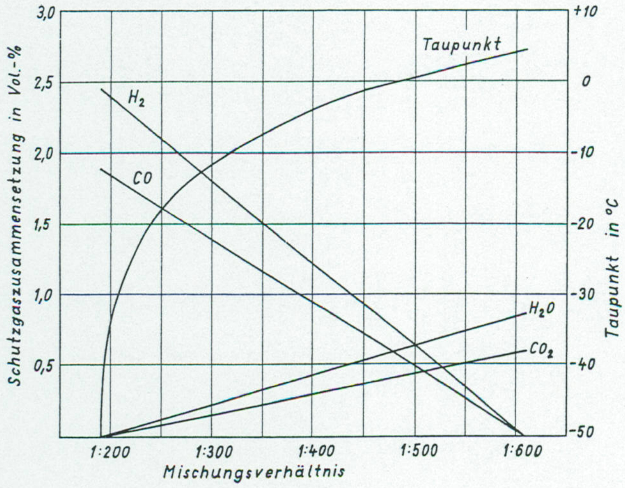

**Fig. 5 Composition of atmosphere gas as a function of nitrogen/LPG ratio, without reference to formation of methane**
commercial nitrogen with 1 vol.% $O_2$
LPG 70 vol.% $C_4H_{10}$ + 30 vol.% $C_3H_8$
Schutzgaszusammensetzung = gas composition; Mischungsverhältnis = mixing ratio; Taupunkt = dew point

The use of endothermic gas for supplementary mixing is favourable (III) as its carbon content is higher than that of mono-gas and the volume required can be considerably less. Using propane for gas generation, the composition obtained is 45 % N, 31 % $H_2$, 23 % CO and traces of $CO_2$, $CH_4$ and $H_2O$.

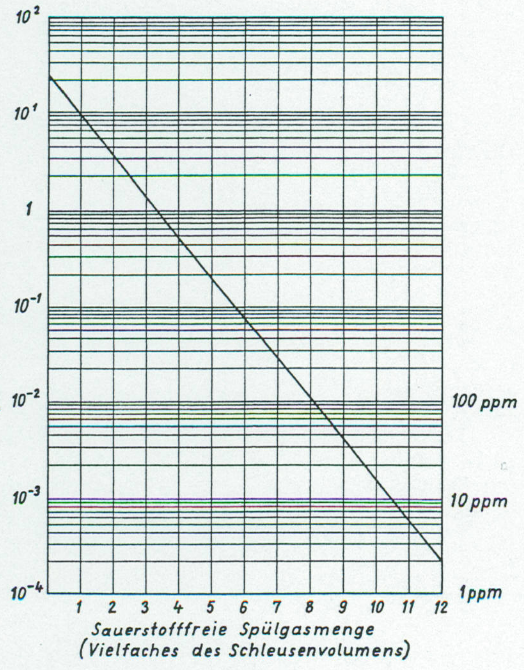

**Fig. 6 Dilution of oxygen during purging of air filled lock**
$O_2$-Gehalt = $O_2$ content; Sauerstofffreie Spülgasmenge = (Vielfaches des Schleusenvolumens) = oxygen-free purge gas volume (as multiple of lock volume)

Investigations with roller hearth furnaces having continuous furnace chambers without separating dampers between the zones show that the furnace atmosphere can be controlled satisfactorily when using different gas atmospheres in the zones. Analytical instrumentation is required to monitor and control furnace atmosphere and gas generator.

The consumption of atmosphere gas is largely determined by gas usage in purging the inlet and exit locks. The air entering the locks during entry and discharge of the charge must be displaced by the atmosphere gas. It is therefore important to enter the charge quickly and keep the lock volume small. The relationship of purge gas flow and oxygen content in purging an air filled lock is shown in figure 6. Normally a gas flow of eight times lock volume after every opening of the outer door is adequate. The furnace chamber atmosphere should be changed about once an hour.

## Heating elements

Controlled atmosphere roller hearth furnaces can be heated by radiant tube or electric element. Each radiant tube, in addition to the burner, is fitted with a built-in recuperator for preheating air. The distance between radiant tubes gives an uneven temperature distribution in the longitudinal direction if the atmosphere is not circulated. Forced circulation of the atmosphere is therefore preferred.

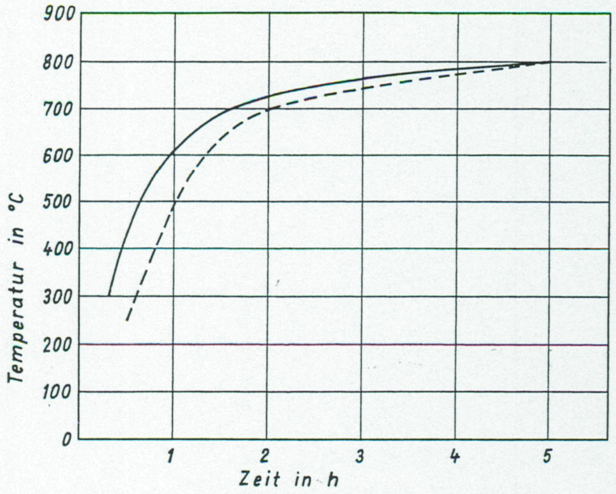

**Fig. 7 Charge temperature curve for wire coils in electric roller hearth furnace without atmosphere circulation**
temperature in coil ——— max – – – – – – min

Electrical heating is by resistance strip or wire elements built into the furnace roof and hearth on refractory supports. Atmosphere circulation is not absolutely necessary as the large number of closely spaced elements can be distributed in accordance with the heat requirements and give uniform temperature zones.

The advantages and disadvantages of radiant tube and resistance element heating in the individual furnace zones for soft annealing wire coils are compared below. The heated furnace space is divided into heating, holding and slow cooling sections for this purpose.

The heating phase in electric furnaces without gas circulation must be very carefully controlled. Rapid heating up is however required to minimise furnace length. Without gas circulation the furnace conditions are unfavourable as the temperature in the coils must be equalised before reaching the transformation temperature. A typical charge temperature curve for a furnace without gas circulation is shown in figure 7. The comparable temperature curve for radiant tube or electric furnaces which atmosphere circulation (fig. 8) shows that uniform charge temperature is reached much more quickly.

If gas circulation is used in all furnace zones, as is required for radiant tube heating, there is constant mixing of the furnace atmosphere and it is not possible to maintain two separate atmospheres of different composition. The carburising characteristics can therefore not be controlled accurately in accordance with zone temperature. With gas circulation confined to the heating up zone or without circulation altogether, the atmosphere composition can be adequately controlled by the use of two gases.

The slow cooling of wire coils at a rate of 10 to 150° C/hr must be highly uniform. Accurate temperature control is particularly important in this furnace zone. The calculated heat balance for this zone shows that the external heat losses are roughly balanced by heat loss from the charge. The external heat supply is therefore only a small proportion of the rated heat input. The rated input is such as to allow the furnace to be brought to temperature quickly from cold and may be about five times normal consumption. Accurate temperature control with radiant tube heating is difficult when the control set point corresponds closely to the minimum tube heat output. Electrical heating in the cooling zones has the advantage that the control range is virtually unlimited at the low end. A general comparison of the operating costs of electric and gas fired radiant tube roller hearth furnaces shows the following situation:

The capital costs for the whole furnace installation are about 5 % higher for gas firing. Servicing and maintenance costs for radiant tubes would also be about 10 % higher than for electric heating.

The cost of heating, however, would generally be 30 to 50 % lower for gas. For a more exact comparison the cost per heat unit of gas and electricity would require to be known. Gas heating is always more economic than electric heating.

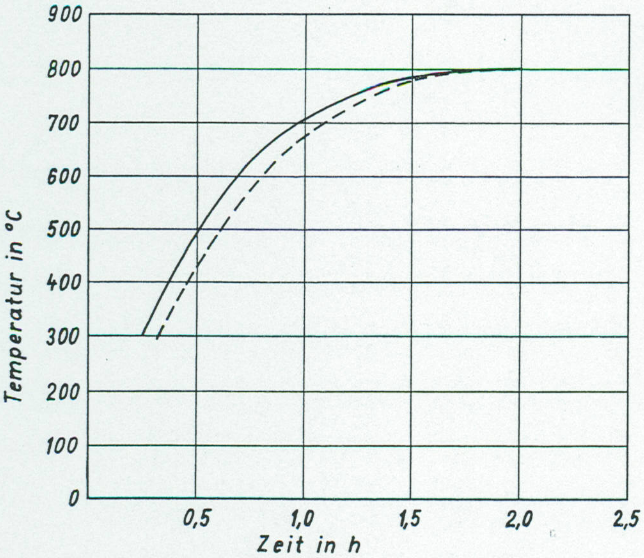

**Fig. 8** **Charge temperature curve for wire coils in electric roller hearth furnace with atmosphere circulation**
temperature in coil ——— max - - - - - - min

Both types of heating have distinct advantages in specific areas, which suggests a combination of the two for optimum operating efficiency. In roller hearth furnaces for annealing ball bearing steels about 70 % of the total heat input is used in the heating up zone, which constitutes at most up to 15 % of the heated furnace length. The heat input is therefore largely concentrated over a short length at the entry side of the furnace. Heating in this section can with advantage be by gas fired radiant tube with forced circulation of the furnace atmosphere. This utilises the advantages of cheaper heating and at the same time uniformity of charge temperature is ensured by the convection effects of gas circulation.

The remaining 85 % of furnace length, taking only about 30 % of the total heat input, is electrically heated. This affords the conditions for precise control of temperature and of atmosphere composition in the furnace chamber. Furthermore, the capital cost for the electric heating installation is low.

The combination of the two heating systems in one furnace installation gives good heat economy while realising the advantages of electric heating.

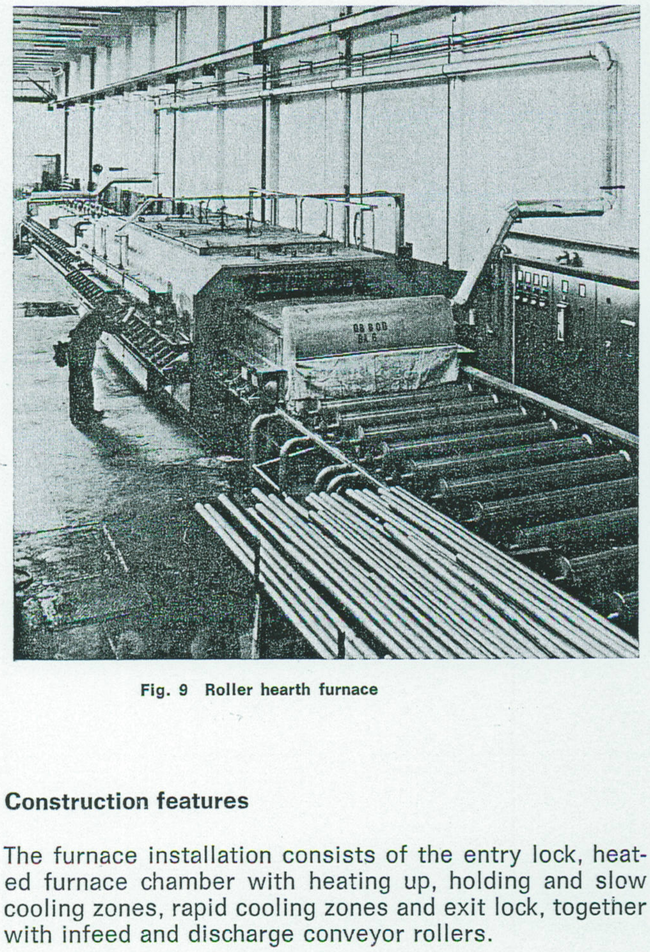

**Fig. 9** **Roller hearth furnace**

### Construction features

The furnace installation consists of the entry lock, heated furnace chamber with heating up, holding and slow cooling zones, rapid cooling zones and exit lock, together with infeed and discharge conveyor rollers.

The charge is transported through the furnace on the hearth rollers under fully automatic control. The doors at the furnace locks and rapid cooling zone are motorised and operate automatically. The rollers in the lock area are driven by separate high speed drives independent of the furnace roller drive. The appropriate entry doors are timed to open immediately before the infeed rollers are actuated to prevent the charge running against the door. The discharge rollers and associated doors are automatic controlled by the position of the charge in the furnace. The speed of the furnace rollers is infinitely variable over a 6 : 1 range for flexibility of operation.

The centrifugally cast heat resistant furnace rollers are supported on roller bearings in gas tight housings on the furnace casing.

The heating up zone is heated by gas fired radiant tubes. Forced atmosphere circulation is provided by fans in the furnace roof.

The holding and slow cooling zones are heated by electric strip elements. The furnace casing in the rapid cooling zone is double walled and water cooled. The atmosphere is circulated by a powerful fan on the furnace roof through a water cooled heat exchanger and returned cold into the furnace. The high velocity gas flow is sufficient to provide 15 atmosphere changes per minute in the rapid cooling zone. The heat exchanger in the system ensures rapid cooling.

The composition of the furnace atmosphere influences the choice of refractory materials used.

A modern continuous roller hearth furnace is shown in figure 9.

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