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Localized Swelling of Fe-Cr-Ni Alloy Rollers in High-Temperature Applications

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Localized swelling has been observed in 24Cr-24Ni-Nb steel transportation rollers used in the normalizing furnace of a plate mill after prolonged service at high temperature. Due to high localized thermal and mechanical stresses, the chromia layer formed on the roller surface ruptures, exposing the roller substrate to furnace oxygen. Oxidation of second-phase carbides results in the formation of carbon monoxide at very high partial pressure. This leads to formation of voids, leading in turn to localized swelling of the roller material.

Keywords Fe-Cr-Ni Alloy, localized swelling, oxidation, void formation

1. Introduction

Iron-chromium-nickel cast alloys are widely used in high-temperature applications (Ref 1, 2). One such application involves transportation rollers located inside the normalizing furnace of a plate mill. In these furnaces, the temperature is maintained in the range of 820 to 950 ° C through heating by a mixture of coke oven and blast furnace gas. The rollers are therefore constantly exposed to mechanical and thermal stresses due to movement of thick plates at high temperature and under the hot gas environment.

The present investigation deals with changes in the physical and material characteristics of transportation rollers made of X 30 Cr Ni Si Nb 24 24 alloy (DIN 17006, Werkstoff No. 1.4855) after prolonged service in a normalizing furnace. The majority of the rollers exhibited localized swelling after service life of approximately 88,000 h. In the present investigation, an attempt has been made to identify the probable causes of this swelling phenomenon and to correlate such causes with the effect of changes in mechanical and microstructural characteristics of the roller material after use.

2. Furnace and Roller Material Characteristics

The rollers under investigation are used in the continuous charging type of normalizing furnace of a plate mill. The plate travels through different zones of the furnace over transportation rollers while undergoing an austenitizing heating cycle. The furnace is 72 m long and its internal width is 3.6 m. There are 144 hollow cylindrical rollers located in nine different zones of the furnace. The inner diameter of the roller is 324 mm and the outer diameter is 368 mm. The roller barrel length is 3.5 m at room temperature. The weight of each roller is 750 kg. Plates travel over the rollers at a speed of 6 to 30 m/min, depending on the plate thickness, which varies from 12 to 63 mm. The length and width of the plates are in the range of 6 to 15 m and 2 to 3.2 m, respectively. The weight per unit length of plate varies between 240 and 1200 kg/m. The furnace is fired with mixed gas (coke oven and blast furnace) of caloric value ≈ 1500 kcal/Nm^3. A typical flue gas analysis is 14% CO_2, 76% N_2, and 10% O_2. The furnace pressure is about 1.004 bar. The furnace temperature in different zones ranges between 820 and 950 °C.

The nominal chemical composition of the roller material before use, in weight percent, is 0.35 C, 1.5 Si, 1.5 Mn, 24.0 Cr, 24.0 Ni, 1.5 Nb, 0.008 S, 0.013 P, 0.72 Mo, bal Fe. The mechanical and physical properties are 220 MPa yield strength (min), 440 MPa ultimate tensile strength (min), 10% elongation (min), 14.6 W/m · K thermal conductivity at 20 °C, and 19.0×10^{-6} m/m · K coefficient of thermal expansion between 293 and 1273 K.

3. Experimental Procedure

Samples containing the swelled area of the used roller were collected for laboratory investigations: hot tensile test, optical metallography, and scanning electron microscopy (SEM).

3.1 *Hot Tensile Test*

Flat hot tensile specimens of 25 mm gage length and 3 mm thickness were prepared from the unswelled areas of the roller. The specimens had orientation parallel to the rotational axis of the roller. Specimens were soaked at 600, 700, 800, 900, and 950 °C for 5 min before they were tested at the strain rate of 1.33×10^{-3}/s in an MTS servohydraulic machine. Load-versus-extension graphs were plotted.

3.2 *Optical Metallography*

Specimens from both the swelled and unswelled portions of rollers were polished and etched using a solution of 10 mL HNO_3 + 2 gm picric acid + 100 mL alcohol. The microstructure was investigated with the help of an optical microscope.

3.3 *Scanning Electron Microscopy*

The unetched portions of the swelled and unswelled roller material were scanned to detect the presence of any voids. The fractured surfaces of the swelled and unswelled tensile specimens at room temperature were observed and fractographs

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were taken to study the mode of fracture. A JEOL scanning electron microscope was used for this purpose.

4. Results and Discussion

The outer and inner surfaces of the used roller are shown in Fig. 1 and 2. Swelling can be seen in the middle portion of Fig. 1. Optical micrographs of the unswelled and swelled portions of the used roller material are shown in Fig. 3(a) and (b), respectively. Both these micrographs show the presence of voids and coarse carbides. It is evident from the micrographs that the carbide size is bigger in the unswelled portion while the void density is significantly higher in the swelled portion. The preferential location of carbides and voids in both cases is along grain boundaries.

The abundance of voids in the swelled portion of the roller material, in comparison to that in the unswelled portion, is confirmed by SEM micrographs of the unetched samples (Fig. 4a, b). Fractographs of unswelled and swelled tensile specimens at room temperature are shown in Fig. 5(a) and (b). It can be clearly seen in Fig. 5(b) that a crack runs across the fractured surface, suggesting that the preexisting voids in the swelled portion have become linked with each other.

The presence of coarse carbides in the unswelled portion (Fig. 3a) is the result of prolonged use at high temperature. Similar findings have been reported for nickel- and iron-base superalloys (Ref 3) and nickel-chromium alloys (Ref 4). During the long exposure of the material to oxidizing atmosphere at high temperature in the normalizing furnace, the coarse carbides are likely to undergo oxidation reaction, provided that oxygen from the flue gas can penetrate the roller material.

Oxygen is initially absorbed by the metal surface, and as the reaction proceeds, it dissolves in the metal and eventually saturates the surface, forming an oxide layer. In chromium-bearing steel, oxidation leads to the formation of Cr_2O_3 on the surface, which generally acts as a protective layer and inhibits further oxidation of roller material. However, even when a continuous film covers the surface, oxidation can still proceed through ionic diffusion (Ref 5). Sometimes, short-circuit paths are also made available for oxygen penetration when cracks occur in the oxide layer, exposing fresh surfaces.

In the normalizing furnace of a plate mill, the stress field created on the roller surface due to the weight of plate and its

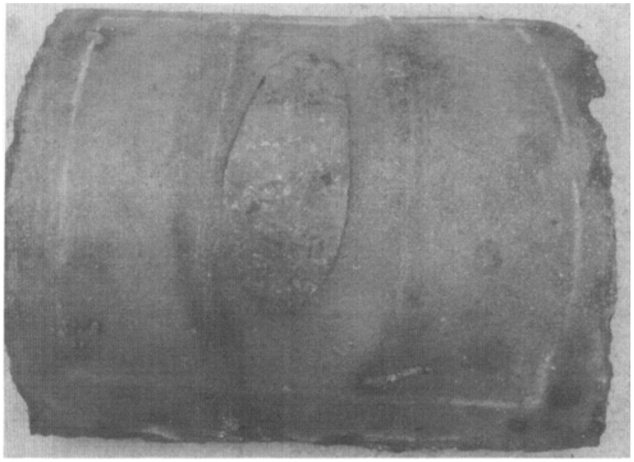


Fig. 1 Outer surface of the used roller

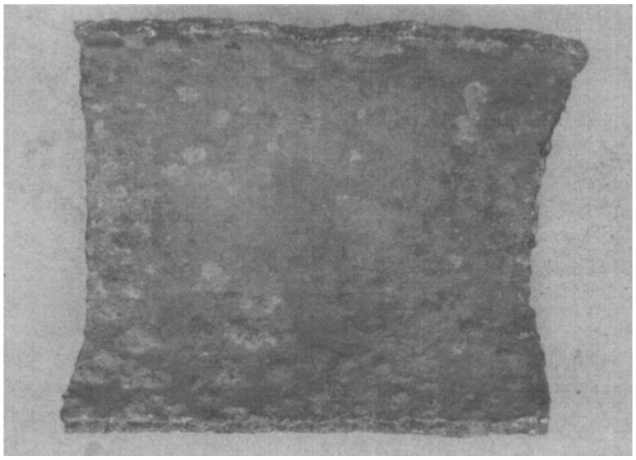
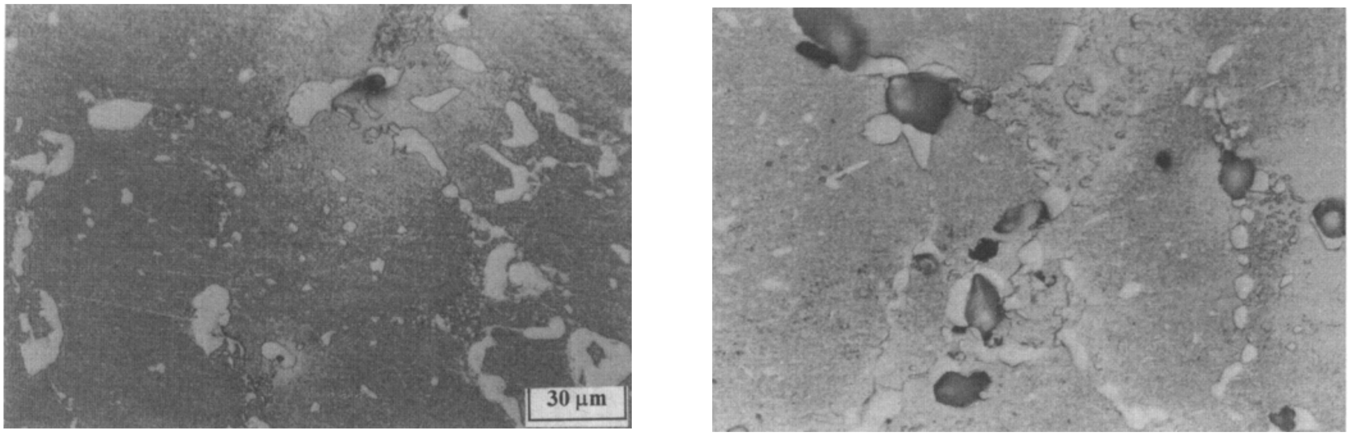


Fig. 2 Inner surface of the used roller



(a) (b)

Fig. 3 Optical micrographs of used roller material. (a) Unswelled portion. (b) Swelled portion own weight is significant. Further, for uniform distribution of stress, the contact between the moving plate and the rotating roller should be that of a line contact. To ensure this, there should not be any thickness variation in the plate or in the roller. However, some of these plates generally have thickness variation across the width and length, and there also exists a longitudinal wall thickness variation along the roller. Hence, instead of proper line contact between roller and plate, there are point contacts. Point load conditions in the roller-plate contact region result in the formation of a very high stress field at such points, and this can be sufficient to break the chromia layer. In addition, as the furnace is heated directly by the mixed gas injected through the burners, the temperature distribution over the roller surface is not uniform. Hot spot conditions on the roller suface locally overheat the roller and produce thermal strain that leads to high localized thermal stresses. This can be sufficient to rupture the chromia layer and expose the roller substrate to furnace oxygen.

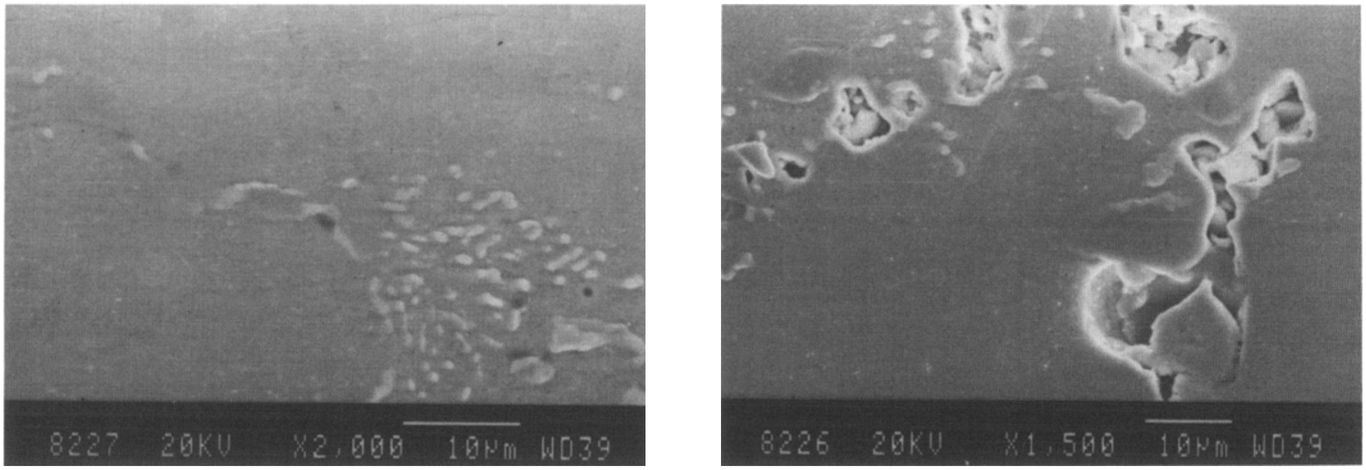
Table 1 Hot tensile properties of unswelled portion of used roller material

Specimen	Test temperature, °C	YS, MPa	UTS, MPa	Elongation, %
1	600	220.1	344.3	7.02
2	700	224.4	345.3	13.48
3	800	165.8	251.6	26.17
4	900	88.7	103.4	28.34
5	950	65.5	90.9	38.85

The aforementioned mechanisms of oxygen transport from furnace atmosphere to the interior of the roller material leads to the oxidation of some of the carbides according to the following reaction:

$$Cr_{23}C_6 + 3O_2 = 23Cr + 6CO \qquad \text{(Eq 1)}$$

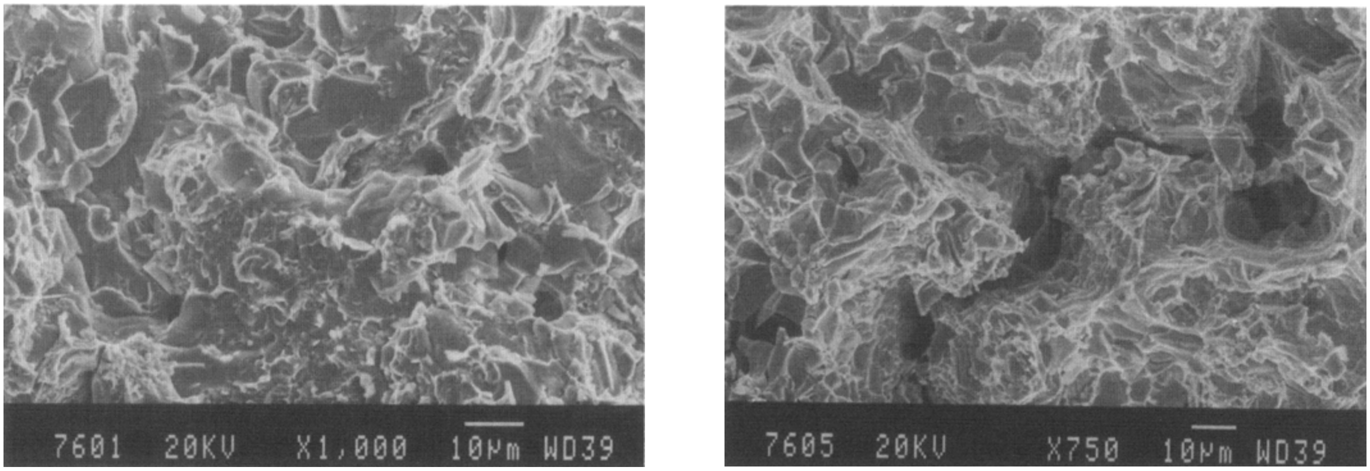
The partial pressure of furnace oxygen in the present investigation has been found to be 0.1 bar. The resulting partial pressure of carbon monoxide in the operating temperature range would be of the order of 10^2 MPa. From Table 1 it can be seen



(a)

(b)

Fig. 4 Scanning electron micrographs of used roller material in the unetched condition. (a) Unswelled portion. (b) Swelled portion



(a)

(b)

Fig. 5 Fractographs of used roller material after tensile testing at 25 °C. (a) Unswelled portion. (b) Swelled portion that a partial pressure of this magnitude is far in excess of the yield strength of the roller material at the operating temperature of 950 °C. Because the material is highly ductile at that temperature (elongation ~39%), the material tries to accommodate the stresses through the formation of voids.

The presence of excessive voids in the swelled portion of the sample is the cause of the localized swelling, because the volume of all these voids taken together is quite large. Hence, in the formation of voids, localized swelling takes place.

Similar investigations for nickel and nickel-base alloys have been carried out by other researchers, who have also reported formation of voids in the interior of material due to oxidation of second-phase carbides (Ref 6-10).

5. Conclusions

- Localized swelling has been observed in 24Cr-24Ni-Nb steel rollers after prolonged use at high temperature.
- Due to high localized thermal and mechanical stresses, the chromia layer ruptures, exposing fresh surface to the oxidizing environment. Oxidation of second-phase carbides results in the formation of carbon monoxide at very high partial pressure. This leads to the formation of voids, ultimately resulting in localized swelling of the roller material.

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