



# Metallurgical analysis of the causes of failure of the hardening furnace conveyor belt

**A. Merda<sup>a</sup>, K. Klimaszewska<sup>a</sup>, M. Sroka<sup>b</sup>, G. Golański<sup>a,\*</sup>**

<sup>a</sup> Institute of Material Engineering, Faculty of Production Engineering and Materials Technology, Czestochowa University of Technology, Al. Armii Krajowej 19, 42-200 Czestochowa, Poland

<sup>b</sup> Institute of Engineering Materials and Biomaterials, Faculty of Mechanical Engineering, Silesian University of Technology, ul. Konarskiego 18a, Gliwice 44-100, Poland

\* Corresponding e-mail address: golanski.grzegorz@wip.pcz.pl

## ABSTRACT

**Purpose:** The aim of the tests was to analyze the microstructure and mechanical properties of a section of the hardening furnace conveyor belt serviced at the temperature of 880-920°C in the carburizing atmosphere, in the context of determining the probable causes of its failure.

**Design/methodology/approach:** The scope of performed tests included: chemical composition analysis of the steel and particles, microstructure investigated using optical and scanning electron microscopy, X-ray phase analysis.

**Findings:** The analysis of the chemical composition showed that the examined material was austenitic steel X15CrNiSi25-21 (S310). Performed metallurgical tests showed that after the service the examined steel was characterized by austenitic structure with numerous precipitates of diverse morphology. In the structure the sigma phase particles and probably the  $M_{23}C_6$  carbides precipitates were observed. The continuous grid of precipitates on the boundaries of grains (mainly the sigma phase) and the influence of the cyclic changing heat loads (or thermo-mechanical loads) were the main causes of failure of the analysed detail.

**Research limitations/implications:** The aim of the work was to determine the probable causes of damage of the material used for a conveyor belt of a hardening furnace.

**Practical implications:** The results of investigation and analysis of the metallographic of heat-resisting austenitic steel X15CrNiSi25-21 (S310) after service at the temperature of 880-920°C are presented.

**Originality/value:** The paper presents the results of research on the microstructure and mechanical properties of the section of hardening furnace conveyor belt made of creep-resisting austenitic steel. The aim of the performed tests was to determine the probable causes of damage of the analysed detail.

**Keywords:** Microstructure, X-ray phase analysis, Precipitates, Failure

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## PROPERTIES

## 1. Introduction

The materials working at the elevated or high temperature should have a proper resistance to high-temperature corrosion – heat resistance. This term is understood as the steel resistance to the effect of gases oxidizing at high temperature. Creep-resisting steels of austenitic structure owe their required oxidation resistance at the service conditions to the high content of chromium, silicon and aluminium. The properly formulated chemical composition allows the layer of oxides (scale) to form on the surface of these steels.

The resistance of heat-resisting steels to oxidation at high temperature increases together with the growth of chromium content. The grain refinement also has a favourable effect. Austenitic steels compared with the ferritic ones show higher heat resistance because of the diffusion processes proceeding more slowly [1]. Austenitic steels are characterized by lower yield strength in comparison with the ferritic steels, high coefficient of linear expansion, low coefficient of thermal conductivity, and the susceptibility to intercrystalline corrosion and stress corrosion, which translates into low thermal endurance of these steels [2].

The service of creep-resisting steels at the elevated temperature as a result of changes in the microstructure leads to the growth of their brittleness and the decrease in plasticity. The reduction of toughness results mostly from the precipitation processes of unfavourable secondary phases on the boundaries of grains, in the case of austenitic steels – the intercrystalline sigma phase. The rate of precipitation of this phase in the structure depends on the chemical composition of steel, as well as the temperature and time of service. The factors that favour the sigma phase precipitation are high content of chromium and silicon. This phase is characterized by high brittleness and hardness and its precipitation not only causes the fall of the plasticity of alloy, but it also has a negative influence on the corrosion resistance. The sigma phase is also characterized

by high susceptibility to coarseness which leads to the fast growth of its size [3,4].

The aim of the work was to determine the probable causes of damage of the material used for a conveyor belt of a hardening furnace.

## 2. Research methodology and material for investigations

The material under investigation was a section of the conveyor belt of the hardening furnace serviced at the temperature of 880-920°C in the carburizing atmosphere. The scope of performed tests included:

- analysis of the chemical composition of the tested material carried out using the SpectroLab spectrometer, while the analysis of the chemical composition of the phases was performed using a scanning electron microscope using the SEM + EDS technique;
- X-ray phase analysis including analysis of the phases in the tested material using the Seifert XRD 3003TT X-ray diffractometer;
- microstructure tests using the Olympus GX41 optical microscope and the SEM Jeol JSM6610LV scanning electron microscope. Metallographic specimens were etched with Mi19Fe reagent and Murakami reagent;
- computer image analysis carried out using Image Pro-Plus.

## 3. Research results and their analysis

The chemical composition of the tested material was shown in Table 1. The material met the requirements for the chemical composition of X15CrNiSi25-21 (S310) austenitic steel according to the requirements of PN-EN 10095:2002.

Table. 1.

Chemical composition of investigation steel, %wt.

	C	Mn	Si	P	S	Cr	Ni	N
	0.18	1.76	2.14	0.023	0.006	22.00	21.03	0.05
Requirement [5]	max. 0.20	max. 2.00	1.50-2.00	max. 0.045	max. 0.015	24.00-25.00	19.00-22.00	max. 0.11

The examined material was characterized by a fine-grained austenitic structure (Figs. 1, 2) of the grain size 9 according to ASTM standard. The fine-grained structure of austenitic steels provides high oxidation resistance and plasticity [6]. In the microstructure numerous precipitates

of diverse morphology were observed. They were located on the boundaries, as well as inside the grains. The X-ray analysis showed, in addition to austenite, the occurrence of  $M_{23}C_6$  carbides and sigma phase in the examined microstructure (Fig. 3). The  $M_{23}C_6$  carbides and sigma

phase precipitates are precipitations rich in chromium. It was proved in the microanalysis of the chemical composition - both the local analysis (Fig. 4), as well as the maps of elements (Fig. 5).

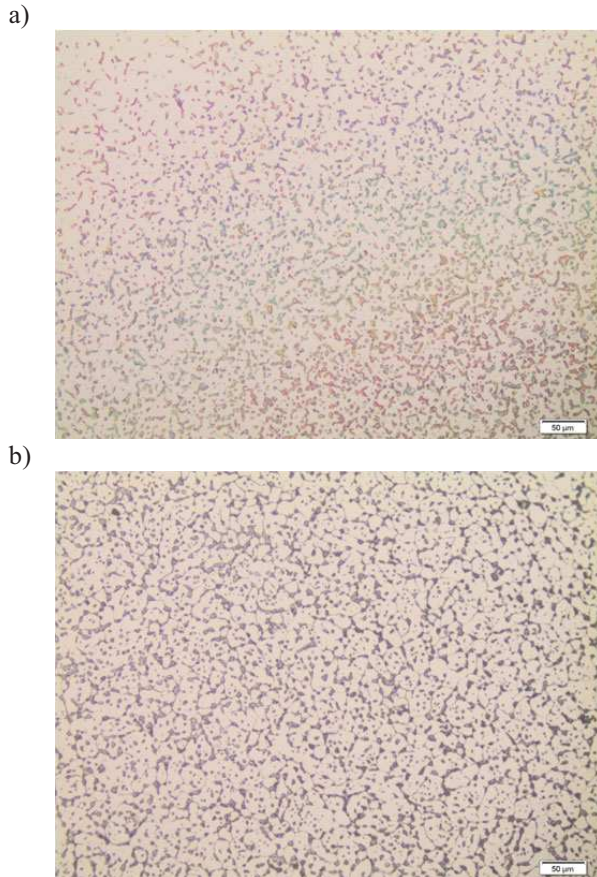


Fig. 1. Microstructure of investigated steel after etching: a) Murakami reagent; b) copper sulfate reagent; OM

The additionally performed etching of the specimen with Murakami reagent, which colours the sigma phase precipitates brown (Fig. 1), proves and confirms the presence of sigma phase precipitates in the microstructure of the examined material. The calculated volume fraction of the sigma phase in the examined steel amounted to about 25%. In austenitic steels the first secondary precipitate appearing in the steel microstructure are  $M_{23}C_6$  carbides. These particles are observed on the boundaries of grains – as the places privileged energetically. The precipitation of these particles is connected with the solubility limit of carbon in austenite. The appearance of  $M_{23}C_6$  carbides on the grain boundaries leads not only to the sensitization of austenitic steels (the growth of the susceptibility to intercrystalline corrosion) but also to the decrease in toughness [7].

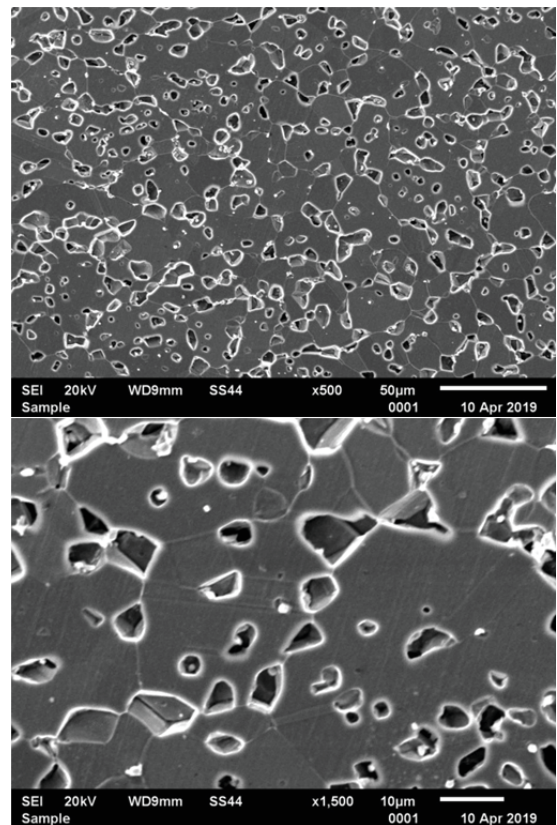


Fig. 2. Microstructure of investigated steel; copper sulfate reagent, SEM

The sigma phase precipitates revealed in the investigated steel, similarly as the  $M_{23}C_6$  carbide precipitates, were observed on the boundaries of grains, and the preferential place of nucleation of this phase was the point of contact of three boundaries of grains. The grain boundaries as the areas of disorder crystalline structure enable faster diffusion, which can locally lead to the growth of concentration of the sigma phase forming elements (chromium, iron), thus making the formation of this phase easier. [8]. The sigma phase precipitation in austenitic stainless steels is mostly aided by high chromium content – the rate and temperature of precipitation of the sigma phase in austenitic steel grow together with the growth of the content of this element. The precipitation of the sigma phase in steels of large chromium content during the service at high temperatures is a natural ageing process bringing the material closer to the equilibrium state. Also the high content of silicon can favour the accelerated nucleation and growth of sigma phase. According to [9], silicon is an element causing strong acceleration of nucleation and growth of sigma phase in austenitic stainless

steels. The effect of silicon content on the growth of behaviour of the sigma phase is explained by Lin et al. [10]. They determined that the sigma phase content in stainless steel with 0.17% Si increases from 0 to 6%, from 0 to 14% and from 0 to 22% for stainless steel with 0.34% Si and 0.76% Si, respectively. The sigma phase precipitation can be accompanied by the dissolution of  $M_{23}C_6$  carbides precipitated on the boundaries of grains, since according to [11] the sigma phase can precipitate as a result of the in situ transition of  $M_{23}C_6$  carbides. The disappearance of  $M_{23}C_6$  carbides precipitated on the boundaries of grains probably leads to the local enrichment of the matrix in carbon atoms, because the solution of carbon atoms (but also nitrogen) in sigma phase is limited [12].

It leads to the possibility of precipitation of  $M_{23}C_6$  carbides inside the grains. Apart from the  $M_{23}C_6$  carbides inside the grains also the sigma phase precipitates can occur. Except that the nucleation and growth rate of the sigma phase precipitates inside the grain in comparison with the sigma phase precipitates on the boundaries of grains is slower. It results mostly from the following two factors: 1. the energy of nucleation inside the grain is bigger than that of the nucleation on the boundary, 2. the volumetric diffusion of the sigma phase forming element is considerably smaller than the diffusion with grain boundaries. The sigma phase is usually regarded as harmful when precipitated in alloys, because it is characterized by high hardness and brittleness.

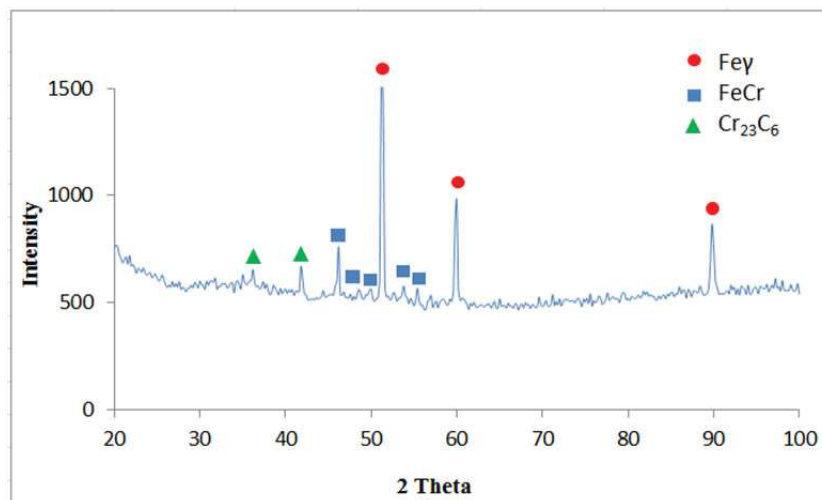


Fig. 3. X-ray phase analysis of the steel

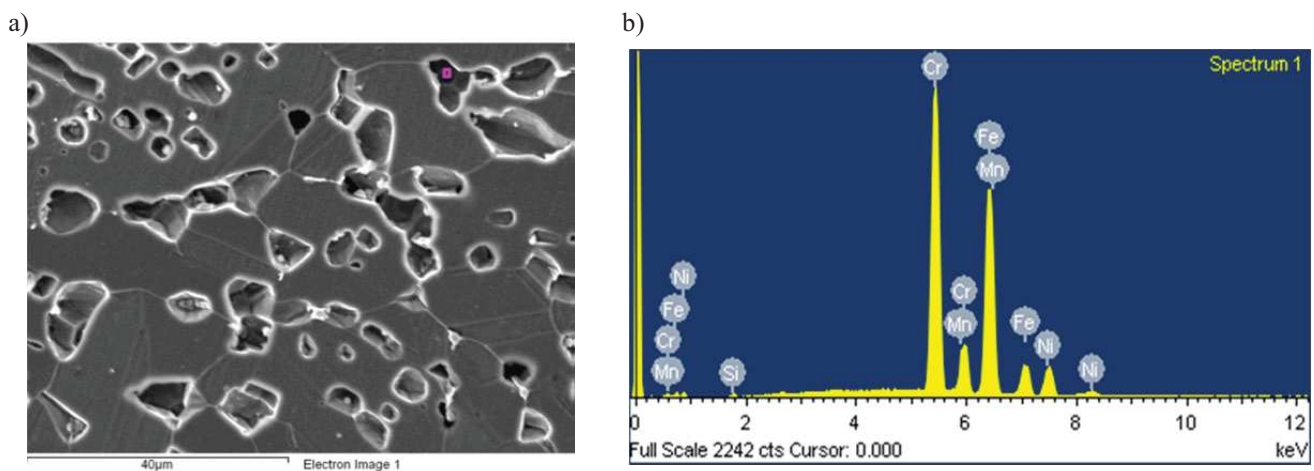


Fig. 4. Chemical composition of the precipitation on the grain boundary; a) SEM image, b) X-ray; Chemical composition, %at.: 0.37% Si; 2.21% Mn; 8.72% Ni; 43.79% Cr; 44.91% Fe

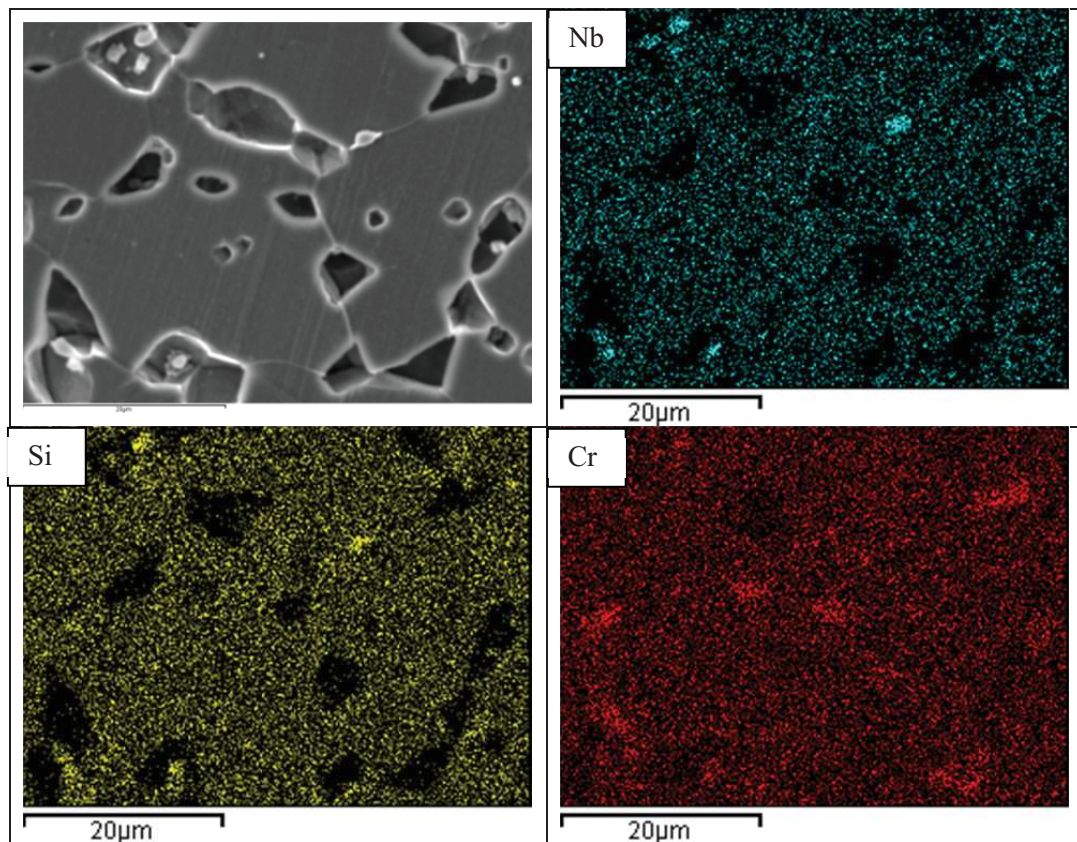


Fig. 5. EDS X-ray mapping of elements in the steel

In austenitic steels (as well as ferritic or duplex steels) the occurrence of sigma phase in the microstructure causes a decrease of not only plasticity and ductility, but also corrosion resistance, which results from removing of chromium atoms from austenite matrix [13-15]. The sigma phase, similarly as the  $M_{23}C_6$  carbides, is characterized by low stability, which leads to relatively fast coarsening of this phase. The calculated volume fraction and mean diameter of the sigma phase in the examined steel amounted to about 25% and 3.97  $\mu\text{m}$ , respectively. The continuous grid of precipitates of the sigma phase on the boundaries of grains, through weakening of the cohesion of the grain boundaries, contributes to a considerable growth of brittleness, a decrease of ductility and plasticity of the examined material, which was probably the direct cause of failure of the analysed element.

#### 4. Conclusions

The material under investigation was the test samples taken from a damaged fragment of a conveyor belt. The belt was made of heat-resisting austenitic steel of the

X15CrNiSi25-21 grade. Performed tests showed that after the service the analysed material was characterized by the austenitic structure with numerous precipitates forming the so-called continuous grid in some areas. The analysis of the precipitates showed the presence of sigma phase precipitates and probably the  $M_{23}C_6$  carbide precipitates in the microstructure. The root cause of the growth of brittleness of the examined material and in consequence the failure of the examined element was the precipitation of sigma phase on the boundaries of grains. Short service time of the investigated element resulted from work in the temperature range that was unfavourable from the point of view of the sigma phase precipitation rate. Additionally, shortening of the service period was influenced by the cyclic changes of temperature having an effect on the examined element during the service – thermal fatigue.

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