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THE EFFECT OF HEAT TREATMENT PARAMETERS ON MECHANICAL CHARACTERISTICS OF 10CrMo9-10 STEEL TUBE BENDS

WPŁYW PARAMETRÓW OBRÓBKI CIEPLNEJ NA CHARAKTERYSTYKI MECHANICZNE ŁUKÓW RUROWYCH ZE STALI 10CrMo9-10

The purpose of the paper was to analyse the effect of diverse heat treatment parameters (normalising and tempering) on mechanical characteristics of the material used to develop ϕ508x20 tube bends made of the 10CrMo9-10 steel by application of induction heating. The research conducted included tests of basic mechanical properties as well as low cycle fatigue and creep at the temperature of 500°C. With reference to the results thus obtained, it has been established that there is a relationship between mechanical properties of bends and individual features of their microstructure conditional to the heat treatment parameters. Among other conclusions drawn in the research, it has been found that the main structural factor conditioning the mechanical properties of bends was the grain size. Heat treatment parameters characterised by lower temperature and shorter tempering time triggered changes in the material microstructure, such as increased grain comminution. The effects of the said changes included improvement of strength characteristics (R_m, $R_{p0,2}$) as well as increased material durability under conditions of fatigue and creep. Main criterion-specific mechanical properties and geometric features of the bends developed conformed with the relevant requirements of reference standards (PN-EN10216-2, PN-EN 12952).

W pracy analizowano wpływ zróżnicowanych parametrów obróbki cieplnej (normalizowanie i odpuszczanie) na charakterystyki mechaniczne materiału łuków rurowych ϕ508x20 ze stali 10CrMo9-10 wykonanych z zastosowaniem nagrzewania indukcyjnego. Przeprowadzono badania podstawowych własności mechanicznych oraz zmęczenia niskocyklowego i pełzania w temperaturze 500°C. Na podstawie uzyskanych wyników stwierdzono, że istnieje związek pomiędzy właściwościami mechanicznymi łuków, a cechami ich mikrostruktury determinowanymi parametrami obróbki cieplnej. Stwierdzono między innymi, że głównym czynnikiem strukturalnym warunkującym właściwości mechaniczne łuku była wielkość ziarna. Parametry obróbki cieplnej charakteryzujące się niższą temperaturą i krótszym czasem odpuszczania, skutkowały zmianami mikrostruktury materiału w tym większym rozdrobnieniem ziarna. Efektem tych zmian był wzrost właściwości wytrzymałościowych (R_m, $R_{p0,2}$) jak również zwiększenie trwałości materiału w warunkach zmęczenia i pełzania. Podstawowe, kryterialne właściwości mechaniczne i cechy geometryczne wykonanych łuków spełniały wymogi przedmiotowych norm (PN-EN10216-2, PN-EN 12952).

1. Introduction

Although a multitude of studies has been devoted to assessment of service life of power generating installations, no one has yet succeeded in developing an explicit methodology dedicated to assessment of technical condition of equipment as well as procedures for forecasting of safe operation of such systems. Nor can one find a material database suitable for dealing with such problems, comprising mechanical characteristics, including creep and fatigue characteristics of materials for both the initial and the operating state. The foregoing particularly applies to steam pipelines. These structures are mainly exposed to the harmful impact of progressing material condition changes, including those triggered by creep processes, and, as in many cases, of thermal and mechanical fatigue processes of low cycle nature [1-4]. Consequently, it is still necessary that further results of material studies should be collected in order to create commonly acceptable procedures for service life forecasting of such structures as steam pipelines and other facilities operating under similar conditions [5,6].

With regard to power pipelines, this problem appears to be particularly important since, as implied by results of the studies being conducted, mechanical characteristics of tube bends, usually exposed to the highest strain under operating conditions, differ considerably from characteristics of the as-delivered tube material [5,6]. These characteristics, in turn, constitute the grounds for forecasting of the service life of power generating installations.

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Tube bends are practically used in nearly every power pipeline. Increasingly often, the technology applied to manufacture them relies on unconventional methods, such as those, for instance, using local tube heating while bending [7-11].

In the research addressed in this paper, it was found reasonable to determine the effect of different technological parameters of the bending process on the mechanical properties of bends. The research material studied comprised tubes made of the 10CrMo9-10 steel, having the dimensions of ϕ508x20, and two bends made from the tubes in question with the bending angle of ϕ=90° and the bending radius of R=762mm.

Industrial tube bending tests with application of local induction heating were conducted at Zakłady Remontowe Energetyki Katowice S.A.

The bends were heat treated on diversified normalising and tempering parameters. Basic mechanical properties were studied, and low cycle fatigue as well as creep were tested at the temperature of 500°C.

2. Preparation of tube bends used for material testing

In order to determine the tube bending process parameters, numerical simulations were conducted by application of the finite element method (FEM) using the Simufact Forming software in version 11.0. The subject of modelling was the process of forming tube bends made of the 10CrMo9-10 steel, assuming the dimensions of ϕ508x20 mm and the bending radius of R=762 mm. What the model studies involved was introducing changes to the heating temperature, the tube pusher operating rate and conditions of the tube bend cooling. Next, the optimum variant was chosen regarding force parameters of the process and the geometrical form of bends, where it was characterised by the pusher rate of v≈12 mm/min, T=890°C and air cooling.

Once the aforementioned process parameters had been established, for purposes of the material testing, two tube bends were prepared at Zakłady Remontowe Energetyki Katowice S.A. It was found that their geometry was highly conforming with the profile defined in the course of the FEM-based numerical analysis (Fig. 1), as shown in Table 1. The geometrical features of the bends complied with the relevant requirements of standards PN-EN 12952 and PN-EN13480. The NT-type heat treatment of the tube bends was conducted under normalising and tempering conditions with diversified parameters, as collated in Table 2.

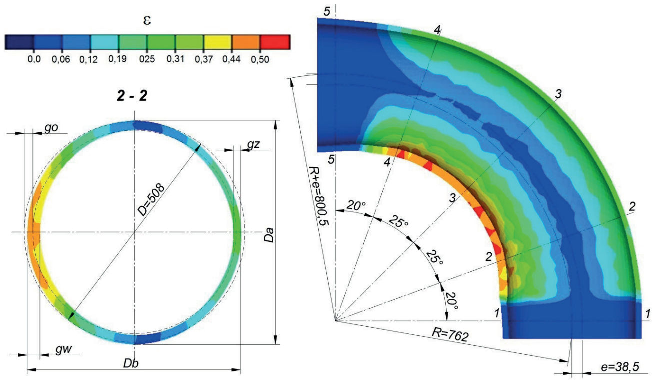

Fig. 1. Geometry of an induction-heated tube bend established by application of FEM

3. Results of material testing

The assessment of basic mechanical properties and the microstructure of tubes with the dimensions of ϕ508x20 in the as-delivered condition subject to the NT-type heat treatment as well as of the bends made from these tubes were conducted based on results of static tension, hardness and impact testing. The material used in tests (sampled from objects in the transverse direction) has been characterised in Table 2. Tests of mechanical properties were conducted using the MTS-810 servo-hydraulic strength testing machine at the room temperature and at 500°C on threaded samples of cylindrical tubes (M16) with the diameter of d_o=10 mm. Results obtained in the tests in question have been collated in Table 3. The microstructure assessment of the materials

TABLE 1

Comparison of calculated, measured and required geometric features of the tube bend analysed

Forming method	Tube wall thickness, mm		Tube diameter, mm		Cross-section ovalisation, %
	Compressed zone g_w	Tensioned zone g_z	D_b	D_a	
FEM simulation	29.0	16.7	491.3	527.8	7.2
Industrial trial	30.8	17.1	487.7	521.3	6.7
PN-EN 12952 standard requirements	>18	>15	---	---	<10

TABELE 2

Characteristics of the material for mechanical and microstructure testing

Test material characteristic	Material designation	Heat treatment parameters
Tube in as-delivered condition	1	Normalising and tempering
Tube bend tension zone HT variant I	2	Normalising: 940°C, 20 min, tempering: 740°C, 30 min,
Tube bend tension zone HT variant II	3	Normalising: 920°C, 20 min, tempering: 720°C, 20 min,

TABELE 3

Collation of basic mechanical properties of as-delivered tubes and tube bends

Test material designation	Testing temperature	Mechanical properties				
		R_m, MPa	R_e, $R_{p0,2}$, MPa	A_5, %	HV10	KV, J
As-delivered tube – 1	room temp.	599	R_e = 454	26	187	247
	500°C	470	$R_{p0,2}$ = 368	19	-	-
Tube bend – 2	room temp.	511	R_e = 358	35	159	128
	500°C	422	$R_{p0,2}$ = 216	19	-	-
Tube bend – 3	room temp.	535	R_e = 368	33	163	179
	500°C	434	$R_{p0,2}$ = 254	19	-	-
Requirements as per PN-EN10216-2	room temp.	480÷630	min. 280	min. 22	150÷197	27

tested was conducted using the Olimpus light microscope and the Hitachi 4200 scanning microscope. The mean grain size A was determined by means of the MetIlo-2 computer program [12]. The results thus obtained have been provided in Table 4.

An analysis of the results of microstructure tests and studies of basic mechanical properties (Tab. 3, 4, fig. 2, 3, 4) revealed that the as-delivered tube material of bainitic structure was characterised by superior strength properties (R_m, R_e) on less advantageous plastic properties (A_5) compared to tube bends of more fine-grained ferritic and bainitic structure. The tube material also showed higher values of KV and HV10 compared to the tube bend material. However, having compared the mechanical properties of bends only, one could establish that the bend marked as "3" subject to heat treatment on lower parameters (Tab. 2), leading to more comminuted microstructure, was characterised by better mechanical properties. At the same time, it could be claimed that the material in the bends made of the 10CrMo9-10 steel met the applicable requirements provided in the PN-EN 10216-2 standard.

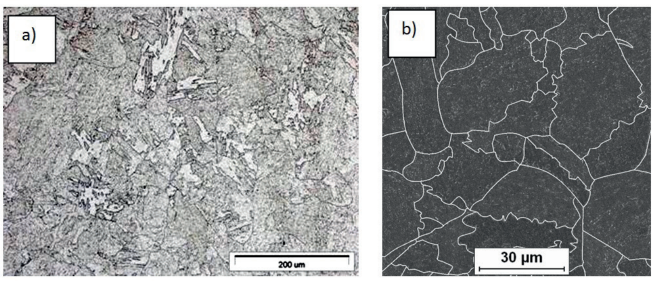

Fig. 2. LM - Bainite microstructure with ferritic areas of tube (a), SEM - and its fragment with grain boundaries outlined (b)

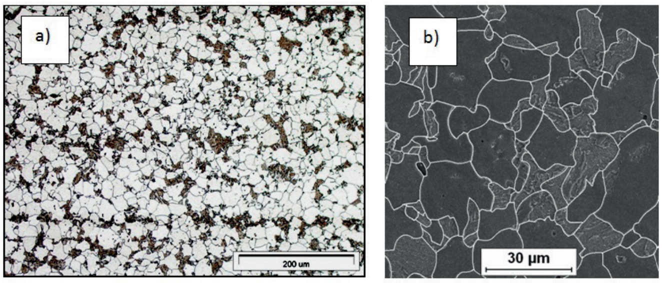

Fig. 3. LM - Fine-grained ferrite-bainitic microstructure of tube bend "2" (a), SEM - and its fragment with grain boundaries outlined (b)

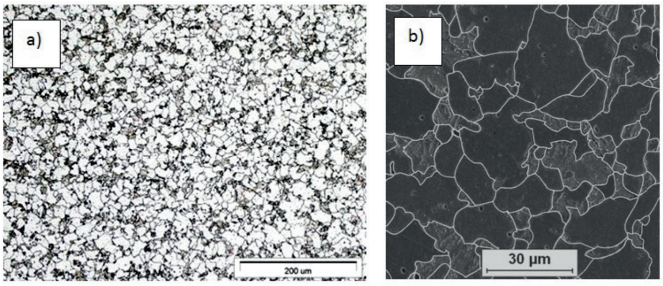

Fig. 4. LM - Fine-grained ferrite-bainitic microstructure of tube bend "3" (a), SEM - and its fragment with grain boundaries outlined (b)

TABELE 4

Mean grain size A in materials microstructure

Material designation	Grain size A, [μm^2]
as-delivered tube – 1	**170**
tube bend – 2	**90**
tube bend – 3	**70**

For the zone of bends subject to tension and the as-delivered tube material, also low cycle fatigue and creep tests were conducted. The fatigue tests simulated the process of the material fatigue under conditions of elastic-plastic deformations. Such destructive processes may occur in the pipeline areas exposed to the highest strain under conditions of unsteady operation of a power unit. The fatigue tests were conducted using the MTS servo-hydraulic strength testing machine on threaded samples of cylindrical tubes (M12) with the diameter of d_o = 9 mm. The tests were performed at the temperature of 500°C on the fixed deformation frequency set at 0.1 Hz. The studies were conducted within the range of total deformation of $\Delta\varepsilon c$ = 0.6% and 0.8%.

Based on the results thus obtained, the low cycle durability was determined (Tab. 5, Fig. 5) and expressed as the number of cycles until rupture of sample N_f. The tube bend material durability (N_f) observed was considerably higher than that of the as-delivered tube material, which implies that bends are more capable of transferring elastic-plastic deformations.

The research also comprised defining characteristics of cyclic deformation of materials, which have been illustrated in Figures 6 and 7. Their analysis implies very intense weakening of the tube material in the low cycle process, the intensity being considerably higher than in tube bends. The foregoing clearly evidences that strength properties of the tube material are very negatively affected under conditions of cyclic deformations of elastic-plastic nature.

TABELE 5

Collation of low cycle (N_f) and creep (t_z) durability of as-delivered tubes and tube bends

Test material designation	Mechanical properties		
	N_f, cycles ($\Delta\varepsilon_t$=0.6%)	N_f, cycles ($\Delta\varepsilon_t$ =0.8%)	t_z, h
As-delivered tube – 1	1,328	992	378
Tube bend – 2	2,284	1,002	322
Tube bend – 3	2,550	1,604	839

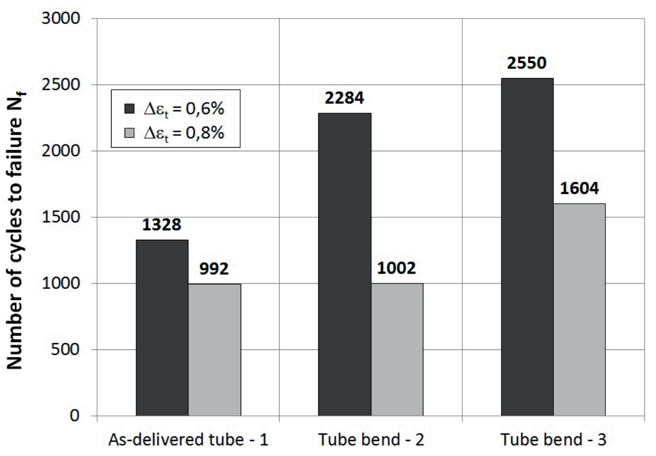

Fig. 5. Collation of low cycle durability characteristics of as-delivered tube and tube bend material

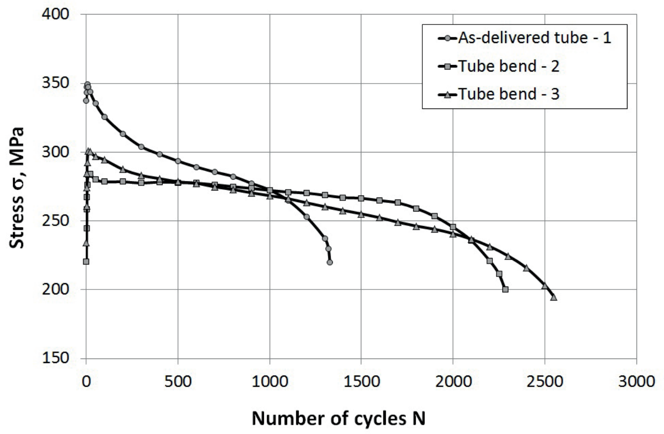

Fig. 6. Characteristics of cyclic deformation of as-delivered tube and tube bend material, determined within the deformation range of $\Delta\varepsilon_t$ = 0.6%

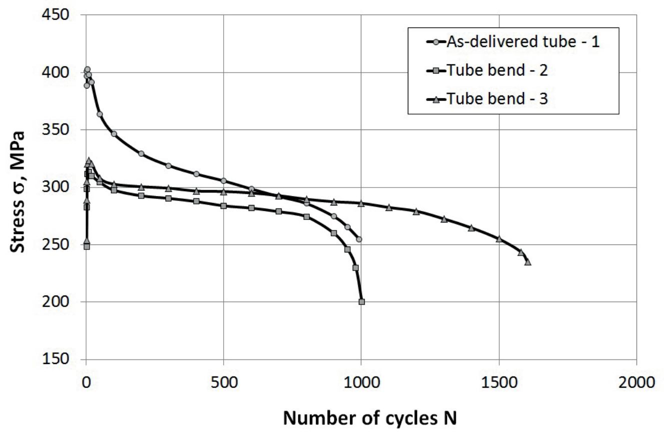

Fig. 7. Characteristics of cyclic deformation of as-delivered tube and tube bend material, determined within the deformation range of $\Delta\varepsilon_t$ = 0.8%

What the creep tests were assumed to simulate was the processes of the pipeline material destruction under conditions of steady operation of power generating installations. Creep tests conducted at the temperature of 500°C and the stress of 250 MPa were performed using the ATS-2330 machine at the Institute of Aviation in Warsaw, according to according reference standard ASTM-E-139. The results obtained have been provided in Table 5 and in Figure 8. The analysis of the results implies that the highest creep durability of tz = 839 h, expressed as the time until the sample rupture, was displayed by tube bend "3" characterised by the most comminuted microstructure. On the other hand, the lowest creep durability of t_z = 322 h was discovered for tube bend "2". The durability of the as-delivered tube material came to 378 h.

The deformation hardening observed based on the creep characteristics (Fig. 8) in the as-delivered tube material of bainitic structure is clearly more profound compared to the tube bend material characterised by fine-grained ferritic-bainitic structure. At the same time, the tube material cracking process, corresponding to the 3rd stadium of creep, is initiated at a lower value of deformation compared to the tube bend material. Comparing the creep durability values for bends of ferritic-bainitic structure only, one may assume that the factor decisive of their durability was the grain size.

More comminuted grain in the microstructure of bend “3” triggered better deformation hardening, lower creep rate and, at the same time, higher durability (Fig. 8). Consequently, one may assume that the predominant deformation mechanism in the creep process was the dislocation mechanism related to the displacement of edge dislocations [1].

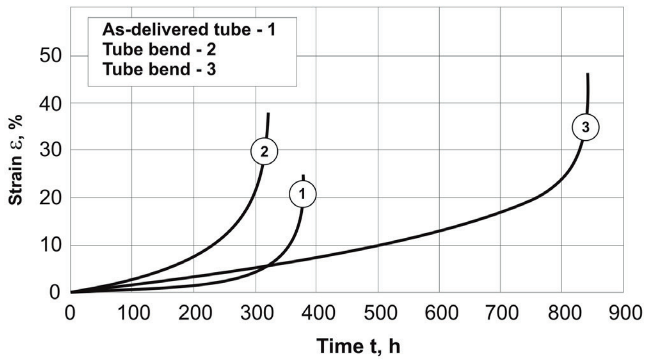

Fig. 8. Creep characteristics for as-delivered tube and tube bend material, established at the temperature of 500˚C and the stress of σ = 250 MPa

4. Conclusions

- The technological process of manufacturing ϕ508x20 tube bends with the bending radius of R=762 mm made of the 10CrMo9-10 steel using diversified heat treatment parameters triggered a change in both the microstructure as well as in mechanical properties of tube bends compared to the tube material in the as-delivered condition. Tube bends were characterised by a fine-grained ferritic-bainitic microstructure, whereas the tube itself featured the bainitic structure. The foregoing was translated into superior mechanical properties (R_m, R_e, KV, HV10) of the tube material compared to the bends.
- A bend subject to heat treatment according to variant 1 (normalising at 940°C/20 min, tempering at 740°C/30 min) was characterised by less extensive grain comminution and inferior mechanical properties (R_m, R_e, KV, HV10) compared to a bend subject to heat treatment which followed variant 1 (normalising at 920°C/20 min, tempering at 720°C/20 min). At the same time, the tube bend material met the relevant requirements provided in standards PN-EN10216-2 and PN-EN12952 for both geometrical features and fundamental mechanical properties.
- Studies of low cycle fatigue at the temperature of 500°C within the deformation range of $\Delta_{\varepsilon c}$ = 0,6% and 0.8% revealed considerably higher low cycle durability N_f of the tube bend material compared to the as-delivered tube material. The tube bend subject to heat treatment according to variant 2 was characterised by considerably higher fatigue durability N_f compared to the one heat treated according to variant 1.
- Under creep conditions, the creep durability of the tube bend subject to heat treatment following variant 2 was significantly higher (more than twice) than that of the tube material in the as-delivered condition as well as of the tube bend heat treated according to variant 1.

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