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Microstructure, properties and welding of T24 steel – critical review

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Abstract

In this paper a new bainitic 7CrMoVTiB10-10 (T24) steel has been described on the basis of our own research results and a review of relevant literature. The T24 creep-resistant steel is known to be intended for membrane walls in power-generation units operating at supercritical steam parameters. Chemical composition, thermal treatment, microstructure and mechanical properties of T24 steel were characterized. Moreover, the processes of microstructure degradation during ageing/creeping and their effects on mechanical properties have been shown. Weldability of T24 steel and the problems connected with cracking of its homogeneous joints, as well as the methods of preventing them, are given in the paper.

Key words: bainitic steels, microstructure, welding, cracking

1. Introduction

Power sectors demand for steels that can operate at supercritical conditions is determined by a necessity to increase thermal efficiency and also to reduce pollution emissions of power units. One of the materials implemented in the power industry is bainitic 7CrMoVTiB10-10 (T24) steel, as a material for membrane water-walls in the power units. T24 steel is a well-known material used for construction of membrane water walls in the steam boilers. T24 steel was developed as a result of a modification in the chemical composition of 10CrMo9-10 (T22) steel which has been used in the power industry for many years. The steel is characterized by higher mechanical properties, proper weldability and forming flexibility [1, 2]. The new type of steel was quickly launched into the market, which caused many technological problems. Industrial practice proved that T24 welded joints are susceptible to thermal, cold and relaxation cracking [1, 3]. In this paper, the characteristics of T24 steel and its use for the parts of supercritical pressure boilers are presented on the basis of our individual research and review of relevant literature. The characteristics of 7CrMoVTiB10-10 (T24) steel and its use for the membrane walls of pressure boilers intended to be serviced at supercritical parameters was shown on the basis of an individual research and literature review.

2. Description of T24 steel

The T24 steel was introduced into the market due to high demand of power industry for a material that could replace old types of steel, Cr-Mo or Cr-Mo-V, used for membrane water-walls. New alloying elements and micro additives, such as: vanadium, titanium, boron and nitrogen [1, 2], were added into the T24 steel chemical composition. A comparison of T22 and T24 steels chemical composition is shown in Table 1.

Vanadium and titanium additives cause the formation of MX (M = V, Ti; X = C, N) and/or MC precipitates which increase the strength properties, including creep strength, as a result of precipitation strengthening. The primary Ti-rich precipitates (precipitating directly from the liquid) are characterized by high thermodynamic stability. TiC titanium

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Table 1. Chemical composition of T22 and T24 steel in wt.% [4–6]

Grade		C	Mn	P	S	Si	Cr	Mo	V	Ti	N	B
T22	min	0.06	0.40				2.00	0.90	–	–	–	–
	max	0.14	0.80	0.030	0.025	0.50	2.50	1.10				
T24	min	0.05	0.30			0.15	2.20	0.90	0.20	0.06		0.0015
	max	0.15	0.70	0.020	0.010	0.50	2.60	1.10	0.30	0.10	0.012	0.0070

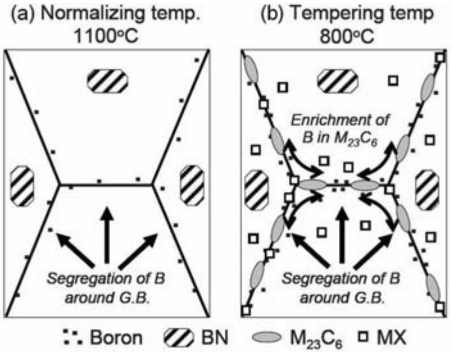

Fig. 1a,b. An idea of enriching border areas and $M_{23}C_6$ carbides in boron atoms during heat treatment of high chromium martensitic steels [11].

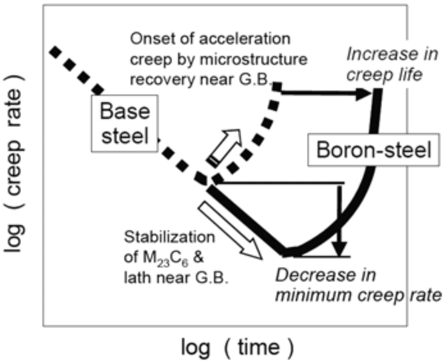

Fig. 2. Influence of boron on the increase in creep strength of high chromium 9–12 % Cr steels [11].

carbide starts to dissolve in liquid in the 1200–1300 ℃ range. Thermodynamic stability of Ti-rich precipitates can be characterized by their values of enthalpy of formation which are: -95 kJ mol^{-1} and -170 kJ mol^{-1} for TiC carbide and TiN nitride, respectively [7]. Their main aim is to slow down the growth of grains during heat treatment. On the other hand, precipitates rich in vanadium are the secondary precipitations which precipitate during high tempering and are responsible for the precipitation strengthening of the steel. The calculations [8] made for P91 steel show that the values of Orowan stress needed to overcome a precipitate particle by dislocation are 15 MPa and 106 MPa for NbC and VN precipitates, respectively. Boron micro additive increases the hardenability of steel (if it is dissolved in solid solution). What is more, boron replaces carbon in $M_{23}C_6$ carbides and forms carboborides $M_{23}(C, B)_6$, increasing their thermodynamic stability (the coarsening process of these precipitates runs more slowly), which stabilizes the bainitic microstructure [9–11]. The idea of enrichment of the near-boundary areas of grains and $M_{23}C_6$ carbides in the atoms of boron during heat treatment is presented on the example of martensitic steels (Fig. 1).

An increase in the thermodynamic stability of $M_{23}C_6$ carbides due to the process of enriching them in boron, and the related stability of a tempered bainite microstructure, results in a rise of creep strength of steel rich in this micro additive. When boron atoms are placed also in the grain boundary areas that are disturbed in crystallographic terms, they make their sliding and diffusion processes difficult in those areas. Similar increase in creep strength was observed in the case of martensitic steels as a result of introducing the micro additive of boron into their chemical composition [11] (Fig. 2).

The modification of T24 steel's chemical composition by the rise of its hardenability – extending the field of supercooled austenite, makes obtaining bainite microstructure easier (Fig. 3).

Heat treatment of T24 steel depends on the thickness of the wall: normalizing and tempering are applied for the thickness up to 16 mm, while hardening and tempering – above 16 mm. The range of temperatures for heat treatment of T24 steel is: 980–1020 ℃ for austenitizing and 730–770 ℃ for tempering [5, 6]. A wide range of tempering temperatures is an optimum combination of strength properties and plastic properties. Lower temperature of tempering allows obtaining high strength properties at low ductility. Rising the tempering temperature allows an increase in the steel ductility at the expense of strength properties (Fig. 4).

After the heat treatment, the microstructure of T24 steel becomes a tempered bainite microstructure or bainitic-martensitic microstructure with numerous $M_{23}C_6$ carbides and precipitations of the MX (MC)

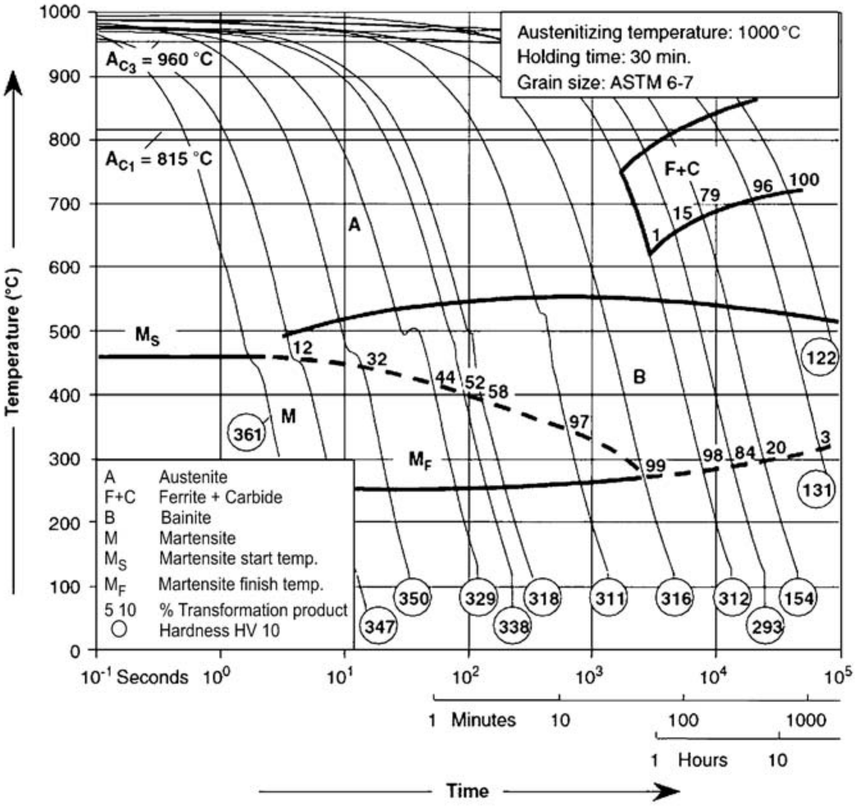

Fig. 3. TTT diagram of T24 steel base material [12].

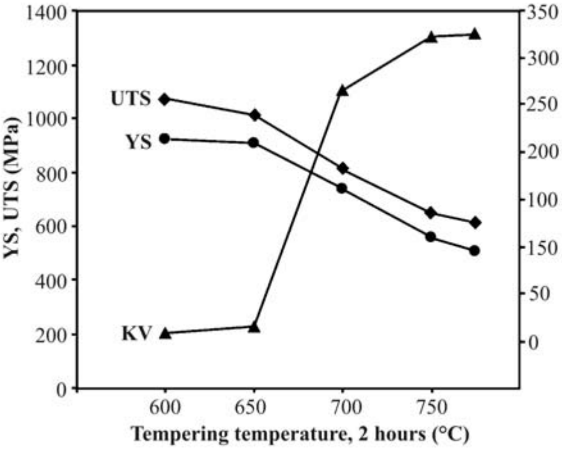

Fig. 4. Influence of tempering temperature on mechanical properties of T/P24 steel [12].

type. Carbides of the $M_{23}C_6$ type are observed mainly on the boundaries of prior austenite grains and the boundaries of laths. However, the MX (MC) precipitations occur inside the laths, frequently on the dislocations [13, 14]. An example of the microstructure of T24 steel is presented in Fig. 5.

Depending on the chemical composition, heat treatment parameters and cooling rate, the pipes and flat bars made of T24 steel can be characterized by

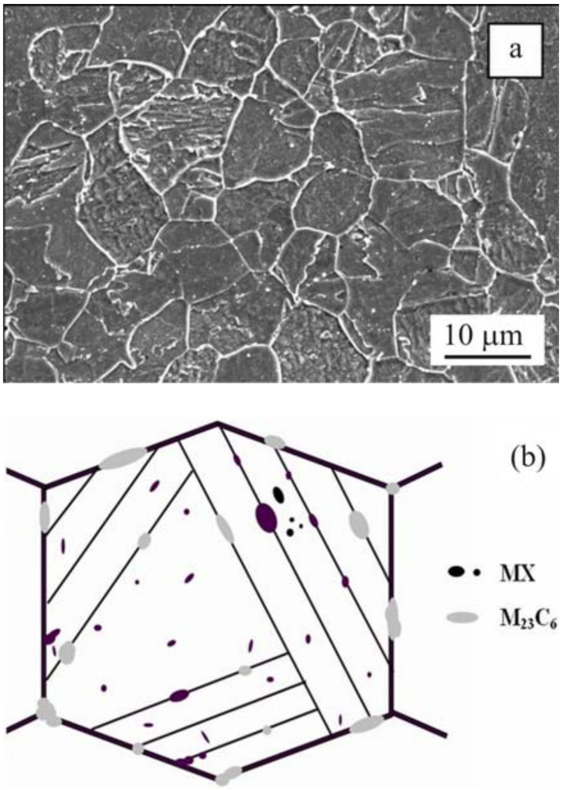

Fig. 5. Microstructure of T24 steel in the as-received condition (after heat treatment) (a) and its scheme (b) [14].

Table 2. Mechanical properties of T22 and T24 steel at room temperature according to ASTM A213 and EN 10216–2 standards [4–6]

Grade		ASTM standard				Grade		EN 10216 – 2 standard					
		YS (MPa)	TS (MPa)	Elongation (%)	HB			YS (MPa)	TS (MPa)	Elongation (%)		Impact energy (J)	
										w	p	w	p
T22	min	205	415	30	–	10CrMo9-10	min	270	480	22	20	40	27
	max	–	–	–	163		max	–	630	–	–	–	–
T24	min	415	585	20	–	7CrMoVTiB10-10	min	430	565	17	15	40	27
	max	–	–	–	250		max	–	840	–	–	–	–

the following microstructures [13, 15]:

- granular bainite with little amount of ferrite;
- lath bainite and granular bainite;
- lower bainite and martensite.

Apart from the differences in volume fraction of the phases occurring in the microstructure of T24 steel after heat treatment, the individual microstructures demonstrate also differences in low and high angle boundaries. In the microstructure with dominant granular bainite (Fig. 6a), low angle boundaries are prevailing. In the bainitic-martensitic microstructure (Fig. 6b), however, wide angle boundaries are dominant. On the other hand, in the intermediate microstructures the amount of low and high angle boundaries is similar.

The low and high angle boundaries are a significant factor influencing mechanical properties of steel. Narrow angle boundaries are characterized by slight mobility, which guarantees stability of substructure in contrast to the boundaries of a large angle. The dominance of narrow angle boundaries in the steel microstructure provides better resistance to creep and slower degradation of the microstructure during service. Stability of subgrain size has a positive influence on the increase in creep strength.

It should be considered that T24 steel with a strengthened microstructure (lower bainite microstructure or a mixture of lower bainite and martensite) will show higher creep strength in the as-received condition. Nevertheless, it will loose its strengthening faster due to lower thermodynamic stability of the microstructure in comparison to steel with granular bainite microstructure, for example.

A comparison of mechanical properties of T24 and T22 steels is presented in Table 2. The T24 steel compared to T22 steel is characterized by: higher strength properties (resulting mainly from the tempered bainitic microstructure strengthening by dispersive MX precipitations) and the lack of ferrite with lower strength properties.

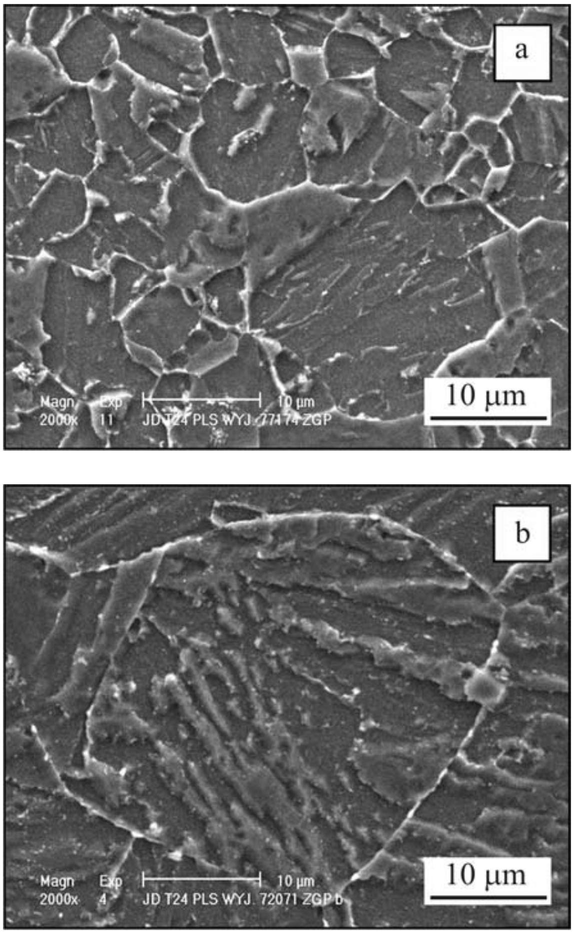

Fig. 6. Microstructure of T24 steel with dominant content of: granular bainite (a) and lower bainite (the microstructures obtained by courtesy of Prof. J. Dobrzański and A. Zieliński, PhD., Institute for Ferrous Metallurgy, Gliwice, Poland) (b).

The research works [14–19] prove that long-time ageing/creeping of T24 steel contributes to the following changes in microstructure:

- privileged carbide precipitation on grain boundaries;
- precipitation of M_2C carbides;
- enriching MX carbides with molybdenum;

– processes of recovery and polygonization of the matrix.

The above-mentioned changes observed in the microstructure cause a slight reduction of strength properties and a significant initial fall of impact energy (about 20 % after 1000 h of ageing in the temperature of 580 ℃). Further ageing (up to 12000 h) practically does not have an influence on the change in impact energy of aged T24 steel [13]. A similar tendency was also observed in the "twin" T23 steel after service under creeping conditions [18]. The influence of long-term ageing at the temperature of 550 and 600 ℃ on mechanical properties of T24 steel is also presented in the work [19]. This research showed that after 30000 h of ageing at the temperature of 600 ℃, the strength properties: YS, TS, YS^{550} (yield stress at 550 ℃) were lower than the minimum requirements. Whilst after ageing at the temperature of 550 ℃, these properties were higher than the required minimum. On the other hand, the impact energy of T24 steel after ageing at the temperature of 550 ℃ was reduced by about 45 %, while after ageing at the temperature of 600 ℃ it was comparable to the as-received state.

The revealed enrichment of MX (MC) precipitations in molybdenum [16] is also the fact worth noticing. Molybdenum enrichment of MC precipitations which are vanadium-rich can lead to the formation of complexes called "H-carbide" [20]. The "H-carbide" complexes consist of a horizontal precipitation of VC and vertical precipitations of M_2C carbides (Mo-rich carbides) nucleating in parallel at counter-sides of VC precipitates (Fig. 7).

Privileged areas for the formation of these complexes are near-boundary areas. The formation of "H-carbide" precipitates at the expense of VC carbides in these areas can lead to an irregular course of creeping process in the grain volume. It can also lead to the faster dislocation process of creeping in the near boundary areas, and premature damage. Similar complexes were observed in low-alloyed Cr-Mo-V steels/cast steels after operation [21]. The danger that lies in a disappearance of fine dispersive precipitations can be seen on the examples of martensitic steels, where the change of MX → Z phase (complex nitride Cr(V, Nb)N) takes place. It results in a rapid fall of creep strength [22, 23].

3. Weldability of T24 steel

The main advantage expected of T24 steel apart from its high mechanical properties was the possibility of welding it without initial heating, and no necessity of conducting the postweld heat treatment with the thickness of a tube wall up to 10 mm [24–27].

The T24 steel belongs to the group of hard to weld materials (Fig. 8), which results mainly from: a narrow range of applicable parameters of welding and the thickness of melted metal of the filler material, which causes difficulty in spreading it in the weld groove [27].

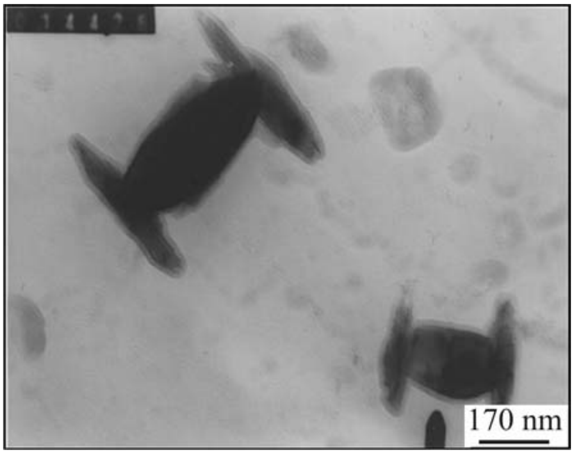

Fig. 7. "H-carbide" precipitate, carbon extraction replica, TEM [21].

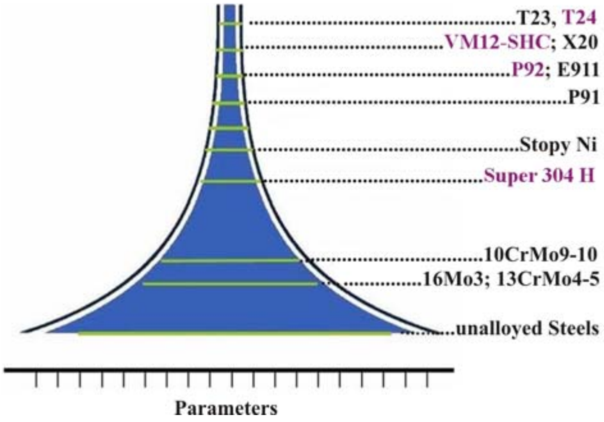

Fig. 8. Comparison of range of welding parameters of older and newly developed steels for power industry [12].

In the case of T24 steel as shown in a Continuous – Cooling – Transformation for welding conditions (CCT-W) diagram (Fig. 9) in a wide range of self-cooling time between the temperature of 800 and 500 ℃ ($t_{8/5}$), bainite microstructures of higher hardness or hardness close to 350 HV will appear.

Practically, only the self-cooling time $t_{8/5}$ longer than 40 s allows obtaining the heat-affected zone (HAZ) of hardness less than 350 HV5, but still of insufficient ductility – impact energy (Fig. 10).

Laboratory tests of homogeneous butt joints and dissimilar welded joints of T24 steel seemed to confirm the data of the steel manufacturer at first [25–27]. However, the research presented in the paper [27] showed a necessity of applying the initial preheating to the temperature of about 150 ℃. Nevertheless, practical experiments [28–31] connected with welding of

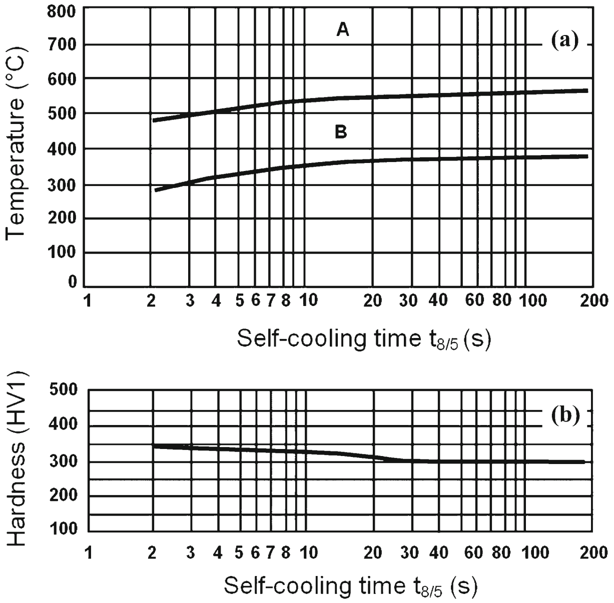

Fig. 9. Diagram of CCT-W weld curve for T24 steel [25].

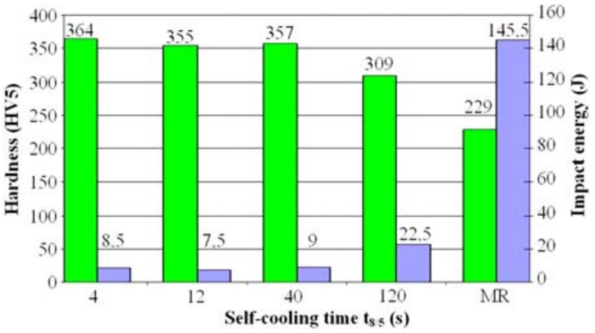

Fig. 10. Hardness and impact energy of T24 HAZ in dependence on self-cooling time, individual study on the basis of [24, 25]. MR-base material.

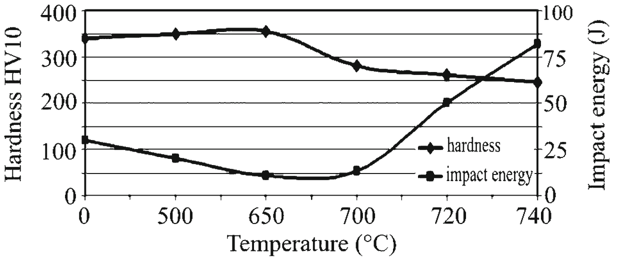

Fig. 11. Influence of temperature of joint heat treatment on its hardness and impact energy, individual study on the basis of [32, 34].

the membrane walls made of T24 steel have shown that after welding or after installation and service, cracks on welded joints appear and they are not detected by a non-destructive testing due to their size. These cracks are intercrystalline and usually appear in the first bead [32].

The research works [28–31, 33, 34] have shown that the main reason for transverse cracking of joints were hot cracks and their further development appearing as delayed cold cracks. Hot cracking of a joint is connected with its high strength properties in the state without treatment (YS $\geq$ 830 MPa, UTS $\geq$ 1000 MPa), in comparison with a similar pipe and flat bar on the level of 700 MPa. High yield point of the weld material prevents relaxation of tensile stresses which are the result of solidification shrinkage causing hot cracks. According to [34], hot cracking occurrence is also influenced by the speed of welding being too high (above 0.7 m min^{-1}).

The delayed cold cracks in the welded joint of T24 steel are generated by: high level of residual stress of the joint without heat treatment (the determined critical stress causing cold cracks in the HAZ of the T24 steel joint amounts to 485 MPa), the presence of hydrogen during welding and the joint microstructures with martensite or lower bainite content. High brittleness of the joint after welding in the state without heat treatment, in combination with additional stresses that occur during, e.g., relocation, assembly or transportation of the mass, contribute to joint cracking.

In order to obtain joints without any cracks it is necessary to apply at least: an initial heating, filler materials of higher yield properties and lower strength properties (comparable to T22 steel) to eliminate the hot cracking tendency, as well as the heat treatment performed after welding or with a technique of tempering beads as an alternative.

Performed research works [32, 34] have shown that applying heat treatment after welding at the annealing temperatures up to 650 °C leads to further increase in strength properties and a decrease in impact energy to the value of 5–12 J (Fig. 11). The increase of strength properties of a joint is connected with the so-called secondary strengthening effect. The welding filler material with the 141 method (submerged welding arc) is a wire which consists of carbide-forming elements: niobium and vanadium. Niobium in the additional material replaces titanium, which would burn during the welding process due to its high affinity for oxygen. The MX (MC) precipitates rich in niobium are directly precipitated from the liquid, thus they have a positive influence on limiting the austenite grain growth. Moreover, their influence on the extent of precipitation strengthening is slight. The MX (MC) precipitates rich in vanadium are precipitated during tempering in a fine-dispersive form and are responsible for an increase in hardness and creep strength. A similar effect of the secondary hardness was observed in a traditional low-alloyed Cr-Mo-V steels [20]. Temperature of treatment higher than 650 °C results in a reduction

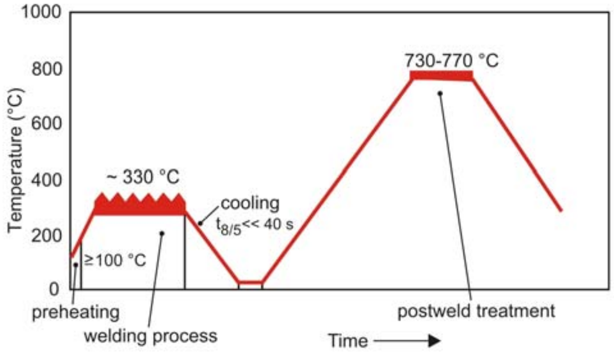

Fig. 12. Proposed draft of thermal welding cycle and postweld treatment of T24 steel.

of strength properties and growth of impact energy. The authors' opinion is that the temperature of heat treatment of a joint should be comparable to the temperature of native material tempering. The time of holding at the annealing temperature should at least amount to 1 h for the wall thickness $t \geq 10$ mm, whilst for $t < 10$ mm, it should amount to 30 minutes. It will guarantee a similar microstructure and properties of a joint as in the initial material. The research has shown that the technology of T24 steel welding based on the manufacturer's recommendations does not guarantee receiving welded joints without cracking, therefore, the authors propose the welding technology presented in a diagram in Fig. 12.

In the work [35] it has been proved that welding with the hybrid method, i.e., combining laser-beam fusion welding and metal active gas (MAG) welding, allows forming panels of membrane walls made of T24 steel without cracks. Researchers associate this with the specificity of hybrid welding: considerably lower stresses occurring during the welding process in comparison with hidden arc welding, and more regular heating up of the pipes on the whole circumference and length. However, what the authors find questionable about applying this method is the possibility of performing necessary repairs in the industrial conditions.

4. Conclusions

A review of literature shows that T24 steel is a fully valued material intended for service in power units working at supercritical parameters. The problems of welded joints cracking result from the manufacturer's too optimistic an assumption that T24 steel can be welded without heat treatment. It was verified in the industrial practice and was a result of numerous delays in technical acceptance and running of new power units. The following paper shows that in order to obtain a high quality joint without any welding discrepancies, it is necessary to carry out both initial heating and a postweld treatment at the temperatures higher than 730 °C, and apply welding filler materials of high plastic properties and lower strength properties.

An alternative for manufacturing membrane walls of T24 steel can be an attempt to design and make a furnace chamber consisting of segments of membrane walls made of various grades of steel, depending on the temperature and stress in a certain area of the chamber. Then only the most loaded elements would be made of T24 steel, and the remaining ones would be made of the Cr-Mo type steel, e.g., T22 steel [36].

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