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**WELDABILITY OF THERMOMECHANICALLY TREATED STEELS HAVING A HIGH YIELD POINT****SPAWALNOŚĆ STALI OBRABIANEJ TERMOMECHANICZNIE O WYSOKIEJ GRANICY PLASTYCZNOŚCI**

The article concerns the issue of weldability of S700MC steel, treated thermo-mechanically, with high yield point. The weakest area of welded joints of this steel is a high - temperature coarse heat affected zone (HAZ) in which due to the nucleation effect of the dissolved phases, strengthening the matrix and their subsequent uncontrolled separation precipitation in the form of finely disperse and rapid decrease impact strength is observed. Performed arc welding tests here have shown that in order to ensure high quality of welded joints, it is necessary to limit the welding linear heat input. During the welding process of S700MC steel, it is not recommended to use pre heating before the welding process and heat treatment after welding, and the number of repairs should be kept to a minimum, because it leads to a reduction of strength and plastic properties in the HAZ area, as a result of aging processes, dissolution of strengthening phases in the matrix and their subsequent uncontrolled precipitation during cooling.

*Keywords:* Weldability, TMCP steel, HAZ

W pracy przedstawiono problematykę spawalności stali obrabianej termomechanicznie S700MC o wysokiej granicy plastyczności. Najłabsze miejsce złącza spawanego tej stali stanowi wysokotemperaturowy, gruboziarnisty obszar strefy wpływu ciepła (SWC), w którym na skutek zarodkowania rozpuszczonych faz umacniających w osnowie i ich ponownego, niekontrolowanego wydzielenia w postaci drobnodispersyjnej, następuje gwałtowny spadek udarność. Przeprowadzone próby spawania łukowego wykazały, że w celu zapewnienia wysokiej jakości złączy spawanych należy ograniczyć energię liniową spawania. Podczas spawania stali S700MC nie zaleca się stosowania podgrzewania wstępnego przed spawaniem oraz obróbki cieplnej po spawaniu, a liczbę napraw należy ograniczyć do minimum, gdyż prowadzi to do obniżenia własności wytrzymałościowych i plastycznych w obszarze SWC, na skutek procesów o charakterze starzeniowym, rozpuszczania faz umacniających w osnowie i ich ponownego, niekontrolowanego wydzielenia w czasie chłodzenia.

**1. Introduction**

Recent years have seen a continuous increase in the global share of welded structures made of steels with an increased and overall high yield point. Quality requirements in many industries such as shipbuilding, civil engineering, hydro and nuclear power, the construction of oil rigs and pipelines dictate that new technologies applied in steel metallurgy and metal forming should be developed and implemented in a manner enabling the obtainment of end products, such as plates and tubes, characterised by a high strength, yet without compromising their plastic properties. The development of new steel grades and higher requirements set for welded structures have inspired detailed studies dedicated to factors affecting the behaviour of such materials in structures during welding and in post-weld operation. Newly developed materials include thermomechanically rolled steels, particularly those with a yield point of 700 MPa. The implementation of thermomechanically processed steels with a high yield point and a relatively low carbon equivalent significantly reduces the duration of welding works by decreasing the temperature of a preheating process

or even by completely removing this processing stage. Furthermore, the reduction of the cross-sectional areas of structural elements makes welded structures more slender and light-weight. The use of the aforesaid steels reduces welding costs by decreasing the cross-sectional areas of joints, thus leading to the reduced consumption of welding consumables as well as to the reduction of welding process duration and to the reduction of time necessary for carrying out construction-related preparatory works or testing welded joints [1,4]. The technical and economic aspects arising from the possibility of making products of these steels and applying them in energy-efficient integrated production lines as well as their suitability for the construction of various structures, including those operating in extreme climatic conditions, are of great importance for the materials science related to this group of steels and for the improvement of technologies used for manufacturing and joining such steels by means welding methods. The usefulness of these materials for the manufacture of welded structures often depends on factors which until recently have not been fully considered while assessing the weldability of the materials

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mentioned above. A major problem affecting these steels is the influence of alloying microadditions, such as niobium or vanadium, on the weldability and properties of welded joints. The microadditions applied in these steels aim to reduce the grain size, which, in turn entails the dispersion of carbides, nitrides and carbonitrides of niobium and vanadium thus increasing the mechanical properties of such steels by intensifying the precipitation phenomenon and reducing the grain size [5-9]. Another factor which helps maintain good plastic properties of steels is grain refining. Weldability tests have revealed that great difficulties while welding thermomechanically treated steels may be caused by the uncontrollable processes related to the separation of MX type intermetallic phases (fine grain segregation of Nb(C,N), V(C,N) carbides/carbonitrides), significantly lowering the plastic properties of welded joints and reducing their crack resistance. It is also necessary to note the negative influence of nitrogen being responsible for ageing processes. The parent metal contains sufficient amounts of active titanium and aluminium in order to bond so-called free nitrogen and form stable and low solubility TiN and AlN type phases in the austenite. In the joint the amount of titanium determines welding properties. If the level of nitrogen in the steel is excessively high, the amount of titanium may not be sufficient to limit ageing processes responsible for the deterioration of the functional properties of joints [10-14].

## 2. The range of investigation

The objective of the research-related tests was to determine the effect of a welding method, welding linear energy, beveling, preheating temperature and a post-weld hold on the properties of welded joints made of 10 mm thick S700MC grade steel, Table 1, 2 [15]. The following welding processes were performed:

- ▶ MAG welding using a G Mn4Ni1.5CrMo solid wire having a diameter of 1.2 mm, an M21 active shielding gas and a variable linear welding energy of 8 and 15 kJ/cm; the MAG welding process was followed by repair welding with one, two and three repairs – simulated welding imperfections were removed by means of arc-air gouging using a graphite electrode,
- ▶ MAG welding using a T Mn2NiCrMo flux-cored wire having a diameter of 1.2 mm, an M21 active shielding gas, a constant linear welding energy of approximately 8 kJ/cm and a variable preheating temperature restricted within a range from 50°C to 200°C,
- ▶ argon-shielded TIG welding using an MT-NiMoCr solid wire with a diameter of 3 mm, a variable linear welding energy of 10 and 30 kJ/cm and a two-hour post-weld hold at 180°C,
- ▶ submerged arc welding under an OK Flux 10.61 low-hydrogen flux, using an S Mn3NiMo1 solid wire having a diameter of 3.2 mm and a variable linear welding energy of 10, 20, 30, 40 kJ/cm,
- ▶ laser beam welding using a TruDisk 12002 disc laser and a linear welding energy of 5 kJ/cm.

TABLE 1

The chemical composition according to the regulation PN EN 10149-2 and mechanical properties of the S700 MC steel subjected to thermomechanical treatment used for cold moulding

Chemical composition, % wt											
C max.	Si max.	Mn max.	P max.	S max.	Al min.	Nb max*.	V max.	Ti max.	B max.	Mo max.	C <sub>e</sub> ** max.
0.12	0.60	2.10	0.008	0.015	0.015	0.09	0.20	0.22	0.005	0.50	0.61
Mechanical properties											
Tensile strength R <sub>m</sub> , MPa		Yield limit R <sub>e</sub> , MPa			Elongation A <sub>5</sub> , %			Impact strength, J/cm <sup>2</sup> (-20°C)			
822		768			19			135			

\* – total amount of Nb, V and Ti should be max. 0,22%\*\* C<sub>e</sub> – carbon equivalent

TABLE 2

The real chemical composition of the original S700 MC steel material

Chemical composition, % wt										
C	Mn	Si	S	P	Al	Nb	Ti	V	N*	C <sub>e</sub>
0.056	1.68	0.16	0.005	0.01	0.027	0.044	0.12	0.006	72	0.33

\* – N: the amount given in ppm, the nitrogen was measured using the high temperature extraction method

TABLE 3

Effect of welding and heat input on mechanical and plastic properties of welded joints

Welding method/ Linear welding energy, kJ/cm	Tensile strength*		Bending*, bend angle, °		Impact strength KCV**, J/cm <sup>2</sup> (test temperature -30°C)			
	R <sub>m</sub> , MPa	Place of rupture	Face of weld	Back of weld	Weld		HAZ	
					KCV, J/cm <sup>2</sup>	Fracture	KCV, J/cm <sup>2</sup>	Fracture
Laser/5	790	FL	180	180	20	Fragile	-	-
MAG <sup>SW</sup> /8	860	BM	180	180	94	Mixed	86	Mixed
MAG <sup>CW</sup> /8	810	BM	180	180	79	Mixed	66	Mixed
TIG/10	812	BM	180	180	72	Mixed	57	Mixed
SAW/10	816	BM	180	180	69	Mixed	48	Mixed
MAG <sup>SW</sup> /15	760	HAZ	180	180	77	Mixed	38	Fragile
MAG <sup>CW</sup> /15	790	BM	180	180	71	Mixed	41	Fragile
SAW/15	797	FL	180	180	68	Mixed	42	Fragile
TIG/30	653	HAZ	180	180	63	Mixed	35	Fragile
SAW/30	685	HAZ	180	180	43	Fragile	27	Fragile
SAW/40	637	HAZ	180	180	29	Fragile	17	Fragile

\* – result the average of two measurements;

\*\* – result the average of three measurements; BM – base material; FL – fusion line; HAZ – heat affected zone; SW – solid wire; CR – cored wire.

### 3. The results of investigation

While welding thermomechanically treated steels of a high yield point, in order to obtain appropriate mechanical and plastic properties in a weld it is necessary to use filler metals having an increased content of Ni, Mo and Cr, i.e. chemical elements which strongly affect the value of a carbon equivalent. As a result, the degree at which a parent metal is stirred with a filler metal used will affect the carbon equivalent of a weld. During welding the mechanically treated S700MC steel, in each case of welding with a filler metal the carbon equivalent of a parent metal is significantly lower than that of a weld. During welding an increase in the parent metal fraction in the weld is accompanied by an increase in the contents of alloying microagents Ti and Nb, particularly at the fusion line (Fig. 1). Significant amounts of hardening element precipitates have a very disadvantageous effect on the plastic properties of a weld.

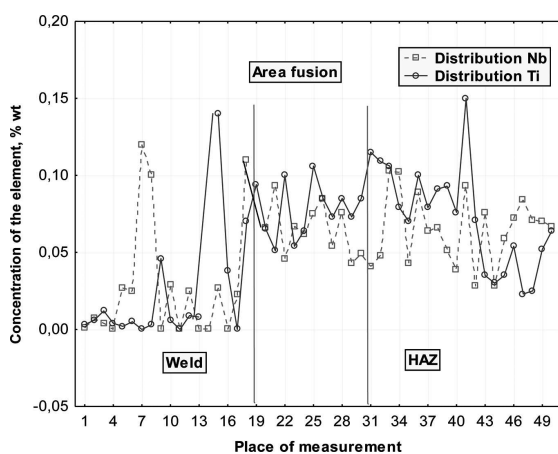


Fig. 1. Distribution of Ti and Nb in the field of fusion welded joint using MAG method and S700MC steel solid wire with linear energy of 8 kJ/cm

The analysis of arc-welded and of laser beam-welded joints revealed the significant effect of a welding method and that of a linear energy on mechanical and plastic properties. An increase in linear welding energy decreases tensile strength and impact strength values (Table 3). The tests conducted have demonstrated that a welding method does not play a significant role in ensuring appropriate mechanical properties. In turn, the impact strength of joints depends on a linear energy and on a welding method. Low values of linear welding energy enable obtaining the high impact strength of a weld and that of HAZ (Fig. 2).

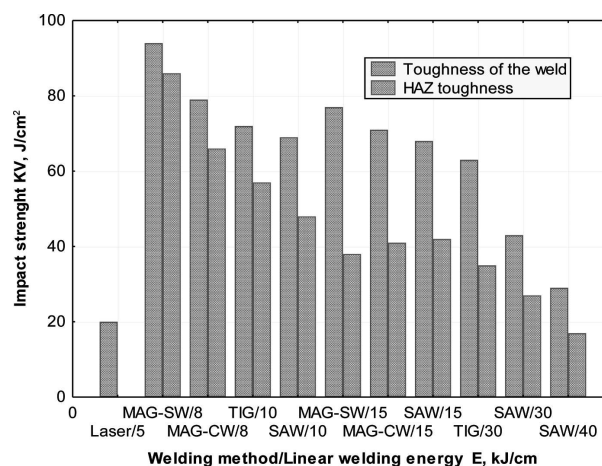


Fig. 2. Effect of welding method and input heat on impact strength of welded joints of steel S700MC

An increase in linear welding energy above 15 kJ/cm results in a significant impact strength decrease in the HAZ area. High HAZ impact strength values in joints welded using low energy values are obtained through the process of recrystallization and precipitation hardening decay (coagulation of precipitates) (Fig. 3). An increase in a linear welding energy, particularly in a high-temperature HAZ, is responsible for

the partial dissolution of hardening components in the matrix. During cooling such hardening components precipitate in an uncontrollable manner in the form of fine-dispersive precipitates (several nanometres in size). This leads to hardening as well as to the increased concentration of dislocations (Fig. 4), which results in a significant impact strength decrease.



Fig. 3. Effect of welding and heat input on mechanical and plastic properties of welded joints of steel S700MC

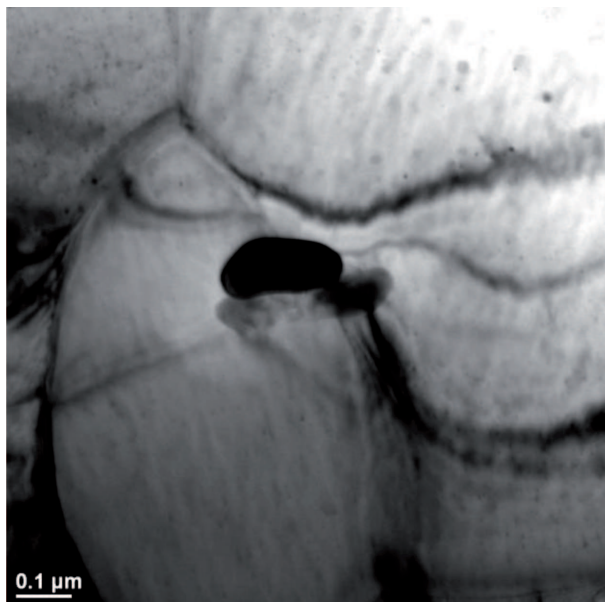


Fig. 4. Precipitation of nitride (Ti,Nb)N together with a number of spherical precipitates with high dispersion of dislocations in plastically deformed matrix surrounding the HAZ S700MC steel, the welding was done using TIG method and linear energy of 30 kJ/cm

The tests conducted have revealed that the decisive factor for ensuring appropriate HAZ plastic properties is a linear welding energy. During arc welding, depending on a welding method and linear energy, it is possible to observe an increase in the fraction of hardening microadditions in a weld. An increase in the fraction of a parent metal in a weld is accom-

panied by the concentration of hardening microadditions in the weld. The longer the time at which a material remains in the liquid state, the greater the amount of microadditions which can dissolve in the matrix and re-precipitate or remain in the solution during cooling. High temperatures of a liquid metal pool dissolve even the most stable TiN particles. The cooling process does not provide appropriate conditions for a controlled re-precipitation of fine-dispersive carbides and carbonitrides (Ti,Nb) responsible for precipitation hardening.

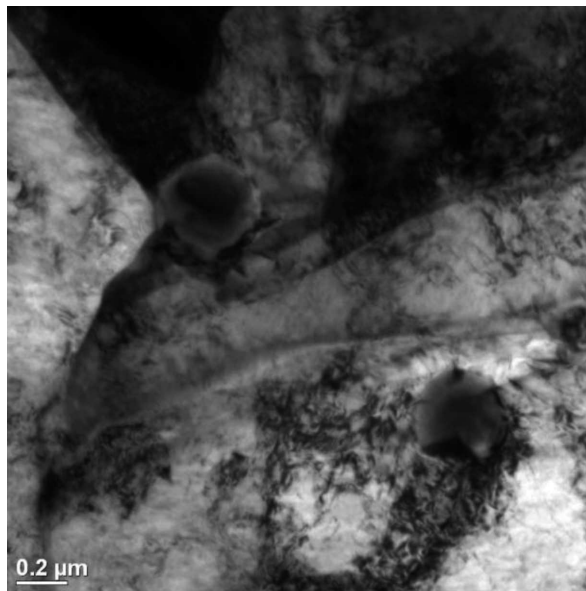


Fig. 5. Spherical TiO precipitation in the weld steel S700MC made using MAG method and solid wire with linear energy of 8 kJ/cm

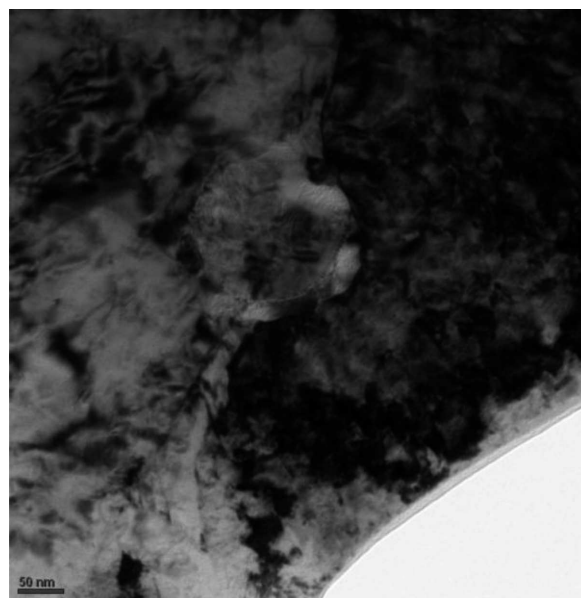


Fig. 6. Precipitation of nitride (Ti, Nb) N together with fine spherical precipitates and dislocations in consolidating joint S700MC steel welded with a laser beam and linear energy of 5 kJ/cm

Welds made by means of arc welding using low linear energy values are characterized by higher impact strength provided by the decay of precipitation hardening effect and by spherical TiO precipitates, being responsible for acicular ferrite nucleation inside austenitic grains (Fig. 5). This, in turn, leads to

the obtainment of the high mechanical and plastic properties of welds. In the case of the welds made using a laser beam, in spite of a low linear energy (5 kJ/cm) and a low carbon equivalent (0.33%), the impact strength obtained is unsatisfactory, i.e. below 20 J/cm<sup>2</sup>. The concentration of microadditions in the weld made using a laser beam is significantly higher than that in the welds made using arc welding, which increases the amount of dispersive precipitates in the weld. A significant fraction of hardening phases in a weld being cooled leads to strong precipitation hardening through fine-dispersive precipitates (Ti,Nb)(C,N) of several nm in size (Fig. 6), which results in the reduction of plastic properties.

While welding thermomechanically treated steels having a high yield point, in which a carbon equivalent and a  $\gamma$ - $\alpha$  transformation do not play a decisive role in providing appropriate properties of welded joints, it is not necessary to apply pre-heating as it may not help or even deteriorate the mechanical and plastic properties of welded joints. The use of pre-heating restricted within a 50-200°C range decreases a tensile strength from 835 to 760 MPa with specimens rupturing in the fusion area or in the HAZ (Table 4). An increase in a pre-heating temperature is also responsible for a decrease in HAZ impact strength (Table 4).

The tests concerning the effect of repair welding confirmed the very low structural stability of the S700MC steel and a significant influence of a thermal cycle on the properties of welded joints. In order to maintain impact strength at the

level not exceeding the permissible criterion of 27 J/cm<sup>2</sup> the number of repairs should be limited to two at the most. More repairs reduce tensile strength and impact strength. After three repairs tensile strength drops to 760 MPa with a rupture taking place in the parent metal area (Table 5). A greater number of repairs decreases the impact strength of a weld from 90 J/cm<sup>2</sup> to 48 J/cm<sup>2</sup>. After two repairs HAZ impact strength amounts to 28 J/cm<sup>2</sup> to fall below the permissible criterion after three repairs (Table 5).

Often in the case of complex structural nodes, in order to ensure the stability of a shape the process of welding is followed by slow, i.e. 2-hour cooling at a temperature of approximately 200°C. In thermomechanically treated steels such a procedure strongly affects their mechanical and plastic properties. The process of post-weld hold is responsible for the very significant reduction of weld impact strength, and particularly of the HAZ, irrespective of a linear welding energy applied (Table 6). The impact strength decrease in the HAZ area can probably be ascribed to ageing taking place in the HAZ, similarly as during the heat treatment. The impact strength of the HAZ of hold-affected welded joints falls below 35 J/cm<sup>2</sup>. The hold-induced weld impact strength decreases two times in relation to welding without the shape stabilizing procedure. Also, the tensile strength of elements exposed to a hold becomes lower; the rupture takes place in the HAZ area with the values of tensile strength dropping below 680 MPa (Table 6), due to the related grain growth.

TABLE 4

The results of strength tests of welded joints MAG powder wire energy 8 kJ/cm steel S700MC with variable temperature preheating

Preheating temperature, °C	Tensile strength*		Bending*, bend angle, °		Impact strength KCV**, J/cm <sup>2</sup> (test temperature -30°C)			
	R <sub>m</sub> , MPa	Place of rupture	Face of weld	Back of weld	Weld		HAZ	
					KCV, J/cm <sup>2</sup>	Fracture	KCV, J/cm <sup>2</sup>	Fracture
-	835	BM	180	180	89	Mixed	77	Mixed
50	817	BM	180	180	76	Mixed	63	Mixed
100	790	Weld	180	180	57	Mixed	52	Mixed
200	760	HAZ	180	180	48	Mixed	41	Mixed

\* - result the average of two measurements; \*\* - result the average of three measurements; BM – base material; HAZ - heat affected zone.

TABLE 5

Effect of repair welding on the mechanical properties of welded joints MAG solid wire energy of 8 kJ/cm steel S700MC

Number of repairs	Tensile strength*		Bending*, bend angle, °		Impact strength KCV**, J/cm <sup>2</sup> (test temperature -30°C)			
	R <sub>m</sub> , MPa	Place of rupture	Face of weld	R <sub>m</sub> , MPa	Place of rupture		Face of weld	
					KCV, J/cm <sup>2</sup>	Fracture	KCV, J/cm <sup>2</sup>	Fracture
Without repair	830	BM	180	180	93	Mixed	65	Mixed
1 repair	817	BM	180	180	87	Mixed	33	Fragile
2 repairs	790	FL	180	180	65	Mixed	28	Fragile
3 repairs	765	HAZ	180	180	48	Mixed	25	Fragile

\* – result the average of two measurements; \*\* - result the average of three measurements; BM – base material; FL – fusion line; HAZ - heat affected zone.

TABLE 6

The results of strength tests of welded joints TIG energy 10 and 30 kJ/cm steel S700MC with and without annealing after welding

Linear welding energy, kJ/cm	Tensile strength*		Bending*, bend angle, °		Impact strength KCV**, J/cm <sup>2</sup> (test temperature -30°C)			
	R <sub>m</sub> , MPa	Place of rupture	Face of weld	R <sub>m</sub> , MPa	Place of rupture		Face of weld	
					KCV, J/cm <sup>2</sup>	Fracture	KCV, J/cm <sup>2</sup>	Fracture
Welding without annealing after welding								
10	810	BM	180	180	72	Mixed	57	Mixed
30	696	HAZ	180	180	63	Mixed	35	Fragile
Welding with annealing after welding at 180°C for two hours								
10	687	HAZ	180	180	46	Mixed	32	Fragile
30	653	HAZ	180	180	36	Fragile	25	Fragile

\* – result the average of two measurements; \*\* – result the average of three measurements; BM – base material; HAZ – heat affected zone.

#### 4. Conclusions

In the case of the thermomechanically treated S700MC steel subjected to precipitation hardening with Ti and Nb carbonitrides, the weldability is affected not only by a carbon equivalent and austenite phase transformations during cooling, but mainly by the stability of hardening phases, the change of hardening phase dispersion and by ageing processes. The S700MC steel is characterised by a strongly defected non-equilibrium bainitic-ferritic structure which underwent hardening through precipitation, solution, strain and grain refining. Welding leads to the change of dispersion and to the decomposition of hardening phases which, during cooling, re-precipitate in the HAZ and weld areas, yet in an uncontrolled manner. The HAZ area also undergoes ageing processes. Low carbon content (0.056%), largely bonded by hardening elements (Ti, Nb), reduces the role of carbon in hardening through the supersaturation of the solid solution  $\alpha$  and limits its effect during the  $\gamma$ - $\alpha$  transformation. Due to the necessity of ensuring proper mechanical and plastic properties of welds made using an electric arc, a filler metal must contain more Ni, Cr and Mo, which increases a weld carbon equivalent to a level above 0.5%, which, in turn, increases the hardness of a weld. The quality of S700MC steel welded joints is strongly affected by a welding method and welding linear energy (the fraction of a parent metal in a weld). The welding process should be performed in a manner enabling the obtainment of the lowest possible fraction of the parent metal in the weld, i.e. the concentration of hardening microadditions having entered the weld. In order to ensure high mechanical and plastic properties of S700MC steel arc-welded joints it is necessary to reduce a linear welding energy to 15 kJ/cm (the fraction of a parent metal in a weld drops to 20%) for the MAG method and to 10 kJ/cm for the TIG method and for submerged arc welding (the fraction of a parent metal in a weld at a level of 50%). During laser beam welding without a filler metal the carbon equivalent of a weld is very low (0.3%). The insufficient impact strength of the welds made using a laser beam and low linear energy (5 kJ/cm) has confirmed the thesis that a carbon equivalent cannot constitute the basis for assessing the weldability of thermomechanically treated steels having a

high yield point. While welding thermomechanically treated steels of a high yield point pre-heating is not recommendable as it may even deteriorate the mechanical and plastic properties of welded joints. In the case of welded joints made of the S700MC steel repair welding should be limited to the necessary minimum as the multiple effect of a thermal cycle during repair welding leads to the loss of the mechanical and plastic properties of the HAZ caused by the grain growth, ageing and an increase in the concentration of hardening agents dissolved in the matrix. In the case of welded joints made of thermomechanically treated steels having a high yield point the post-weld heat treatment aimed at shape stabilisation is not recommendable as it reduces the mechanical and plastic properties of the HAZ.

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