Tomasz Pfeifer

Plasma Welding of Thermo-Mechanically Processed Steel

Abstract: The article presents the course and results of tests involving the technological plasma welding of 3 mm thick butt joints made of steel S700MC using the melt-in welding technique and the key-hole welding technique. The technological tests made it possible to determine parameters enabling the obtainment of joints representing quality level B in accordance with the PN-EN ISO 5817:2014 standard. The tests discussed in the article included tensile tests, bend tests, hardness tests as well as macro and microscopic metallographic tests involving the use of light microscopy. The test results were subjected to detailed analysis performed to identify the effect of high arc energy used in plasma welding on the structure and properties of the test joints. The test results revealed that the melt-in welding technique (characteristic of the TIG method) did not ensure the obtainment of minimum tensile strength.

Keywords: plasma welding, welded joint, light microscopy, TMCP steels

DOI: *10.17729/ebis.2021.6/1*

Introduction

Recently, various industrial sectors have seen the growing use of high-strength steels, both as regards toughened steel grades and steels subjected to the thermo-mechanical control process (TMCP). The above-named steels are usually used in the shipbuilding industry, civil engineering, water-power engineering and nuclear power engineering, off-shore structures (oil rigs) as well as in the fabrication of pipelines and the manufacturing of road-making equipment and machinery. The application of high-strength steels enables the fabrication of significantly lighter structures of smaller dimensions, yet without compromising appropriate strength-related properties. The aforesaid reduction of weight and dimensions has translated into lower costs of transport and welding (as the amount of filler metals and, consequently, time needed to make welded joints have decreased significantly) [1–3].

Modern heavy-industry sectors (construction of pipelines and production of building machinery) continuously attempt to increase production efficiency and decrease manufacturing costs (improving competitiveness) also in terms of structures made of high-strength steels [4–12]. The foregoing necessitates the search for solutions making it possible to speed up welding operations by increasing the welding rate or the thickness of layers (particularly of root runs). The analysis of available research publications has revealed that one of the methods enabling the achievement of the aforementioned goals could be the application of plasma welding processes.

dr inż. Tomasz Pfeifer – Łukasiewicz Research Network – Instytut Spawalnictwa, Research Group for Welding Technologies

Tests discussed in this article aimed to identify the effect of high arc energy emitted during the (plasma) melt-in welding process and the keyhole welding process on the structure and mechanical properties of TMCP steel S700MC as well as the development of a welding technology enabling the making of butt welded joints characterised by appropriate tensile strength and plasticity.

Test rig, materials and testing methodology

The technological tests of the plasma welding process involving high-performance MAG methods were carried out using a MultiSurfacer D2 Weld automated test rig (Welding Alloys) provided with a microprocessor control system enabling the setting of a required welding rate as well as the repeatable positioning of the welding torch fixed in the set of test rig supports. Plasma welding tests were performed using a Eutronic GAP 3001 welding machine (Castolin) equipped with a plasma arc power supply along with a control system, a gas console, a cooling unit and a machine welding torch. The plasma welding of butt joints was performed without the use of a filler metal. The tests involved the use of structural TMCP steel S700MC in accordance with PN-EN 10149-2:2014. The chemical composition of the test steel is presented in Table 1, whereas the mechanical properties of the steel are presented in Table 2.

The technological tests first involved the plasma welding of 3 mm thick sheets made of high-strength steel S700MC (100×200 mm). Test elements were cut out of a sheet (using laser, cleaned with a rotating brush, degreased and mounted in fixtures ensuring the repeatable positioning of the test elements in relation to the welding torch and preventing the deformation of the joint during welding. The technological tests involved the welding of joints subjected to square butt weld preparation without the gap and made in the flat position (PA) using various process parameters of the melt-in and keyhole welding processes. The welding processes did not involve the use of a backing strip as it would impede the making of joints using the key-hole technique. The primary technological parameters, modified during the tests and having the greatest impact on the welding process and the quality of joints were the following:

- welding current restricted within the range of 150 A to 200 A,
- welding rate restricted within the range of 35 cm/min to 60 cm/min,
- plasma gas flow rate restricted within the range of 1.5 l/min to 2.2 l/min,
- shielding gas flow rate restricted within the range of 10 l/min to 15 l/min.

The following stage involved visual tests of all joints and the determination of parameters used to make 400 mm long joints. Afterwards, the joints were sampled for specimens used in the macro and microscopic metallographic

Table 1. Chemical composition of steel S700MC in accordance with PN-EN 10149-2:2014

Steel grade	**Chemical element content, % by weight**											
	C max	Si max	Mn max	P max	S max	Mo max	B max	Ti max	V max	Al min	Nb max	CEV %
S700MC	0.12	0.60	2.10	0.025	0.15	0.50	0.005	0.22	0.20	0.15	0.09	≤ 0.61

Table 2. Mechanical properties of steel S700MC

Steel grade	**Yield point**	**Tensile strength**	**Impact energy**	
	R_{eH}, MPa min	**R_m, MPa min – max**	**T = -20°C J**	**T = -40°C J**
S700MC	700	750 – 950	40	27

tests, tensile tests, bend tests and hardness measurements.

Test results

The technological tests of the melt-in welding process revealed that the scope of parameters enabling the making of joints representing quality level B was very narrow. It was also noticed that the most important parameters, critical for the quality of joints, included plasma welding current and the welding rate. The welding tests enable the identification of the most favourable parameters and the making of joints used in further tests. Figure 1 presents the various views and the macrostructure of the joint made using the melt-in welding technique.

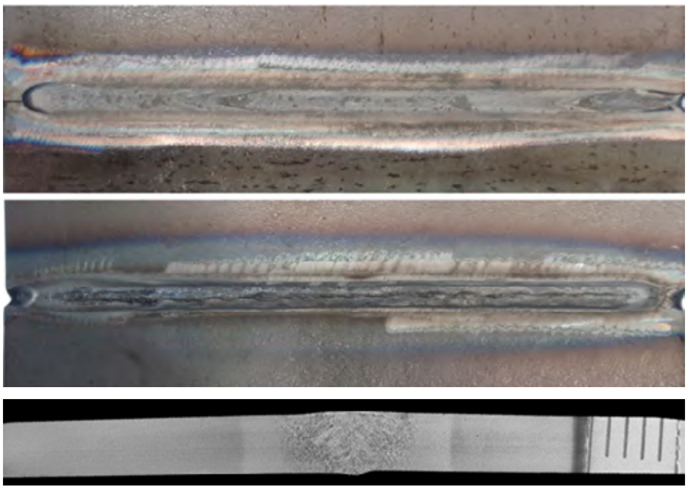


Fig. 1. Joint made of steel S700MC obtained using the melt-in welding technique: a) view from the weld face side, b) view from the weld root side and c) macrostructure; current: 170 A, welding rate: 40 cm/min and the flow rate of plasma gas: 1.5 l/min

The application of lower current (< 170 A) or higher welding rate (> 40 cm/min) resulted in the lack of penetration or excess weld face penetration. In turn, the application of higher current (> 170A) led to burn-through or, when combined with an increased welding rate, to the formation of undercuts.

The technological tests of the keyhole welding process revealed that the making of joints representing quality level B in accordance PN-EN ISO 5817 required the meticulous preparation of elements before welding (precise mechanical treatment and careful degreasing) as well as the very precise fixing of elements (in the fixtures) and their positioning in relation to the welding torch. In addition, similar to the melt-in welding process, the range of key-hole welding parameters enabling the making of proper joints was narrow. Apart from welding current and the travel rate, it was also necessary to appropriately adjust the flow rate of plasma gas. An excessively high flow rate of plasma gas could preclude the closing of the gasodynamic channel. As a result, instead of being formed, the weld material would be melted and blown outside the gap. In turn, an overly low flow rate of plasma gas could preclude the formation of the channel and, consequently, result in the lack of penetration. Figure 2 presents the view of the joint from the weld face and weld root side as well as the macrostructure of the joint made using the key-hole welding technique.

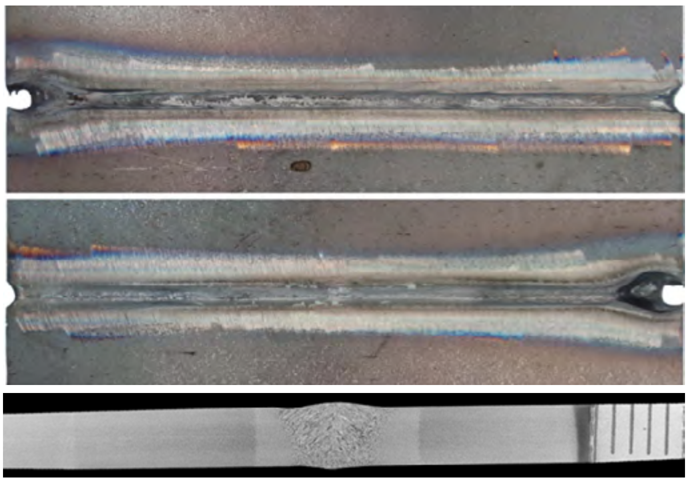


Fig. 2. Joint made of steel S700MC obtained using the key-hole welding technique: a) view from the weld face side, b) view from the weld root side and c) macrostructure; current: 200 A, welding rate: 65 cm/min and the flow rate of plasma gas: 1.7 l/min

The macroscopic metallographic tests revealed that, when using the key-hole technique, the width of the HAZ and that of the weld were narrower than those obtained when using the melt-in technique. In addition, it was more difficult and laborious to prepare workpieces and adjust parameters enabling the obtainment of joints characterised by good quality, i.e. satisfying the requirements of quality level B. Afterwards, the test joints were sampled for specimens subjected to tensile tests, bend tests, hardness measurements and microscopic metallographic tests.

The tests of mechanical properties (5 specimens in relation to both plasma welding variants) revealed that the tensile strength of the joints obtained using the melt-in technique (arithmetic average based on 5 results – 735.5 MPa) did not satisfy the requirements concerning the minimum value (presented in the PN-EN 10149-2:2014 standard (750 MPa)). The above-named test results were by approximately 40 MPa lower than those obtained using the key-hole technique (arithmetic average based on 5 results – 773.8 MPa), which could be ascribed to a greater heat input during the welding process and resultant weld structure. The bend tests produced a positive result, i.e. the obtainment of a bend angle of 180° when using a bending mandrel having a diameter of 20 mm.

Hardness measurements were performed in one line in the base material (points 1–3 and 13–15 in accordance with Table 3), in the HAZ (points 4–6 and 10–12) as well as in the weld (points 7–9). Table 3 presents the arrangement of measurement points and results of Vickers hardness tests (performed under a load of 98.1 N).

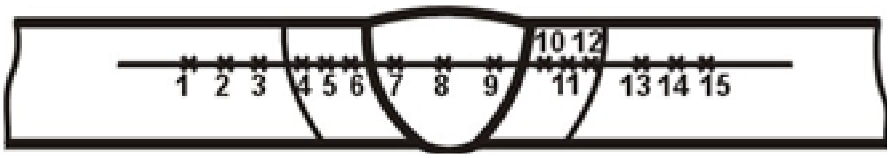
The hardness test results revealed, in relation to each specimen, the satisfaction of the criterion concerning the maximum permissible value (380 HV10). As regards steel S700MC, the hardness in the HAZ and that in the weld were comparable (restricted within the range of 227 HV10 to 242 HV10), yet they were significantly lower that the hardness of the base material (restricted within the range of 276 HV10 to 284 HV10). The joints (in the HAZ in the weld) made using the key-hole welding technique were characterised by slightly higher value. The foregoing could imply that an excessive heat input (lower welding rate) accompanying the melt-in welding process could be responsible for the change of the structure (annealing) and grain growth.

The microscopic tests were performed in relation to all of the welded joints made within the study. Figure 3 presents the microstructure of the joints made of steel S700MC using the melt-in technique. Figure 4 presents the microstructure of the joints made of steel S700MC using the key-hole welding technique.

Table 3. Hardness test results concerning the plasma-welded butt joints

Specimen no.	Measurement line	Hardness HV10 in measurement point														
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1	A	277	277	276	227	227	236	228	234	234	228	234	233	284	285	284
2	A	283	280	281	241	238	241	232	239	234	235	238	242	280	283	278

Arrangement of measurement points



Numbers and designations of specimens:
1 – steel S700MC, thickness 3 mm, melt-in welding technique
2 – steel S700MC, thickness 3 mm, keyhole welding

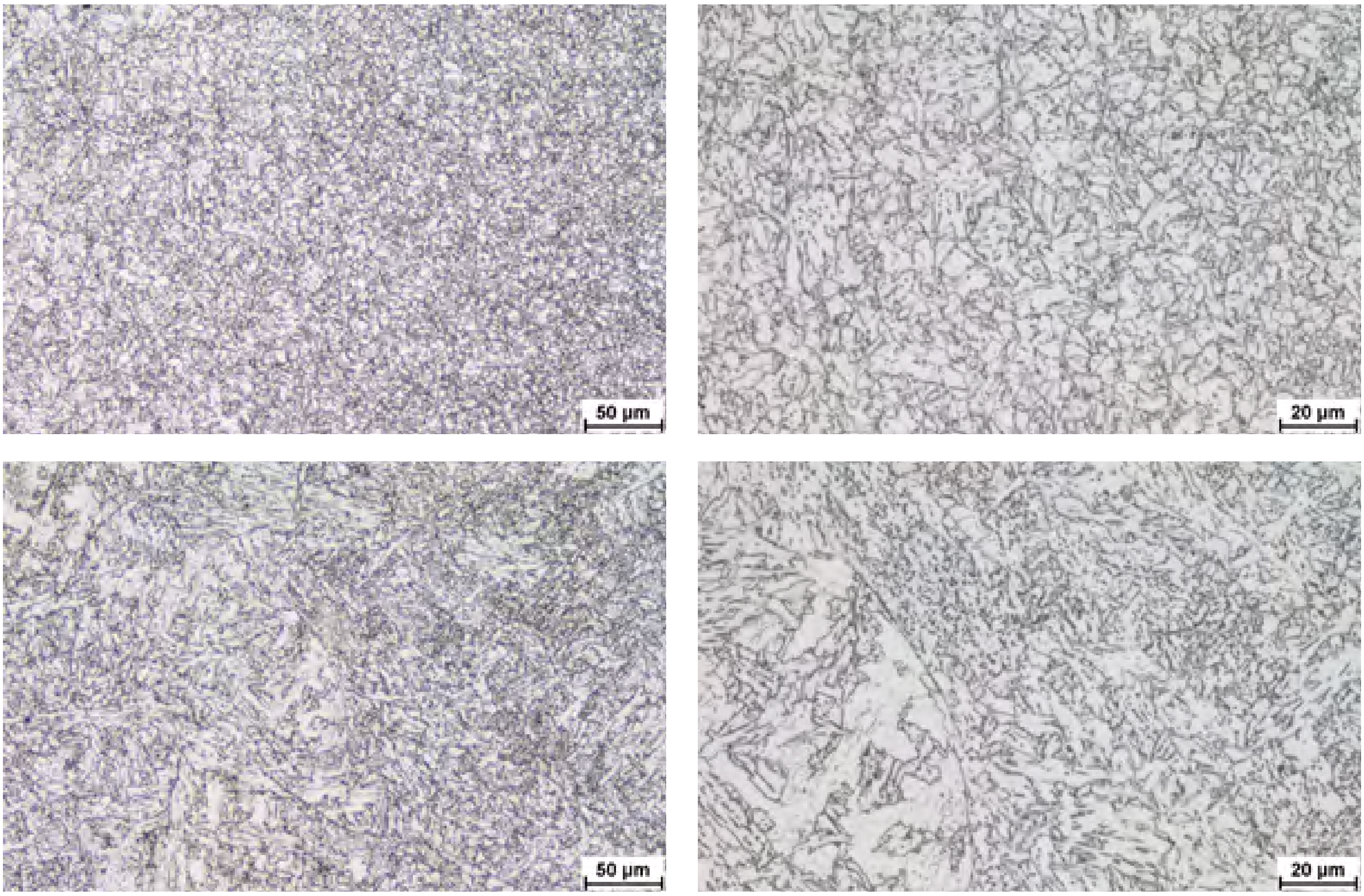


Fig. 3. Microstructure of the plasma welded butt joint made of steel S700MC using the melt-in technique: a) and b) – HAZ and c) and d) – weld

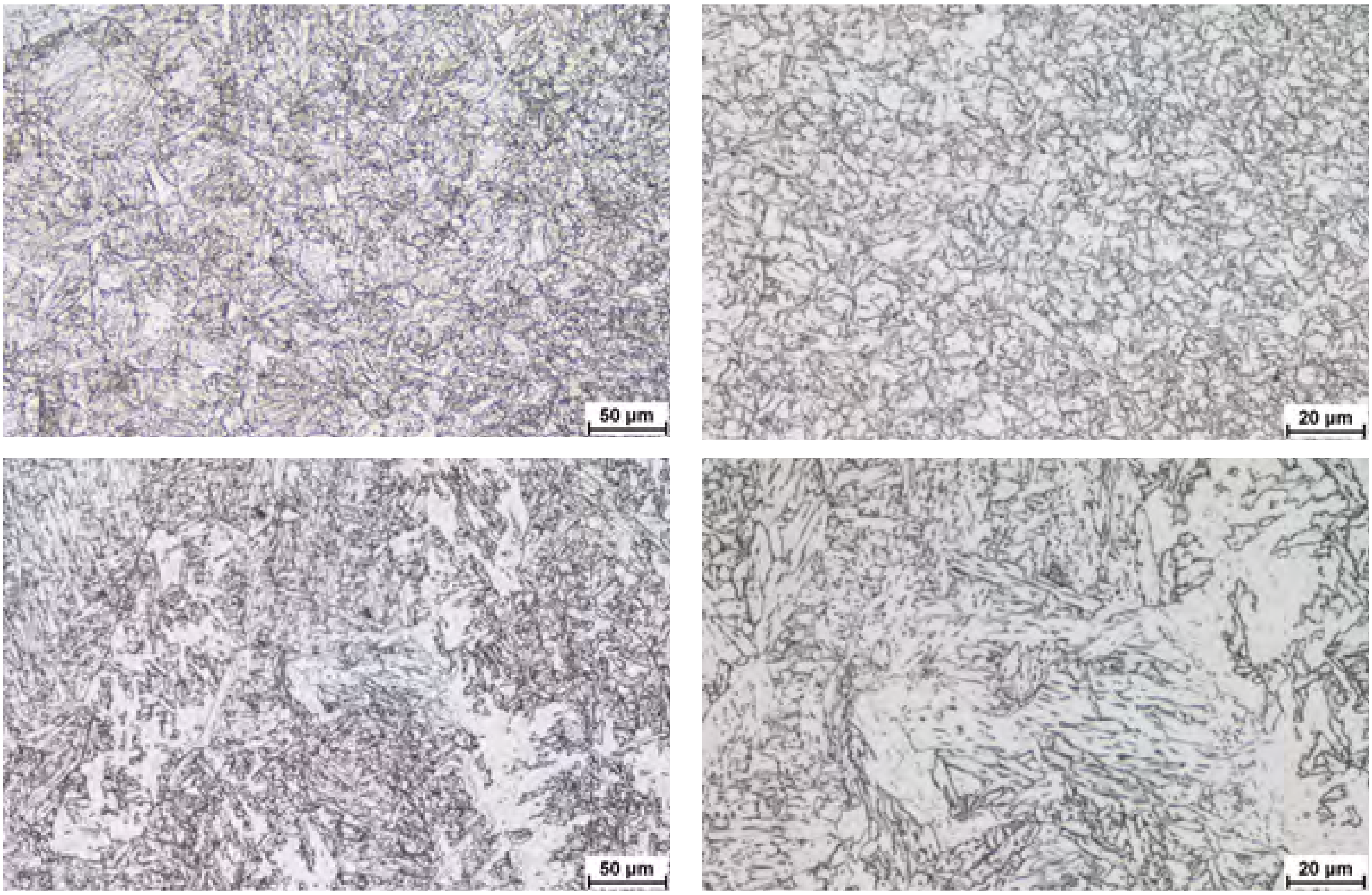


Fig. 4. Microstructure of the plasma welded butt joint made of steel S700MC using the keyhole technique: a) and b) – HAZ and c) and d) – weld

The microscopic metallographic tests revealed the recrystallization-triggered loss of grain banding. The structure of the steel was ferritic-bainitic. It was also possible to observe the increased content of ferrite in the HAZ in comparison with that observed in the base material. The zone was not characterised by significant grain growth. The foregoing could be attributed to the presence of Nb and Ti additions preventing the grain growth. As a result, the heat-input triggered hardening effect was not entirely eliminated. The HAZ, as a result of being exposed to high temperature, contained significantly more carbide precipitates than in the base material. The coarse-grained weld metal structure was bainitic-ferritic. The grain size was visibly bigger in the joint welded using the keyhole technique than in the joint made using the melt-in welding method. As a result, the joint plasticity was not decreased, which was demonstrated by related bend test results. The weld of the joint made using the keyhole technique contained numerous fine precipitates of carbides, which could be reason for higher tensile strength.

Summary

The technological plasma welding tests followed by visual, penetrant and macroscopic metallographic tests revealed that it was possible to determine welding conditions and parameters enabling the obtainment of joints representing quality level B. The melt-in welding technique enabled the making of joints having thicknesses of up to 3 mm. In turn, the use of the keyhole method enabled the welding of sheets having thicknesses of 3 mm and more. The tests revealed that the scope of parameters enabling the obtainment of proper joints was very narrow. The primary technological parameters dependent on the thickness of a sheets, the length of a joint and a welding position included the value of (welding) current, the welding rate and the plasma gas flow rate. It should be noted that the use of the keyhole welding process made it possible to apply the run-off plate, thus enabling the formation and the stabilisation of the gasodynamic channel. Starting the welding process without the run-off plate frequently precluded the obtainment of proper joints (because of the lack of weld formation).

The tensile tests revealed that the joints made using the melt-in technique failed to satisfy the requirements concerning the minimum value of tensile strength. In turn, the joints made using the keyhole welding technique satisfied the aforesaid requirements. The bend tests revealed the proper plasticity of the joints, whereas hardness measurements revealed that the joints satisfied the criterion 380 HV10. The microscopic metallographic tests revealed that the structures of all the areas were typical joints welding using arc methods. Only the weld structure was characterised by the greater grain size than that observed in welds made using different welding methods. The foregoing was the reason for decreased tensile strength in the joints made using the keyhole welding technique.

References

[1] Makles K.: Spawalność i wybrane właściwości złączy stali ulepszanych cieplnie. Przegląd Spawalnictwa, 2014, no. 8.

[2] Górka J.: Właściwość spoin stali obrabianych termomechanicznie o wysokiej granicy plastyczności. Przegląd Spawalnictwa, 2011, no. 12.

[3] Brózda J.: Stale konstrukcyjne i ich spawalność. Instytut Spawalnictwa, Gliwice 2007.

[4] Górka J.: Spawalność stali obrobionej termomechanicznie i o wysokiej granicy plastyczności. Biuletyn Instytutu Sawalnictwa, 2010, no. 5.

[5] Tasak E.: Spawalność stali. Wydawnictwo FOTOBIT, Kraków 2002.

[6] Sueyoshi T., Ishikawa N., Iwase A.: The role of niobium in the retardation of the early stage of austenite recovery in

hot-deformed steels. Materials Science and Engineering, 1998, vol. 250, no. 1.
[7] Górka J.: Stal obrobiona termomechanicznie S700MC i jej spawalność. Biuletyn Instytutu Spawalnictwa, 2012, no. 6.
[8] Węglowski M.: Nowoczesne stale ulepszane cieplnie – własności i korzyści z ich zastosowania. Biuletyn Instytutu Spawalnictwa, 2012, no. 4.
[9] Tasak E., Ziewiec A.: Spawalność materiałów konstrukcyjnych, cz. 1. Wydawnictwo JAK, Kraków 2009.
[10] Gruszczyk A., Górka J.: Niejednorodność składu chemicznego i struktury spoin i napoin. Przegląd Spawalnictwa, 2010, no. 2.
[11] Hardox, Weldox Welding. Materiały informacyjne firmy SSAB, 01.05.2003, [Online] http://www.brunswicksteel.com/pdf/hardox/welding-hardox-and-weldox.pdf.
[12] Kuzmikova L., Li H., Norrish J., Pan Z., Larkin N.: Development of safe optimized welding procedures for high strength Q&T steel welded with austenitic consumables. Soldag. Insp. São Paulo, kwiecień/czerwiec 2013, vol. 18, no. 2.