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Welding of advancedhigh-strength steels

Introduction

Resistance spot welding (RSW) is the most commonly applied method for joining car body elements made of steel (over 90%) [1]. The application of this technology for joining elements made of mild or high-strength steels does not pose any greater difficulty. Introduction of more restrictive requirements related to environmental friendliness and passenger safety was accompanied by the application of advanced high-strength steels *(AHSS)* in the production of car bodies. These steels are characterised by better strength-related properties and reduced elongation. Due to their properties, these steels require a special approach with regards to the quality of the welding process [2].

The resistance spot welding process is conducted by means of welding machines provided with upper and lower electrodes, appropriately shaped on their tips, between which one places a sheet to be welded. After exerting and stabilisation of pressure force, welding current flow is activated at a specific moment and elements to be welded undergo melting in the faying interface area, between sheets being welded. Afterwards, when current stops flowing, the molten material of the weld nugget is cooled under electrode pressure, switched off after the solidification of the material. The use of advanced high-strength steels, which in comparison to mild steels, are not only characterised by their high strength but also by their high hardness and higher specific resistance forces to changes in welding parameters, i.e. the application of higher values of pressure force and lower values of welding current [2].

Steels used in the automotive industry

Steel sheets used in the automotive industry are divided into several types according to several criteria. One of them is the designation of steel due to its metallurgical properties. According to this classification, commonly applied steels include [1, 3]:

- low-strength steels – mild, low-carbon plasticity steels (IF, *mild steels*),
- conventional high-strength steels (*HSS*) (BH, CMn, HF IF, HSLA),
- advanced high-strength steels (*AHSS*) (DP, TRIP, CP, Mart).

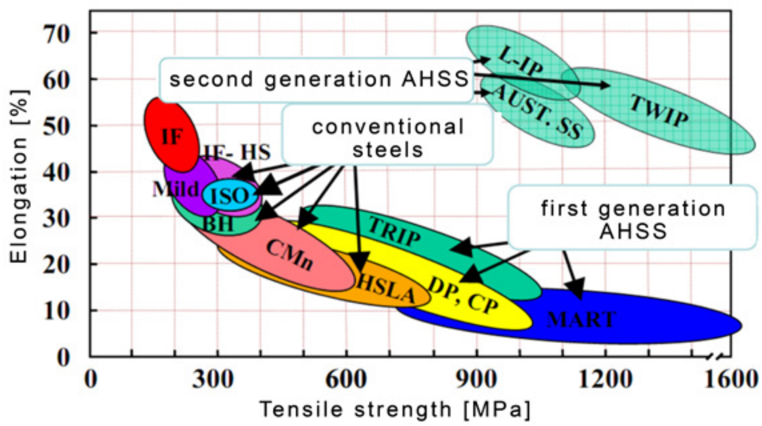

Fig. 1. Steels applied in the automotive industry. Dependence of elongation on tensile strength [2]

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The first two groups are used on a mass -scale in the production of car bodies. Steels from AHSS groups more and more often replace the most critical elements of car bodies made of steels from the HSS group.

The basic difference between HSS and AHSS lies in their microstructure. HSSs are ferritic (single phase) steels, whereas AHSSs are characterised by a microstructure other than ferritic, pearlitic – e.g. martensitic, bainitic, austenitic and/or containing tempered austenite [4].

Another group of steels is the second generation of AHSS, currently still under development and prior to market introduction. This group contains stainless austenitic steels (*AUST. SS*), twinning induced plasticity steels (*TWIP*) and lighter weight steels with induced plasticity (*L-IP*®) [3].

Welding of steels with protective coatings

An essential issue for the continuity of a production process is the steady, repeatable quality of joints. Steels sheets are manufactured with certain accuracy, as to their thickness, protective coating, and chemical composition. Pressure in the industrial utilities supply system of a welding shop may fluctuate. These factors are somehow independent from the manufacturers of

Table 1. Marketed metallic coatings applied on sheets in automotive industry [5-7]

Protective coating designation	Characteristics	Typical applications
Z	Zinc protective coatings obtained by means of the immersion method; a significant range of coating mass; typical mass of coating: 60-100g/m^2	Internal and external body panelling, structural elements
ZF	Protective coatings obtained by means of the immersion method; contain approx. 10% iron, the rest: zinc; typical mass of coating: 40-60g/m^2	Internal and external body panelling, structural elements
AS	The first type of aluminium protective coatings obtained by means of the immersion method; coatings contain 8-12% silicon, the rest: aluminium; typical mass of coating acc. to class 25 (38 g/m2) and class 40 (60g/m2)	Exhaust systems, chassis elements
AZ	The second type of aluminium protective coatings obtained by means of the immersion method; coatings are alloys containing 55% aluminium, 1.5% silicon, the rest: zinc; typical mass of coating: 75g/m^2	Exhaust systems, air filter covers, brake shells, chassis elements
ZM	Protective coatings obtained by means of the immersion method; contain approx. 1% magnesium, the rest: zinc; typical mass of coating: 80-100g/m^2	Internal and external body panelling
ZA	Protective coatings obtained by means of the immersion method; contain approx. 5% aluminium, the rest: zinc; typical mass of coating: 80-100g/m^2	Suspension elements, electric motor housings, air filter housings
ZE	Electrolytic zinc coatings, applied in a significant range of coating mass: 30÷100g/m^2; typical mass of coating: 60 and 70g/m^2; available as one-sided and two-sided coatings and with a different coating mass on each side	Internal and external body panelling
ZN	Electrolytic zinc and nickel coatings; contain 10÷14% nickel; typical mass of coating: 20÷40g/m^2	Internal and external body panelling

welded products. A welding process is also accompanied by phenomena connected with changes in the shapes of electrode tips in the production cycle. Such changes (electrode wear) are mainly manifested by reduced electrode length and a change of electrode tip and are mainly caused by the welding of sheets provided with protective coatings [8, 9]. The most popular protective coatings are presented in Table 1.

Other types of sheets applied in automotive production have multilayer coatings provided with an organic layer on the surface (known as *Corrosion Protection Primers* – CPP). The purpose of such a solution is to enable welding. Such steel sheets are used in areas/elements particularly exposed to corrosion. An advantage of the protective coatings is enhanced corrosion resistance, particularly important in car cavities, on flanges of bottom parts of doors and overlap joints [9, 10] (Fig. 2).

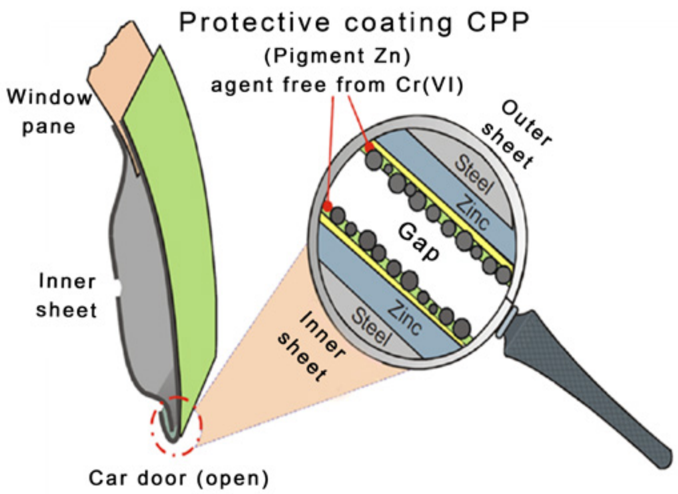

Fig. 2. Arrangement of sheets with protective coating in car door [10]

From a car manufacturer's point of view, the application of materials with protective coatings of better anti-corrosion properties results in the reduction of corrosion of elements crucial to car body safety and decreases the corrosion of outer elements, improving the aesthetics and appearance of a vehicle in the long run. The application of protective coatings also contributes to the reduction of costs by simplifying or even eliminating some stages of production (e.g. seal fixing) [11]. An example of the production process simplification is presented in Fig. 3.

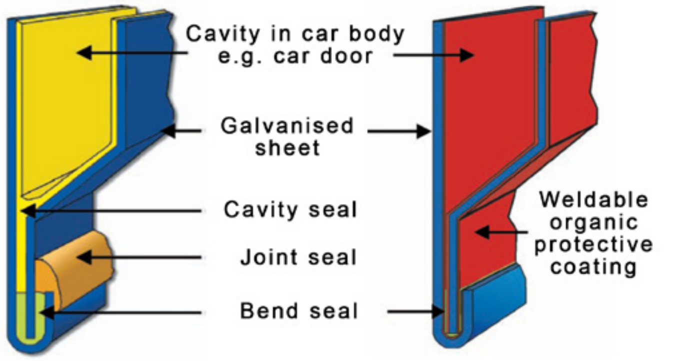

Fig. 3. Scheme of seal reduction using sheets with CPP coating [11]; a) conventional, b) with the use of CPP

The weldability of protective coatings with an organic layer is ensured by adding pigment in the form of powdered zinc or Fe_2P [9]. By exerting pressure during welding, conductive particles create "paths" for flowing current. Organic coatings, however, also significantly contribute to the increased wear of electrode tips. In this way electrode life can be reduced by 50% or more when compared with sheets provided with an electrolytic zinc coating [11]. The manufacturers of steels with such coatings recommend that during welding, a material with a one-sided organic coating should be located from the faying interface side (so that it is not touched by electrodes) [12].

During the welding of galvanised sheets, the interface between a material being welded and an electrode tip is better than during the welding of sheets without protective coatings. This is due to the fact that when exposed to force and welding current, a zinc coating adapts to the shape of an electrode tip (faster than a sheet without protective zinc coating) and, at the same time, reduces the resistance of the interface between an electrode and a material being welded. For this reason it is necessary to apply higher welding current. The welding of protective-coated sheets provided with an organic layer requires lower current values due to the higher resistance of the interface between an electrode and the material being welded (due to the coating material).

The welding of sheets with protective coatings contaminates an electrode tip with substances contained in the protective coating. This fact has particular implications for batch welding, performed on robotised stations, where as many as 60 welds per minute are built up [13]. Reference publications direct attention to several mechanisms of electrode wear; these phenomena take place during the welding of galvanised sheets [14]:

- softening of electrode tip surface,
- re-crystallisation of electrode tip material,
- alloying of electrode material with zinc,
- increased size of electrode tip (the so-called *wing formation*, taking the shape of a mushroom, i.e. *mushrooming*),
- formation of gaps after electrode material deposited on a surface being welded or cracking of an electrode tip leading to a loss in electrode material in the central area of an electrode tip,
- oxidation.

The most commonly applied electrodes used for resistance welding in automotive industry are grade A2/2 electrodes made of copper-zirconium alloy acc. to PN-EN ISO 5182:2009, of dimensions and shapes specified in PN-EN ISO 5821:2010. These electrodes are characterised by relatively high electrical conductance (43 MS/m), hardness of approx. 150 HV and a softening point of 500°C.

In order to obtain good quality welds in the aspect of electrode wear, one may choose from three various approaches. The first and the simplest method is the correction of an electrode tip after building up a strictly specified number of welds. Such a correction is carried out through grinding, which should be performed in relation to an increase in the electrode tip diameter. The second method is the application of a controller with welding current correction. In the case of batch welding, the value of welding current is increased after the fabrication of a specified number of joints. The purpose of this approach is to maintain an appropriate level of current density, in order to melt a specified amount of material and form a weld nugget of required dimensions. The third method, which to a limited extent enables welding in spite of electrode wear, is the use of controllers with a special welding software application automatically adapting to detected resistance characteristics. This resistance is tested by means of a pulse of low current value at the initial stage of welding (e.g. system IQR by Harms & Wende [15]).

Welding of advanced high-strength steels

The welding of advanced high-strength steels is impeded by several factors, partly because these steels are characterised by a chemical composition determining a high carbon equivalent. During their production, the steels also undergo a special heat treatment leading to the formation of a specific structure. During welding a special structure formed during rolling is destroyed and weld nuggets of high hardness are formed. If compared with mild steels, AHSSs are also characterised by smaller parameter ranges, within which one can obtain good quality welds [16, 17].

Reference publications suggest that AHSS sheets should be welded by means of technologies enabling the reduction of the cooling rate of the material being welded after joining has taken place. In order to be effective, such technologies should feature various welding programmes, including pre-heating, multi -pulse welding, or post-heating [2].

One of the most important issues in the welding practice is the stability of a welding process and, consequently, of the production. The notion of quality and stability refer to the strength of the obtained joints in a whole batch of welds, and thus to the diameters of the weld nuggets. A quality criterion related to a weld nugget diameter with reference to thickness g of the sheets to be welded is defined by the formula 5√g. Properly built-up welds are of a weld nugget diameter greater than 3.5√g or 4√g. The upper limit is the greatest diameter of the weld produced without liquid metal expulsion [16].

In view of this and in relation to weld sizes it is assumed that the welding current range (WCR) at a constant welding time and pressure force is:

$$\Delta I = I_W - I_{X\sqrt{g}}$$

where:

I_W – welding current for the upper limit of a weld diameter,

$I_{X\sqrt{g}}$ – welding current for the lower limit of a weld diameter.

The welding current range reflects the possibilities of adapting a welding process to changeable production conditions. The greater the value of welding current range, the more reliable the welding process [17].

During welding of AHSSs it is possible to observe an increase in WCR accompanying the application of greater pressure force (up to 5.5 kN). This increase is the greatest for TRIP-type sheets and smaller for CP-type sheets. In turn, the extension of the welding time (up to 400 ms) results in a significant WCR increase both for CP and TRIP steels [8].

Welding of TRIP-type steels

Instytut Spawalnictwa carried out tests of the welding of TRIP-type *(Transformation Induced Plasticity)* sheets in homogenous joints configuration. Apart from defining the most advantageous conditions for the welding of 1.5mm-thick TRIP-type sheets, provided with a 7µm protective zinc coating, the aim of these tests was to determine essential factors that influence the formation of micro-cracks in the structure of welds.

The tests involved the use of Sorpas® software developed by the company Swantec. The results of calculations were verified experimentally through destructive testing (strength tests, metallographic tests and peeling) and non-destructive tests (the measurement of electrical and technological parameters of the process).

Testing station

The research was conducted using a Harms & Wende inverter welding machine with the short-circuit current of 27 kA and the application of electrode pressure of up to 550 daN. The materials were welded with electrodes commonly applied in the automotive industry. The electrodes were made of A2/2 alloy and met the requirements specified in EN ISO 5821 F16.

The testing station was equipped with sensors for measuring welding current and voltage as well as with sensors for measuring electrode travel and pressure. The parameters of the process were recorded using the LogWeld system developed at Instytut Spawalnictwa. The system enables the recording of basic parameters, i.e. welding current and voltage, electrode travel and pressure as well as derivative values, i.e. static slope resistance, momentary power, and energy supplied to the weld. The aim of the tests was to record parameters for various welding conditions in order to determine the most advantageous.

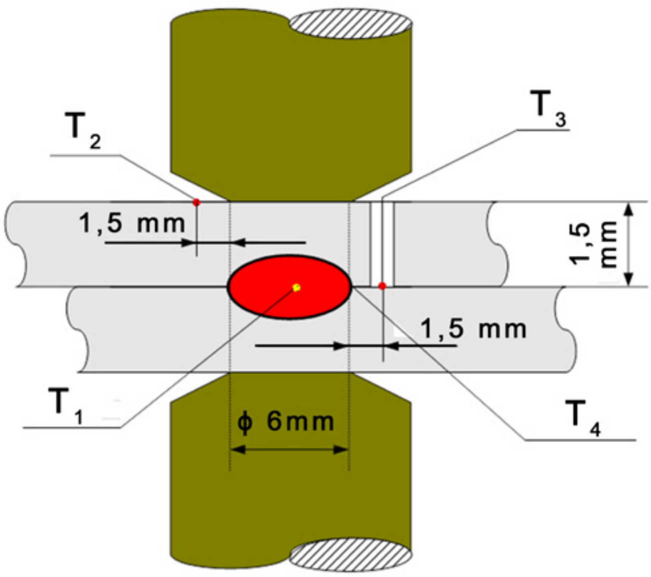

Fig. 4. Welding area with points marked for FEM calculations and temperature measurements

The testing station was additionally provided with National Instruments equipment which was used for measuring temperature during the time of welding.

FEM calculations and methodology of tests

According to reference publications it is necessary to apply such welding technology which would initiate the formation of micro-cracks in the weld [16]. The materials susceptible to micro-crack formation are TRIP, MART and DP. The above negative phenomenon intensifies when homogenous joints are built up. Micro-cracks are formed as a result of intensive cooling of the materials being welded, following the flow of the welding current. An especially intensive heat off-take proceeds towards the electrodes.

One possible solution is provided by a multi-pulse technology using a heating pulse. The first pulse is to create a joint with a weld nugget of the required diameter, whereas the second pulse causes the heating of the welding area in order to slow down the rate of cooling. From a micro-crack generation point of view, the outer edge of the weld nugget is a critical spot. The calculations were carried out using Sorpas® software with the purpose of determining the parameters of the second pulse and thus ensuring slower cooling than the one accompanying the single-pulse technology. Figure 4 presents the welding area with points marked for FEM calculations and temperature measurements.

Figure 5 presents temperature courses for the T_4 point, with different programs of welding used.

A point of departure for the determination of technological parameters was to obtain a weld nugget with a diameter of 6 mm. Next, parameters of the second pulse were selected in such a way that this current pulse started precisely when the temperature on the edge of the weld nugget, in the interface of sheets, at point T4 amounted to 1000^{O}C. Afterwards, it was necessary to select the time and value of current in order to obtain the required (slower) cooling rate. In the first phase, calculations were made for the values of the first pulse current of 9 kA and time of 300 ms, and for the values of the second pulse current of 5.0 kA, 5.5 kA, 6.0 kA respectively and for a longer time of 2000 ms.

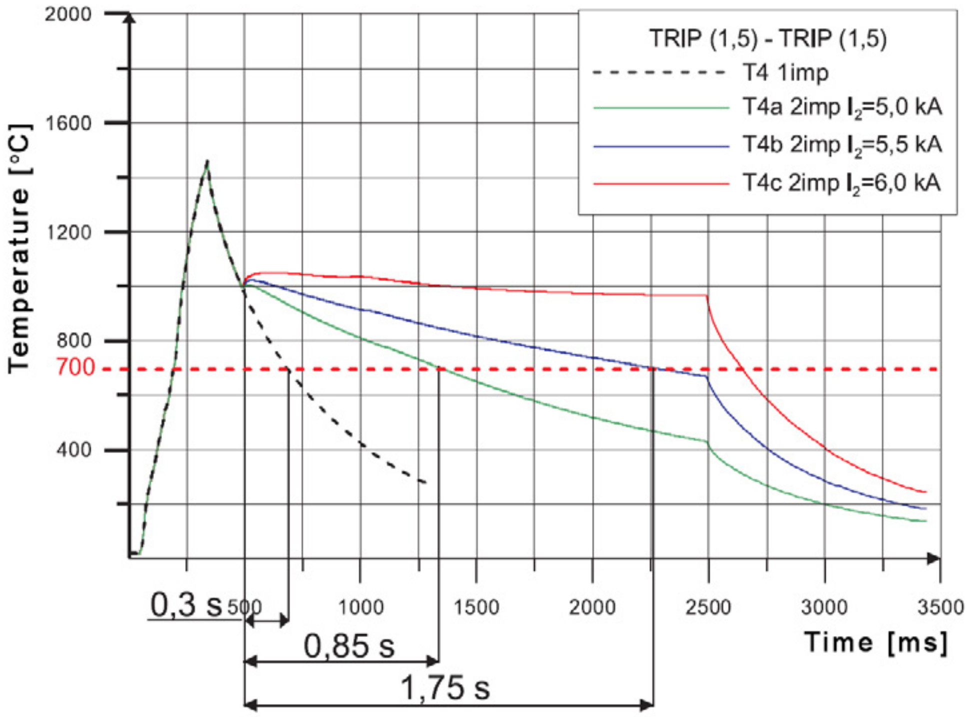

Fig. 5. Calculation of temperature courses for welding area points, located in the point of contact of welded materials, on the edge of the weld core. Cooling speed for the welding programms:

$V_{T4\ 1000/700} = 1000^{o}C/s$

$V_{T4a\ 1000/700} = 353^{o}C/s$

$V_{T4b\ 1000/700} = 171^{o}C/s$

In order to achieve the temperature value of 1000^{O}C, measured at point T4, the time of the interval between the pulses had to amount to 150 ms.

Available reference publications do not provide any accurate information concerning the conditions which should be satisfied in order to guarantee a high quality welded joint in the TRIP–TRIP configuration – particularly in view of temperature conditions. This paper focuses on the analysis and investigations within the temperature range of 1000^{O}C – 700^{O}C as it is within this temperature range that the probability of occurrence of conditions facilitating micro-crack formation is the highest.

For the second pulse current of 6kA, analysis of the temperature course at point T_4 located on the edge of the weld nugget at the interface of the sheets reveals that cooling is occurring too slowly. Reducing the value of current to 5.5 kA makes it possible to obtain a cooling rate of 150^{O}C/s. This is very convenient due to slow rate of cooling in the selected point. In turn, further reduction of current to 5 kA causes an increase in the rate of cooling to 300^{O}C/s, which is lower than the value for one current pulse but may trigger micro-crack formation.

Further research involved experimentation to verify FEM calculation results. Experimental verification can be carried out by measuring temperature in available points of the welding area. In the case under discussion, the available points enabling temperature measurements are T_2, located on the surface of the materials being welded, 1.5mm away from the edge of an electrode and T_3, located in the interface of the welding materials, 1.5 mm away from the edge of the weld nugget. Results of the temperature measurements (Fig. 6) are contained (with slight deviations) in an area limited by temperature courses obtained in FEM calculations. The slight deviations can be attributed to the use of a 200 µm-diameter thermocouple, characterised by certain inertia, particularly in the initial range of temperature changes [18].

Applying the two-pulse technology affects the hardness obtained in the weld nugget. The results of hardness tests of welds obtained using the simple programme and by

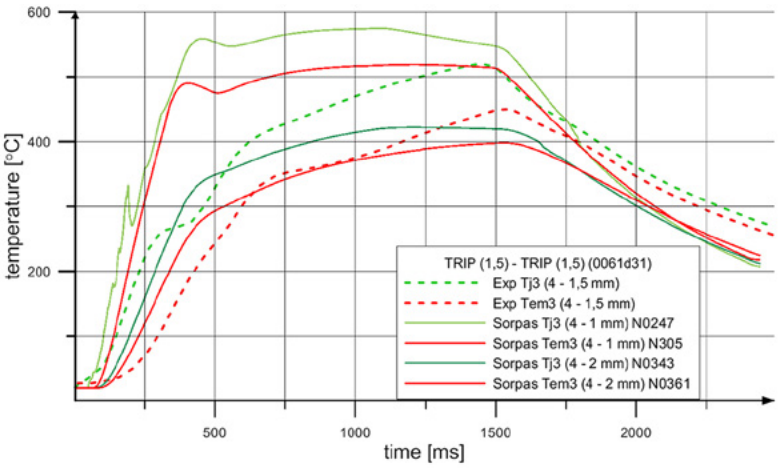

Fig. 6. Courses of temperature measurement for points T_2 and T_3 (dashed lines) and calculation results for points T_2 and T_3, located +/- 0.5 mm away from temperature measurement points (solid lines)

means of the two-pulse technology are presented below (Fig. 7).

If compared with the simple technology, the application of the two-pulse technology leads to a decrease in weld hardness. The greatest impact is visible when the programme with the longest (2000ms) second heating pulse is used, hardness in the weld nugget being 450 HV. The peeling tests (Fig. 8) revealed a change of the type of peeling, i.e. from a rupture in the trans-crystallisation plane (for the simple programme and the two-pulse programme with a 300ms-long second pulse) to complete peeling (for the two-pulse technology with the time of the second pulse being 1000 ms and 2000 ms).

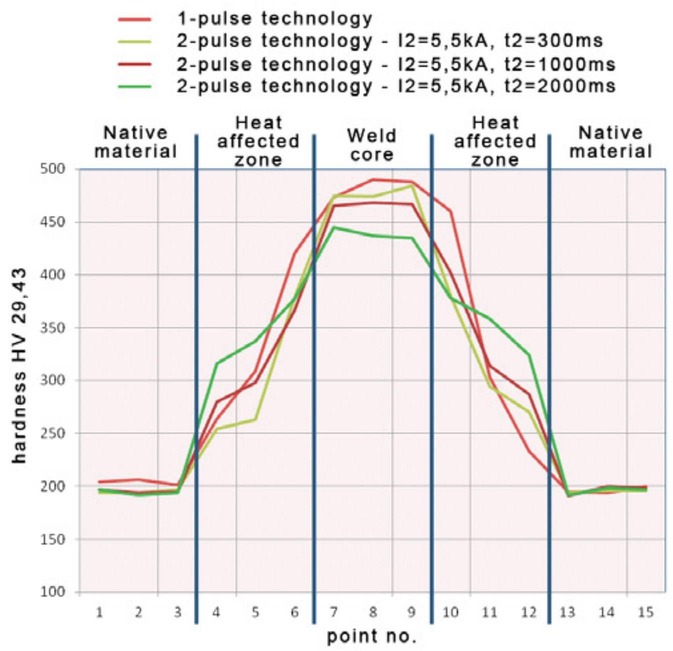

Fig. 7. Results of hardness measurements of welds of homogenous joints of TRIP steel for one- and two-pulse programmes

Summary

Due to their specificity, the welding of advanced high strength steels continues to pose a challenge for the industry. In addition to their special behaviour during welding, resulting from their chemical composition, the steels are covered with protective coatings, which also affect the course of the welding process, particularly in batch production. Welding of protective-coated steels with an organic layer significantly contributes to the contamination of electrode tips, resulting in more frequent breaks to repair electrode tips or replace whole electrodes.

Welding of AHSSs, and in particular, of TRIP-type steels generates micro-cracks in a weld when a classical welding programme is applied. This phenomenon is manifested, among others, by a rupture in the trans-crystallisation plane during a peeling test. Although it does not significantly affect strength in a static tensile test, the type of peeling has a considerable effect on fatigue strength values [19].

The necessity of improving the quality of welded joints of 1.5mm-thick TRIP-type sheets inspired Instytut Spawalnictwa to carry out research in the two-pulse programme with heating of a joint. A Sorpas® software application for modelling a welding process was used to define a proper interval time and the value of the second pulse. In the case under discussion (high strength TRIP steels),

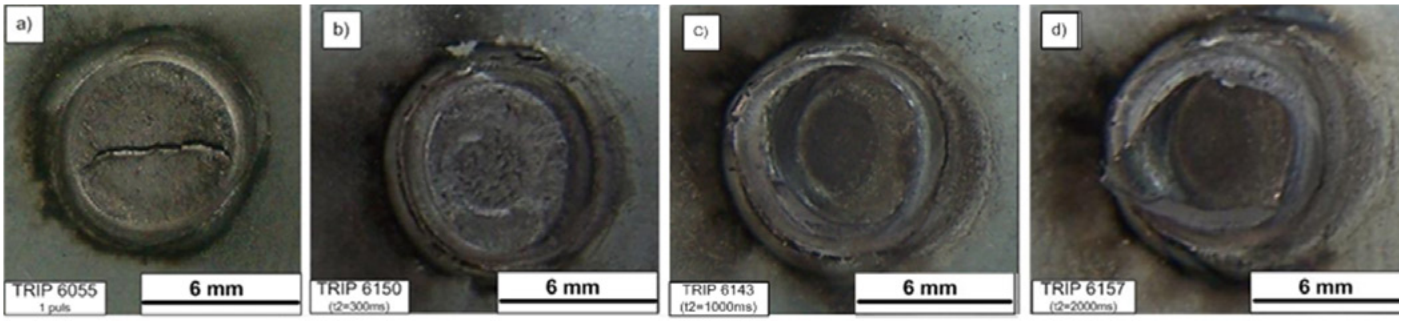

Fig. 8. View of welded joints after peeling tests for: a) one-pulse technology b) two-pulse technology, time of the second pulse: 300 ms, current of the seconds pulse: 5.5 kA b) two-pulse technology, time of the second pulse: 1000 ms, current of the seconds pulse: 5.5 kA c) two-pulse technology, time of the second pulse: 2000 ms, current of the seconds pulse: 5.5 kA

FEM simulation enables precise determination of technological parameters. Calculation results were verified experimentally through temperature measurement. The verification proved significant coincidence of measurement results with the results obtained by means of the computer-aided simulation.

The results of tests of joints welded by means of the two-pulse technology revealed that a weld cooling rate affects the hardness of built-up joints. The tests also showed that using a programme with a 1000ms-long second heating pulse of 5.5 kA enables the complete peeling of the weld nugget during a peeling test and that the use of 2000ms-long second pulse makes it possible to reduce the hardness level in the weld nugget below 450 HV.

The conducted tests included the application of a welding technology utilising current modulation. At present Instytut Spawalnictwa is conducting an investigation of the welding of high-strength steels by means of a welding technology using modulated pressure.

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