Managing the influence of microstructure defects on the strength of EN AW 5754 aluminium alloy welded joints executed with the TIG method

mgr Piotr Woźny[1*], *prof. dr hab.in Józef Błachnio*[2]
[1]Wojskowe Zakłady Lotnicze (*Military Aviation Works*) no. 2 S.A. ul. Szubińska 107, 85-915 Bydgoszcz, Poland
[2]Air Force Institute of Technology, ul. Księcia Bolesława 6, 01-494, Warszawa 46, Poland

Abstract: The paper concerns the issue of the impact of welding defects on the strength of EN AW 5754 aluminium alloy welded joints, executed with the TIG welding method (tungsten inert gas, i.e., a method of welding with a non-consumable tungsten electrode shielded with inert gases). The article presents examples of operating damage to welded joints and discusses the factors impacting the weld quality. The strength test results of welding samples taken under different process parameters were presented. The impact of welding defects and non-conformities identified with a CAT test on the weld joint impact was analysed. The studies showed a strong relation between the presence of welding defects, welding process parameters and weld strength.

1. Introduction

In order to ensure safe and reliable operation of welded structures, it is necessary to satisfy numerous process requirements. The criteria for the evaluation of the fulfilment of these conditions relate to strength and durability of a joint [5]. Owing to favourable strength properties, aluminium alloy welding plays an important role in joining structural elements of machines and equipment [9]. Aluminium alloy welded joints are also used in the process of manufacturing load-bearing elements, which transfer various load types [16]. It especially applies to the aviation, shipbuilding, automotive and construction industries. Moreover, the design-wise attractiveness of machine element welded joints made from aluminium alloys is decided by the anti-corrosion and chemical resistance, as well as their relatively low mass density.
In the course of the operation of a machine, malfunctions and damage to elements executed with a welding method occur, which result from the impact of the external environment, ageing and wear processes [12]. Moreover, weld defects and non-conformities arising as a

* Corresponding author: piotr.wozny@wzl2.mil.pl

result of incorrect selection of process parameters and execution errors associated with the failure to comply with welding procedure requirements, contribute to their formation [10]. The second group of factors causing damage to the elements with welded joints are mechanical and thermal loads of varying value and character. Both static, as well as dynamic loads appear. A static load is constant or changes very slowly over time in terms of value, direction and point of application. Static forces induce deflections caused by constant load on a structure. Whereas dynamic loads are characterized by a variable and sometimes rapid action of external or inertia forces, induced as a result of mass acceleration [3, 4, 11, 18].
Examples of operating damage to welded elements of a manoeuvring aircraft are shown in fig. 1.

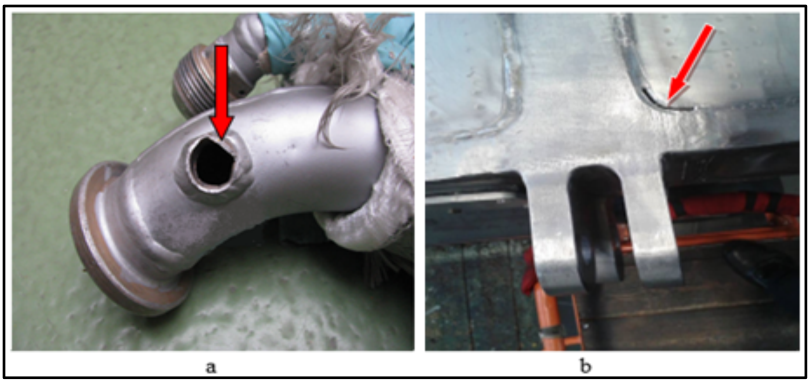

Fig. 1. a. Air-con system duct port broken off by the weld in the heat transfer zone [19] b. Crack in the weld of a wing fuel tank [19]

2. Impact of TIG welding parameters on the weld quality

The EN AW 5754 grad aluminium alloy was adopted for the tests. Five welds numbered from SPI to SPV were executed with the TIG method (tungsten inert gas, i.e., a method of welding with a non-consumable tungsten electrode shielded with inert gases). The impact of the welding procedure on the quality of the joints was analysed and the best welding parameters and conditions were selected in relation to the weld quality. Joints, in which the number of defects and non-conformities did not exceed the permissible value stipulated in the standards was adopted as the welding conditions and parameters selection criterion [24, 25]. Particular attention was paid to: no penetration, crack, porosity, gaseous cavities, undercuts, excessive root bead, excessive weld root reinforcement [26]. The main objective of the tests was to obtain a weld with the smallest defects possible to be visually evaluated. The welding parameters were changed based on the external defect evaluation. The welding current intensity and balance, shielding gas outfeed, welding speed and filler type were subject to changing. 99.996% argon was used as the shielding gas. Two types of filler metal were used in the tests: standard AlMg3 and AlMg5 welding wire. The obtained results indicated that achieving welds with the lowest possible number of external welds (SPIV and SPV) required increasing the current intensity value up to 140A, relative to SPI, SPII, SPIII welds executed with 130A.Moreover, in order to execute the SPV weld, it was necessary to increase the shielding gas flow rate to 20 l/min. Due to unsatisfactory results subject involving a high number of varied welding defects, the filler metal for the SPIII, SPIV, SPV welds was changed from AlMg3 (SPI and SPII) to AlMg5.An advantageous impact of decreasing the welding speed to an average value of ca. 0.03m/min. for the SPIV and SPV welds was also observed. With increasing welding speed, the fusion depth decreases, causing a defect in the form of no penetration, whereas, when the speed decreases, parameters such as: fusion depth, face width and reinforcement height increase, which is of advantageous impact on the correct weld shape [13, 15, 17, 20].

In addition, a visual assessment of the joint after changing the parameter defined by the literature as A/C balance was conducted [10, 13, 14, 15]. The value of this parameter expresses a relation between the positive and negative welding voltage values for an alternating current within the welding process. This parameter determines the distribution of delivered heat between the welded material and the electrode. Majority of positive voltage values enables more efficient removal of the aluminium oxide top layer, while negative values increase the penetration and heating of the welded material, at the expense of a less efficient oxide removal. The balance value of the used welding machine was able to vary from -50% to 0%. The default setting was -25%, i.e., heat division between the welded material and the electrode was uniform. The best strength results within the executed tests were obtained for the SPIV and SPV welds, where the -10 balance setting was used, i.e., the oxide removal from the top aluminium layer was four times longer than the material penetration time.

3. Testing the impact of microstructural defects on the strength during a static tensile test

Despite the development of modern, non-destructive diagnostic methods (computed tomography and digital radiography), strength tests are required in order to validate the quality of a welded joint and other connections [6, 8]. The basic strength test for butt joints is a static tensile test. In order to execute a tensile test for a butt joint, samples from the tested welded joints were collected as per the standard PN-EN ISO 15614-2:2008 [21]. The collected samples were prepared as per the standard PN-EN ISO 6892-1:2010 [22].

The static tensile test was conducted with the use of a Zwick Z100 universal testing machine with a permissible test load of 100 kN and the maximum test speed of 200 mm/min. The force measuring system accuracy meets the class 1 requirements. This means that the relative limit permissible errors will not exceed ±1% of the set static load. The testXpert strength test machine software enabled automatic data recording in a stress-percentile elongation system at rupture and a graphic presentation of the results.
Samples collected from five EN AW 5754 aluminium alloy butt joints, marked with SPI to SPV symbols were subjected to the test. Seven samples marked with 1 to 7 were collected from each weld. The tests were conducted as per the methodology in the standard [22]. The samples were stretched with at a deformation rate of 8 mm/min at static load. Moreover, in order to determine the reference strength parameters, static tensile tests of EN AW 5754 parent metal were conducted (fig. 2). Fig. 3, 5, 7 show tensile graphs in the stress-percentile elongation system at rupture, for samples collected from the SPI, SPIV, SPV joints. The tested aluminium alloy weld joint strength obtained during the tensile test should not be lower than 75% of the parent metal strength. This stems from the requirement stipulated in the standard PN-M-69414:1975 [23] regarding the weld strength coefficient. The value of this coefficient depends on the adopted welding procedure, parent material grade and the filler grade.

In order to present weld microstructural defects, a tomograph (fig. 4, 6, 8,) showing the joint condition was shown for each ruptured sample.

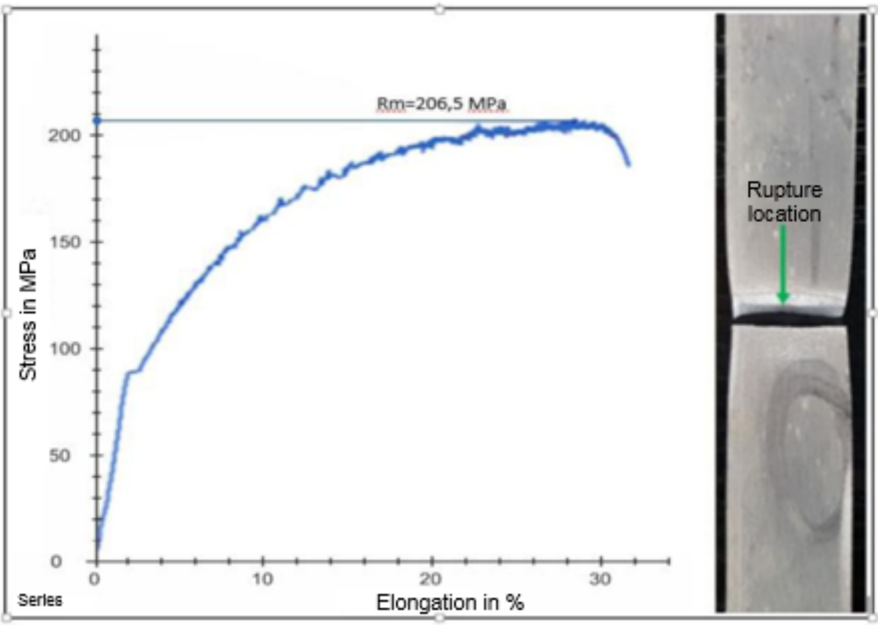

Fig. 2. EN AW 5754 parent material sample tensile test results, sample 1

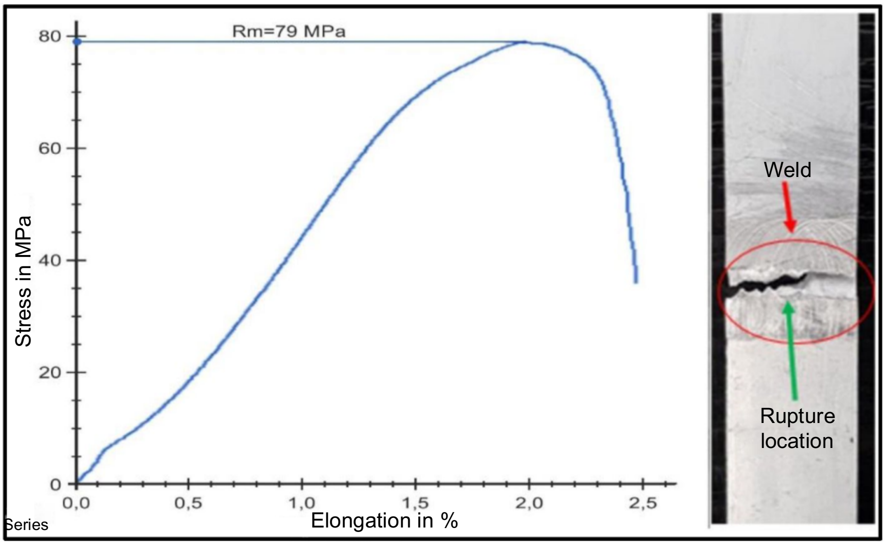

Fig. 3. SPI weld sample no. 1 tensile test results – sample was ruptured at the weld location

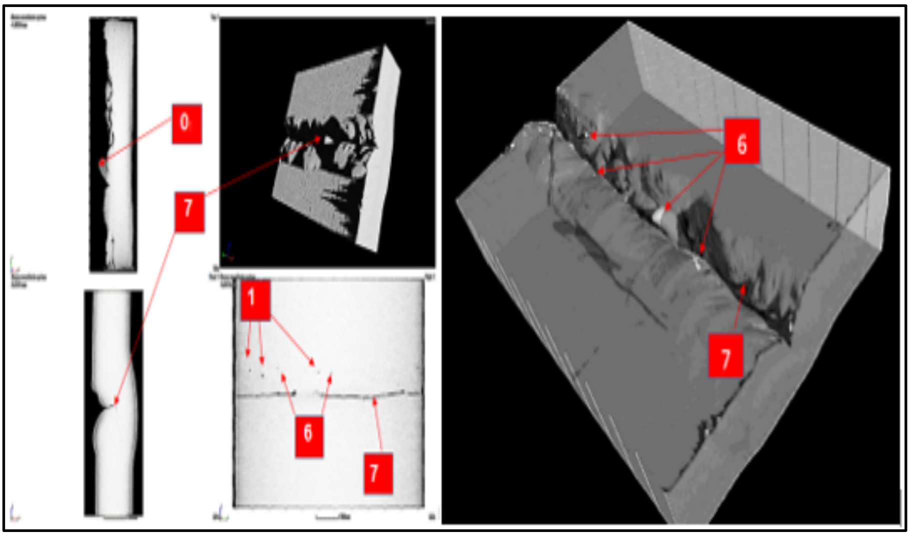

Fig. 4. SPI weld sample no. 1 tomograph (0-weld root excess bead; 1-gas spherical pores; 6-solid intrusions; 7-no penetration) [1]

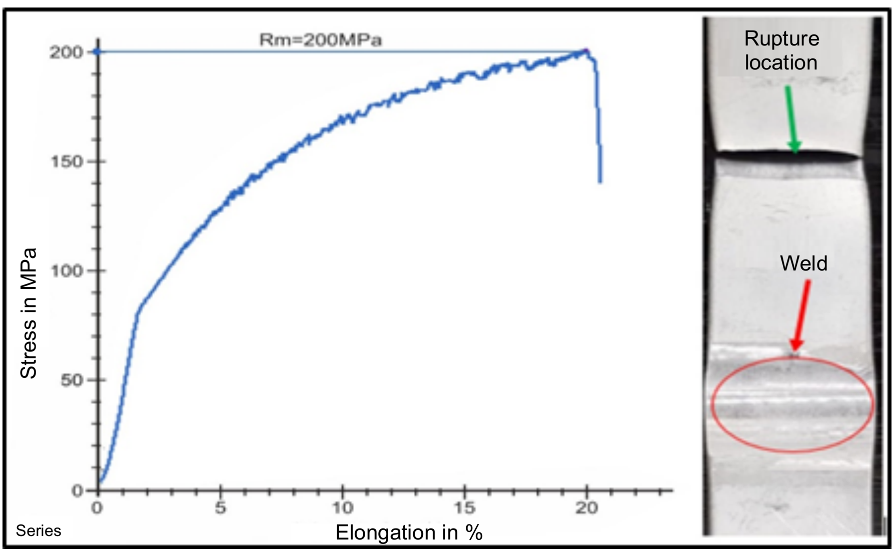

Fig. 5. SPIV weld sample no. 1 tensile test results – sample was ruptured in the parent metal

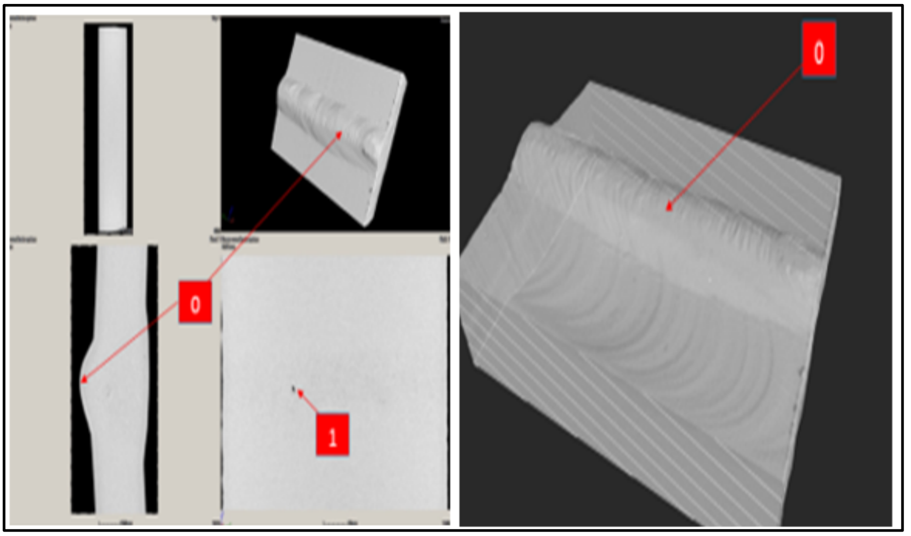

Fig. 6. SPIV weld sample no. 1 tomograph (0-weld root; 1-gas pores) [1]

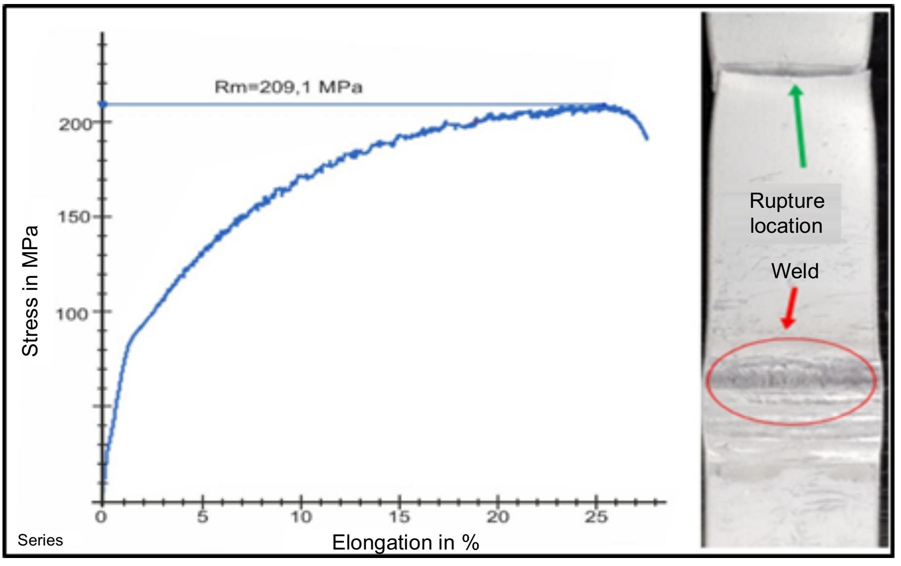

Fig. 7. SPV weld sample no. 1 tensile test results – sample was ruptured in the parent metal

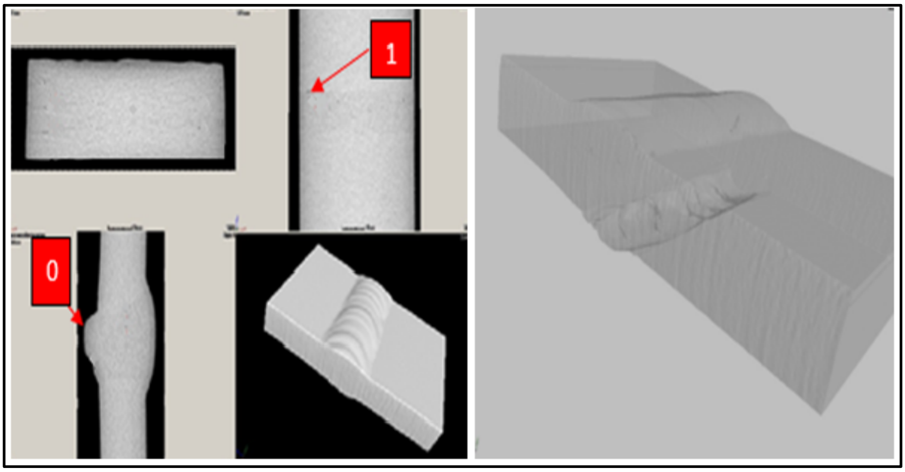

Fig. 8. SPV weld sample no. 1 tomograph (0-weld root excess bead; 1-gas pores) [1]

The static tensile test enabled the determination of strength properties for TIG welded joints. Based on the obtained graphs, the tensile strength, yield strength and elongation strength were determined.

Based on the conducted analysis of the mean values determined from the measurements, it was concluded that the SPI÷SPIV welded joints have a lower yield strength and tensile strength values than the parent metal, with its values are R_e=90 MPa and R_m=206.5 MPa, respectively. The best results, comparable to the parent metal, of R_e=90.7 MPa and R_m=207.7 MPa was obtained for the SPV joint. The highest elongation of 28% was recorded for the SPV joint, while the lowest, at 2.9%, for SPI. Significant discrepancies between strength results are caused by variable joint quality, that is, a changing number of appearing welding defects. The introduced changes of the welding parameters resulted in obtaining a better weld penetration and mitigating the appearance of internal defects, which had an advantageous effect on the strength parameters of the tested joints. The tested samples of SPI and SPII welded joints were sustained damage to the weld due to the lack of a complete penetration and the presence of welding defects (fig. 6). The SPIII joint samples sustained damage at the heat affected zone as a result of using another filler metal type (AlMg5) and the presence of welding defects. A parent and filler metal (AlMg3 and AlMg5) mixture, with intermediate strength properties for these alloys was formed in the penetration zone. The parent material was damaged in samples of the SPIV and SPV welds (fig. 5, 7). The reason is the use of filler metal with strength parameters better than the parent metal, and the selection of welding process parameters, which enables obtaining a weld without significant welding defects and imperfections (fig. 6, 8). Based on the test results, the Rm = ΔL and Re = ΔL functional relationships were determined (fig. 9, 10).

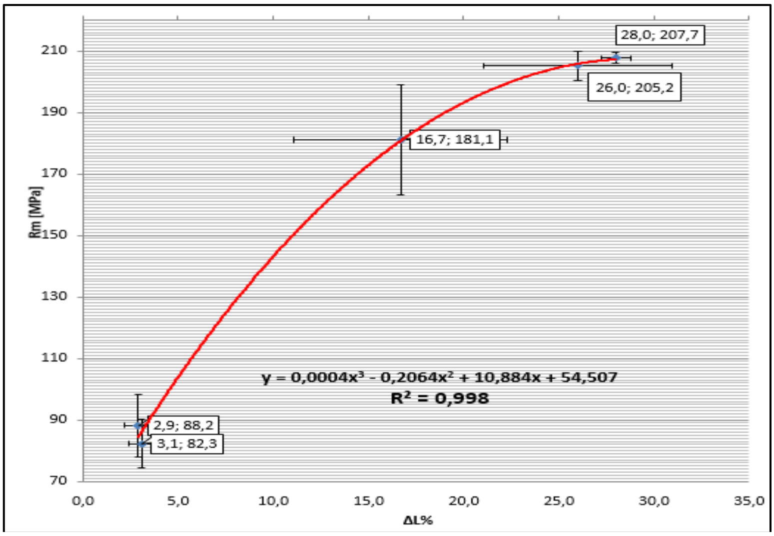

Fig. 9. Rm = ΔL value relationship for the SPI, SPII, SPIII, SPIV and SPV samples

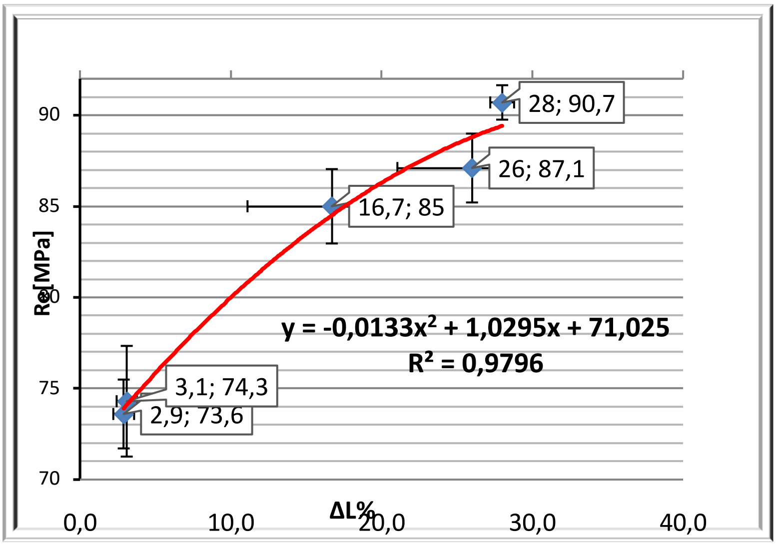

Fig. 10. Re = ΔL value relationship for the SPI, SPII, SPIII, SPIV and SPV samples

4. The relations between tensile strength and microstructural defects

Based on the strength test results, the Rm and Re functional relationships were determined (fig. 18, 19). The value of Rm and Re parameters was adopted as a mean calculated for individual SPI÷SPV welded joints. The surface of defects in a weld microstructure was adopted as a sum of defects for individual welded joints. The size of defect surfaces for individual welded joints was estimated based on the recorded tomographs [2]. The conducted analysis of the graphs showed the existence of a strong relationship between strength parameters and microstructural defects. Moreover, in order to expand the analysis, the welding defects expressed in the function of their length and the welding non-conformities regarding the shape were compared with the strength parameters.

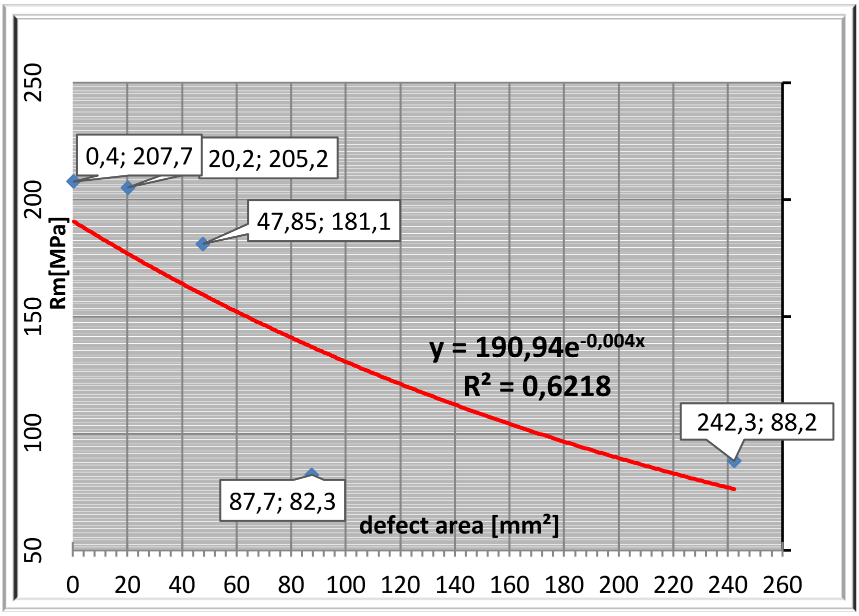

Fig. 11. Dependency of an Rm parameter on the defect area in a weld microstructure

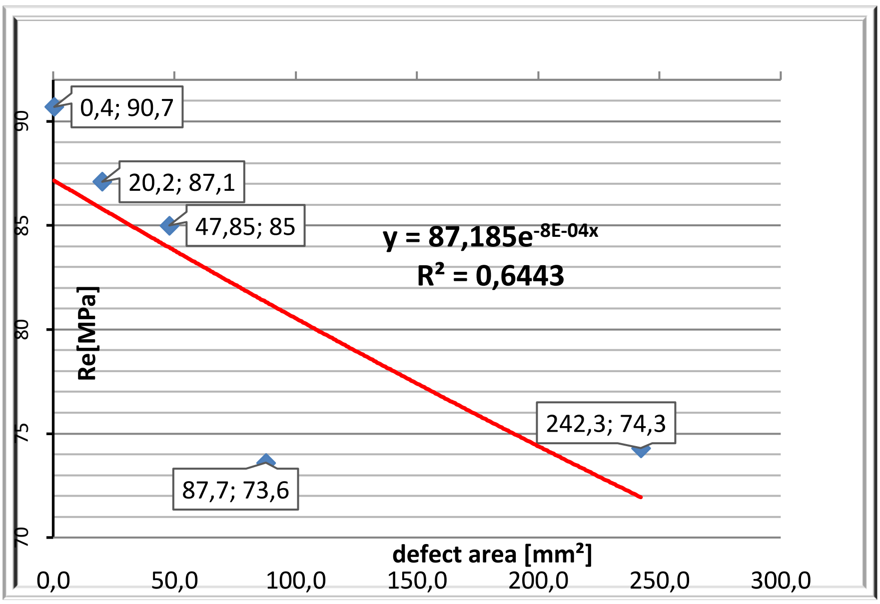

Fig. 12. Dependency of an Re parameter on the defect area in a weld microstructur

5. Conclusions

The tensile test of TIG welded joints unambiguously confirms the significant impact of welding non-conformities and defects on the value of weld strength parameters [15]. Owing to the highest strength and lowest presence of welding defects, confirmed by computed tomography [20], it should be noted that the parameters used for the execution of welds SPIV and SPV enabled to obtain the best qualities of butt joints [14]. The tensile test of these connections confirmed meeting the strength requirements. Relative to the parent material strength parameters of R_m=206.5 MPa, R_e=90 MPa (fig.2.) the following values were respectively obtained for the SPIV joints R_m=205.2 MPa R_e=86.4 MPa and SPV R_m=207.7 MPa R_e=90.7 MPa. The biggest presence of welding defects was identified in the SPI ÷ SPIII welds, which is co-dependent on lower strength values of these joints. The lack of penetration and solid intrusions in the weld microstructure turned out to have the greatest impact on the strength parameters. Moreover, the dependency of strength results on shape defects was observed. Shape defects in the form of a fault, excess weld root bead and excess face reinforcement were identified in the SPI÷SPIII welds. Based on the analysis of the relationship between the welding defects, it was shown that regardless of the fact whether the weld surface area or the weld length was adopted for the evaluation, there was a strong relationship between the strength of the tested connections and welding defects (fig. 11 and 12). It was possible to reliably determine these relationships thanks to a non-destructive computed tomography method.

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