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Numerical analysis of MIG welding of butt joints in aluminium alloy

Abstract: Analyses based on FEM calculations have significantly changed the possibilities of determining welding strains and stresses at early stages of product design and welding technology development. Such an approach to design enables obtaining significant savings in production preparation and post-weld deformation corrections and is also important for utility properties of welded joints obtained. As a result, it is possible to make changes to a simulated process before introducing them into real production as well as to test various variants of a given solution. Numerical simulations require the combination of problems of thermal, mechanical and metallurgical analysis. The study presented involved the SYSWELD software-based analysis of MIG welded butt joints made of 5251 aluminium alloy sheets. The analysis of strains and the distribution of stresses were carried out for several different cases of fixing elements and for different times of releasing elements welded.

Keywords: FEM, SYSWELD, welding strains, welding stresses, MIG, aluminium

Introduction

The numerical simulation of welding processes is one of the more complicated issues in analyses carried out using the Finite Element Method. This is due to a number of factors. A welding process thermal cycle directly affects the thermal and mechanical behaviour of a structure during the process. High process temperature and subsequent cooling of elements being welded generate undesirable strains and stresses in the structure being made. For this reason it is necessary to possess extensive knowledge related to the behaviour of materials subjected to welding thermal cycles. Obtaining such data requires not only vast knowledge but also access to a wide range of laboratory examination focused on the mechanical and thermo-metallurgical properties of the materials used. Also knowledge concerning the welding process itself and the proper selection of boundary conditions poses a significant challenge for engineers wishing to apply this area of knowledge in their practical studies [2,3,6,7].

However, even vast theoretical knowledge, often supported by extensive laboratory tests, is not sufficient for obtaining high accuracy of numerical analysis results using accidental tools. Software is of vital importance here. A short product life cycle between subsequent changes of models or solutions make classical prototyping both unprofitable and often unfeasible due to time restrictions and the quickly increasing complexity of products manufactured today [4,5]. More than a decade ago 3D engineering software opened engineering personnel to new possibilities. Equally beneficial

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was the market introduction of advanced calculation packages based on the Finite Element method and creating the "new quality" in designing countless versions of details aimed to obtain the maximum quality, durability and specific utility features. Additional specialisation of such packages makes their use significantly more flexible and complete within the industries for which they have been intended. Ready-made solutions provided to engineers working on new products offer quick and unambiguous answers to questions posed not only by engineers but also by economists actively participating in designing equipment and machinery elements [2,3,5,6,12,13].

Analytical tools

The research conducted involved the use of the SYSWELD software package developed by the ESI Group. This software enables FEM-based simulations including welding and heat treatment issues. SYSWELD covers all the problems related to non-linear analyses, i.e. non-linear heat conduction in every space, non-linear geometry of great strains, isotropic and kinematic metal hardening or phase transformations (Fig. 2). Combining the influence of such a great number of phenomena taking place during a welding process makes it possible to obtain the mentioned high compatibility of simulation results with the actual behaviour of an element or structure.

SYSWELD enables the simulation of welding processes within a very wide range, i.e. both with and without filler metals, for heat sources having (friction welding, spot welding) and not having (electric arc, laser beam, electron beam) physical contact with the element being welded. The range of simulating heat treatment is equally wide and includes, among others, tempering, (laser, induction, electron beam, plasma, friction) hardening, carbonising and nitriding.

Computational process input data are the following:

- method used in a welding process,
- welding process linear energy/welding process parameters,
- geometry of an element/structure being welded (import from popular CAD systems in Pro/E, CATIA, UG, I-DEAS, Patran, Ansys, IGES, STL, STEP formats etc.),
- material,
- preheating temperature,
- number of runs/joints and their location and sequence,
- manner of stiffening/fixing a structure to be welded,
- post-weld heat treatment parameters, if any, etc.

Equally important are results obtained by means of simulation (Fig. 2), such as:

- temperature field and gradients,
- contents of phases in the individual areas of a joint,
- strains,
- internal stresses,
- displacements,
- hardness [14].

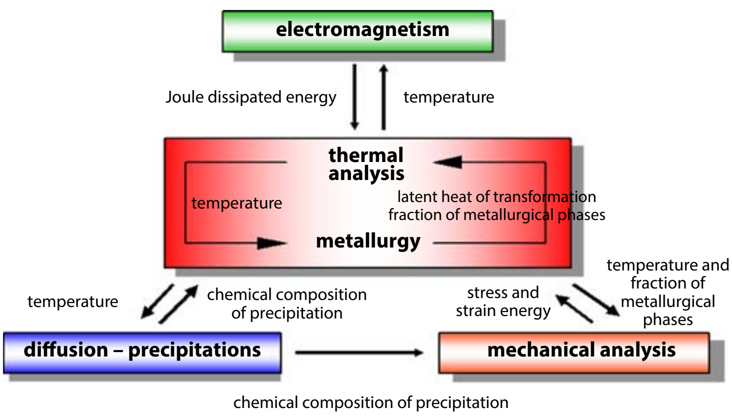

Fig. 1. SYSWELD structure [14]

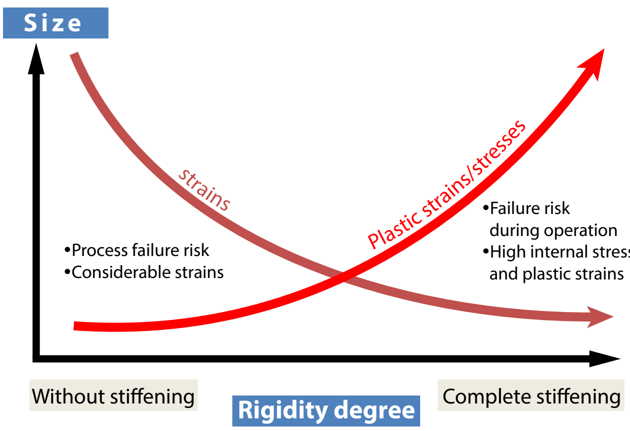

Fig. 2. Opposing effect of structural rigidity on plastic strains and internal stresses [14]

Problem description

During a welding process, the heat source supplies a specific amount of energy to the material being welded. As a result, the material undergoes partial expansion, yet this movement is partly limited by elements being welded, by the base on which these elements are rested and by the fixtures of a welding stand. Consequently, thermal stresses are generated in the welding area. While temperature increases, a plasticised material undergoes plastic deformation, which after cooling of a joint generates stresses and strains of elements welded.

Stresses generated in a welded joint depend, among others, on the manner in which a structure is stiffened during a welding process. A high structure stiffening degree generates slight strains at the cost of the high level of stresses and, vice versa, a low structure stiffening degree causes a significant decrease in these stresses resulting in a significant increase in welding strains. This entails the necessity of developing a technology for the optimum fixing of elements to be welded, i.e. reducing the level of post-weld stresses while at the same time maintaining a low level of strains. Otherwise, it may become necessary to use another procedure in a production process, i.e. straightening, which however, can be costly and sometimes even unfeasible.

The problem of modelling welding processes using FEM is complex. The determination of the level of welding stresses, strains and temperature field distribution is highly complicated due to the complex character of dependences between temperature, shrinkage, thermal expansion and variable material properties in time and space. In order to simplify the analysis, thermal and mechanical states are often analysed separately. This approach is dictated by an adopted principle, according to which changes in the mechanical state (stresses and strains) do not change process temperature, whereas a change in temperature is clearly reflected in the changing distribution of strains and stresses. For this reason, the first analysis of a welding process in such a case is concerned with the distribution of temperature fields during a welding process. The results are then used to determine the changes in the distribution of stresses and strains. Such a type of analysis is based on an assumption that heat generated during plastic deformation is significantly lower than heat supplied by an electric arc. That is why it is possible to carry out thermal and mechanical analysis as two separate analyses one after the other [2,8,9,10,11].

Another crucial issue in numerical analysis is the manner of describing how heat is supplied to a welded joint. Reference publications related to the numerical modelling of welding processes contain, among others, the 2D-Gaussian surface heat source model (2D Gauss), the double-ellipsoidal heat source model (so-called Goldak model, Fig. 3) or the 3D-Gaussian conical heat source model. Each of these sources has its own application in modelling a specific welding process or heat treatment. A surface heat source can be successfully used in modelling heat treatment processes, gas welding processes or MMA welding processes. The Goldak model proves useful in situations where a process is carried out using "melt-in welding" and the possibilities of changing the shape of a model enable its adjustment to a specific welding method. In turn, the conical model successfully represents welding methods characterised by

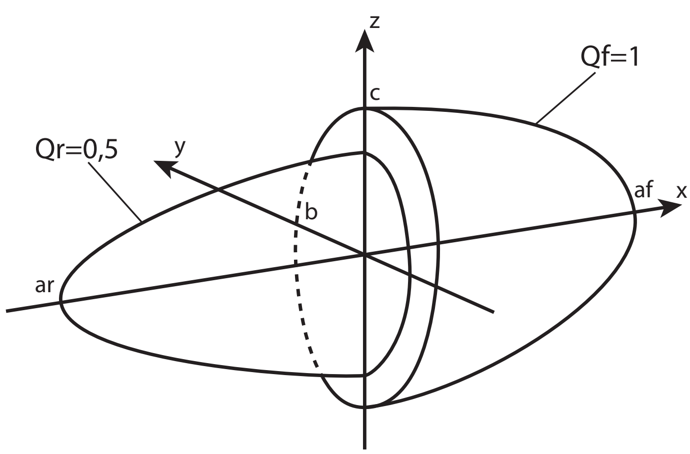

Fig. 3. Double-ellipsoidal heat source model (the Goldak model) [14]

high energy and deep penetration. An example of these applications can be laser or electron beam welding using "key-hole welding" [3,6,9,10,14].

The Goldak model used in the tests presented is made up of two ellipsoids described with the following equations

front part of the model:

$$Q(x,y,z)=Q_f \exp\left(-\left(\frac{x^2}{a_f^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}\right)\right)$$

rear part of the model:

$$Q(x,y,z)=Q_r \exp\left(-\left(\frac{x^2}{a_r^2}+\frac{y^2}{b^2}+\frac{z^2}{c^2}\right)\right)$$

where Q_f and Q_r represent the maximum power density of the front and rear part of the model respectively and a_f, a_r, b and c represent parameters which enable changing the model geometry and adjusting the shape of the heat source model to results obtained in real welding tests (Fig. 3) [14].

Discrete model and its assumptions

The numerical analysis of MIG welding of butt joints of 5251 (AlMg2) alloy required the use of a discrete model. Each of the test sheets had the following dimensions: 100×50×1 mm. The mesh of finite elements composed of three dimensional solid-type elements contained 64648 elements and 50704 nodes. In order to increase the accuracy of analyses to be conducted, the mesh was concentrated in the joint area as well as in the area adjacent to it. The model selected as a heat source model was that having the shape of a double ellipsoid. In order to optimise the shape of a virtual liquid metal pool and to make its shape as similar as possible to the one obtained in welding tests (Fig. 4), the model underwent initial calibration in the "Heat Input Fitting" module. Calculations were carried out by means of a "transient" method using the sequence according to which the thermal analysis was followed by the mechanical one. The results of the analyses were

Table 1. Chemical composition and mechanical properties of aluminium alloy 5221

Alloy – state **5251 H16**	Thickness **0.5-1.5 [mm]**	Tensile strength $R_{m\ min}$ **230 [MPa]**	Tensile strength $R_{m\ max}$ **270 [MPa]**

Yield point $R_{p0.2\ min}$ **200 [MPa]**	Yield point $R_{p0.2\ max}$ **- [MPa]**	Elongation min. A_{50mm} **2 [%]**	Elongation min. A **- [%]**	Bend angle 180° **3.5t**	Bend angle 90° **1.5t**	Brinell hardness **71 [HB]**

Chemical composition [% wag.]

Cu	Mg	Si	Fe	Mn	Zn	Ti	Cr	Al
0.15	1.7-2.4	0.4	0.5	0.1-0.5	0.15	0.15	0.15	rest

Table 2. Welding parameters for MIG-welded butt joints made of 1.0 mm thick aluminium 5251 sheets

Current [A]	Arc voltage [V]	Welding rate [mm/s]	Linear energy [J/mm]	Exposed length of electrode wire [mm]
35	15.6	15	38.48	10

Others:
shielding gas: argon, flow rate: 15 dm3/min; wire type: AlMg4.5 – wire diameter 1.2 mm;

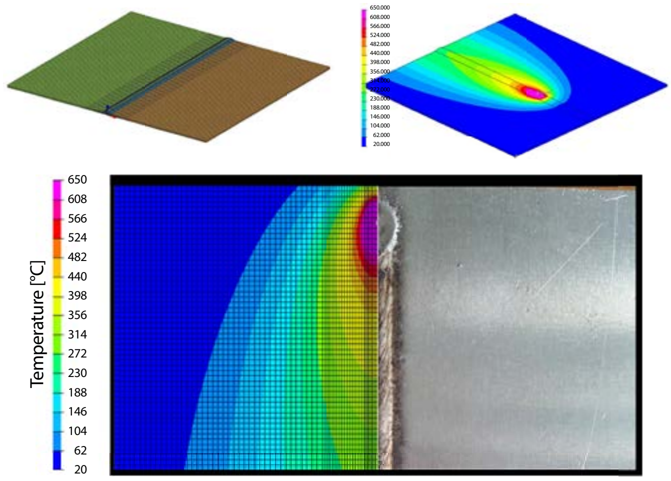

Fig. 4. Discrete model of a welded joint and the calibration of a heat source

compared with the welding tests carried out using the pre-defined set of parameters ensuring obtaining good quality joints (Table 2, Fig. 10).

The calculations were conducted for 6 variants of fixing sheets (in accordance with the designations in Table 3 and Figure 5):

Table 3. Analysed variants of fixing elements during welding (Fig. 5)

Fixing variant	Sheet fixing variants at individual time intervals			
	welding	joint cooling		
	t = 0-6.67[s]	t = 6.67-30 [s]	t = 30 – 3600 [s]	t = 3600 – 4000 [s]
1	A	A	A	A
2	B	B	B	A
3	B	A	A	A
4	C	C	C	A
5	D	D	D	A
6	D	D	A	A

1. sheets completely released during the welding process followed by the cooling process – bindings in corners necessary for the determinability of the analysis conducted (Fig. 5A),

2. sheets pressed with fixing elements 10 mm away from the joint axis (Fig. 5B) at the time from 0 to 3600 s of the analysis conducted, and next released at the time from 3600 to 4000 s of the analysis (Fig. 5A),

3. sheets pressed with fixing elements 10 mm away from the joint axis (Fig. 5B) at the time from 0 to 30 s of the analysis conducted, and next released at the time from 30 to 4000 s of the analysis (Fig. 5A),

4. sheets stiffened on the whole length of their outer edges (Fig. 5C) at the time from 0 to 3600 s of the analysis and next released (Fig. 5A),

5. sheets pressed with fixing elements 10 mm away from the joint axis and stiffened on the whole length of their outer edges (Fig. 5D) at the time from 0 to 3600 s of the analysis and next released (Fig. 5A),

6. sheets pressed with fixing elements 10 mm away from the joint axis and stiffened on the whole length of their outer edges (Fig. 5D) at the time from 0 to 30 s of the analysis and next released (Fig. 5A).

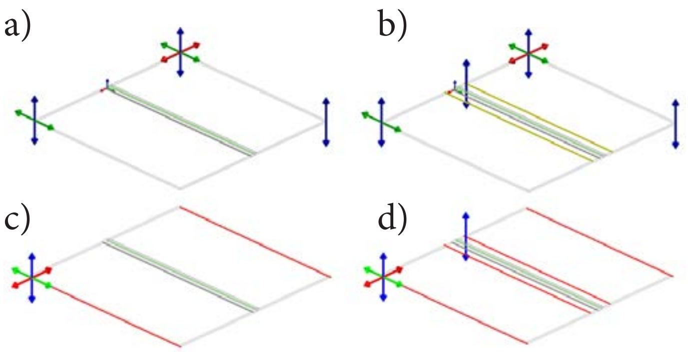

Fig. 5. Sheet fixing variants during analysis –'rigid' fixing (arrows designate taking away the freedom degrees of a point in the indicated direction, in Figures C and D – all the points on the red line and in Figure B along the yellow line)

Results of analyses and summary

Due to the small thickness of welded elements it was possible to assume the flat state of stresses. As a result, the state of stress adopted for a joint was the one with constituents σ_x and σ_y. The condition for forming the flat state of stresses was local heating of elements, which in relation to welding, was fulfilled.

In all cases, the types of stresses (tensile/compressive) along the joint axis were similar. Transverse tensile stresses were present in the central part of a joint, whereas transverse compressive stresses were present at the beginning and end of a run (Fig. 6). Taking into consideration the previously mentioned and assumed flat state of stresses, the level of stresses perpendicular to sheets being welded could be considered as negligible due to the small thickness of elements.

On the basis of previously conducted calculation it was observed that the values of stress constituents σ_x and σ_y fluctuated slightly regardless of the manner of stiffening elements being welded. What changed was the distribution of these constituents, causing differences in the shape and size of strains for various manners of sheet fixing.

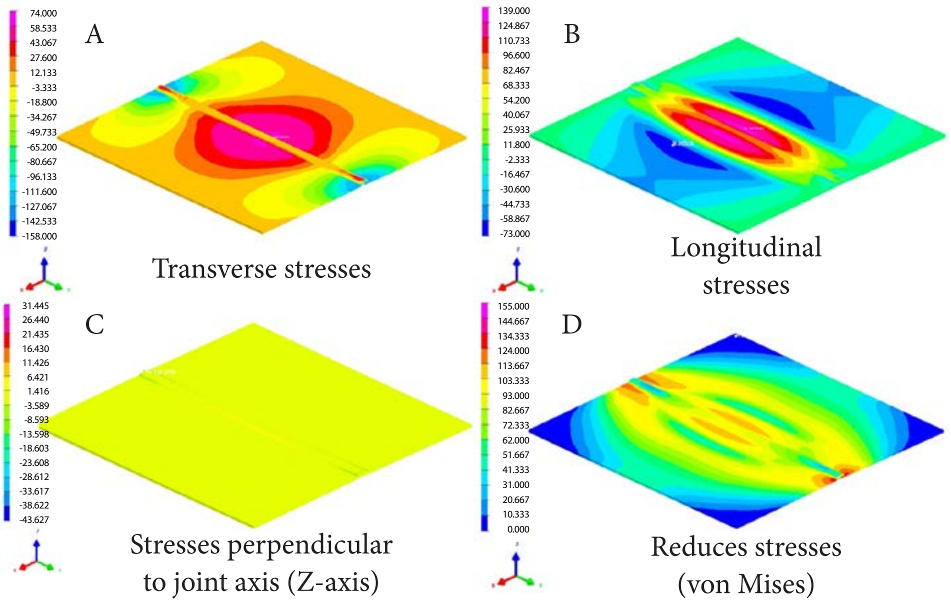

Fig. 6. Distribution of stresses in the welded joint analysed, sheet fixing manner – Table 3

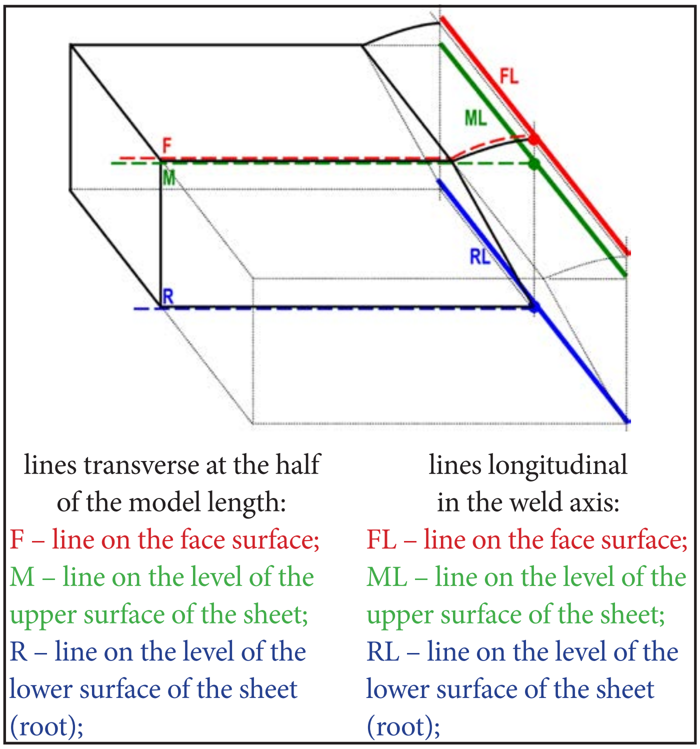

Fig. 7. Position of lines for determining the level of stresses in the model analysed

In order to analyse the distribution of stresses more precisely it was necessary to determine 6 measurement lines in the model and draw the distribution of longitudinal and transverse stresses along these lines. These included three lines drawn across in relation to a welding direction at the half of a run length and three longitudinal lines in the weld axis (Fig. 7). Considerations concerned fixing manner no. 1, i.e. welding sheets completely released during a welding process and cooled afterwards.

The analysis of longitudinal stresses in three lines drawn as in Figure 7, i.e. at the half of a joint length, confirmed the presence of longitudinal tensile stresses in the weld area and in the area directly adjacent to it. Approximately 15 mm away from the joint axis the nature of the stresses changed from tensile to compressive (Fig. 8). In the case of the constituent acting transversely to the joint axis, the stresses (transverse) were tensile with their value decreasing to zero along with a growing distance from the joint axis in the direction of the sheet edge (Fig. 8).

The average value of stresses analysed in the line transverse to the joint axis indicated the presence of a tensile stress zone in the weld and the area adjacent to it. What could also be observed was a characteristic of aluminium alloys, a slight decrease in this value in the weld itself and in the area adjacent to it. It was also possible to observe the presence of a compressive stress zone approximately 18 mm away from the joint axis (Fig. 8). Reference publications state that materials which, due to heating, lose their mechanical

Table 4. Strains of welded sheets depending on the manner of stiffening during welding and cooling, sheet fixing manner – Table 3

Fixing variant	Strains [mm]						
	UX		UY		UZ		U_{norm}
	min	max	min	max	min	max	max
1	-0.320	0.087	-0.249	0.018	-0.159	0.700	0.715
2	-0.319	0.082	-0.249	0.017	-0.128	0.364	0.394
3	-0.319	0.082	-0.249	0.017	-0.126	0.369	0.399
4	-0.365	0.040	-0.245	0.061	-1.021	0.003	1.080
5	-0.387	0.038	-0.256	0.054	-0.395	0.020	0.536
6	-0.339	0.042	0.257	0.052	-0.057	0.273	0.386

properties obtained by cold work or heat treatment (e.g. cold rolled steel or Al alloys) are characterised by decreased stresses in the softened zone, not exceeding Re in the softened state [1].

The analysis of stresses carried out along the three determined lines of welding direction confirmed the presence of transverse tensile stresses in the central part of the joint (on the length extending approximately 20 mm from the beginning of the joint to 80 mm) (Fig. 9). In the remaining part transverse compressive stresses were present. An exception was the line drawn on the upper surface of the sheet being welded and on the weld face – in this case stresses changed their character to opposite in relation to those observed in the two remaining cases and obtained slight values in the central part (Fig. 9).

The longitudinal stresses observed along the joint axis were tensile. They grew in the direction of the weld root and obtained practically zero at the beginning and at the end of the weld (Fig. 8). The average stresses along the weld axis had the distribution similar to that of transverse stresses and, in each of the lines examined, were tensile in the central part of the run and compressive on the edges (Fig. 9).

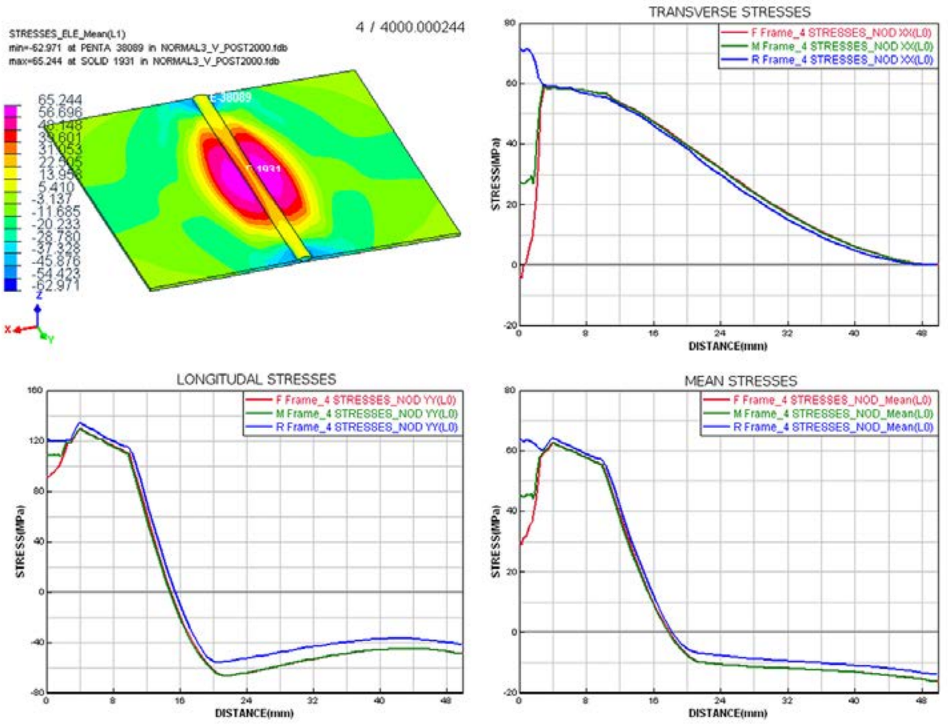

Fig. 8. Distribution of stresses on the cross-section at the half of the joint length – sheet fixing manner: variant no. 1 – Table 3

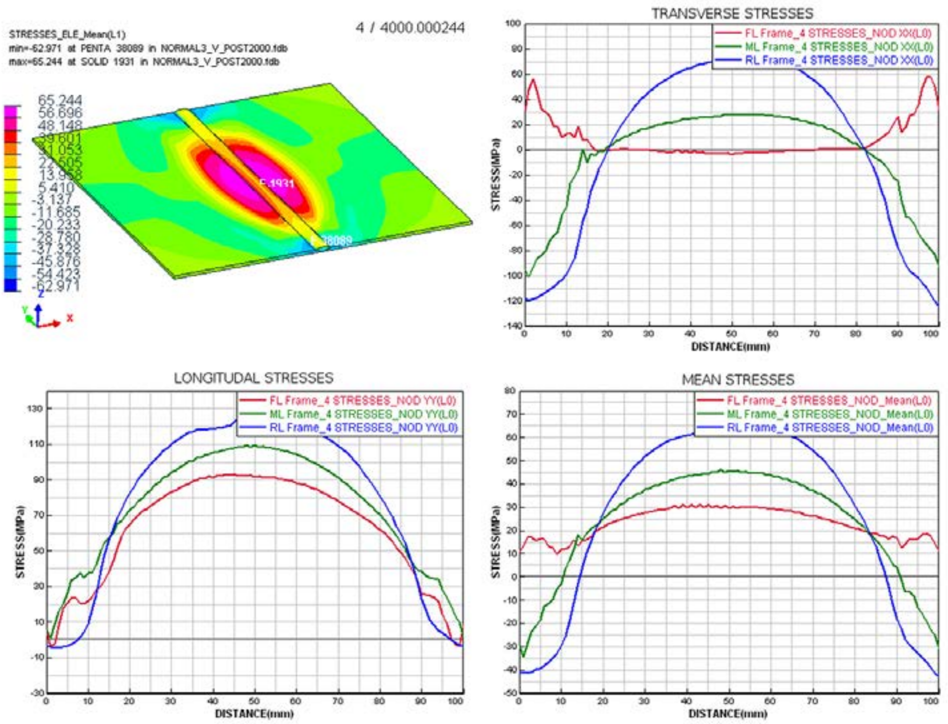

Fig. 9. Distribution of stresses on the cross-section at the half of the joint length – sheet fixing manner: variant no. 1 – Table 3

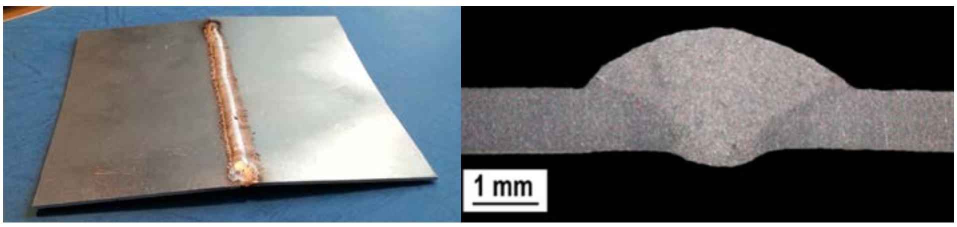

Fig. 10. Welded joint and macrostructure – fixing variant no.1, welding parameters – Table 2

Such a state of stresses was reflected in the manner of sheet deformation during welding (Fig. 10, 11). While the level of stresses in all the cases analysed was similar, their distribution resulting from the sheet fixing manner had an effect on the final levels of strains, particularly in the direction perpendicular to the surface of elements welded (Fig. 11, table 4).

What was characteristic was the fact that in the first group of non-fixed elements, along the whole length of the edges (fixing variant 1-3), irrespective of whether the pressed element underwent cooling or was released after about 20 seconds following the completion of welding, pressing elements along the whole length of the joint during welding caused an approximately 50% decrease in the levels of strains in the direction of Z-axis. In the case of elements fixed along the edges, the case corresponded more to the analysis of a structure section and not to the real stiffening by means of fixing elements (e.g. elements between two massive elements not undergoing deformations) but also demonstrated the influence of additional fixing on the distribution of strains in the element being welded. Removing the possibility of moving along the Z-axis changed the character of a strain and reduced its value.

Conclusions

On the basis of the numerical analysis of welding butt joints in aluminium alloys it was possible to observe that

- the degree of stiffening an element during welding and post-weld cooling affects the manner of element deformation and the distribution of post-weld stresses,
- in the case of aluminium alloy sheets, deformations are not the consequence of significant differences in stress values but result

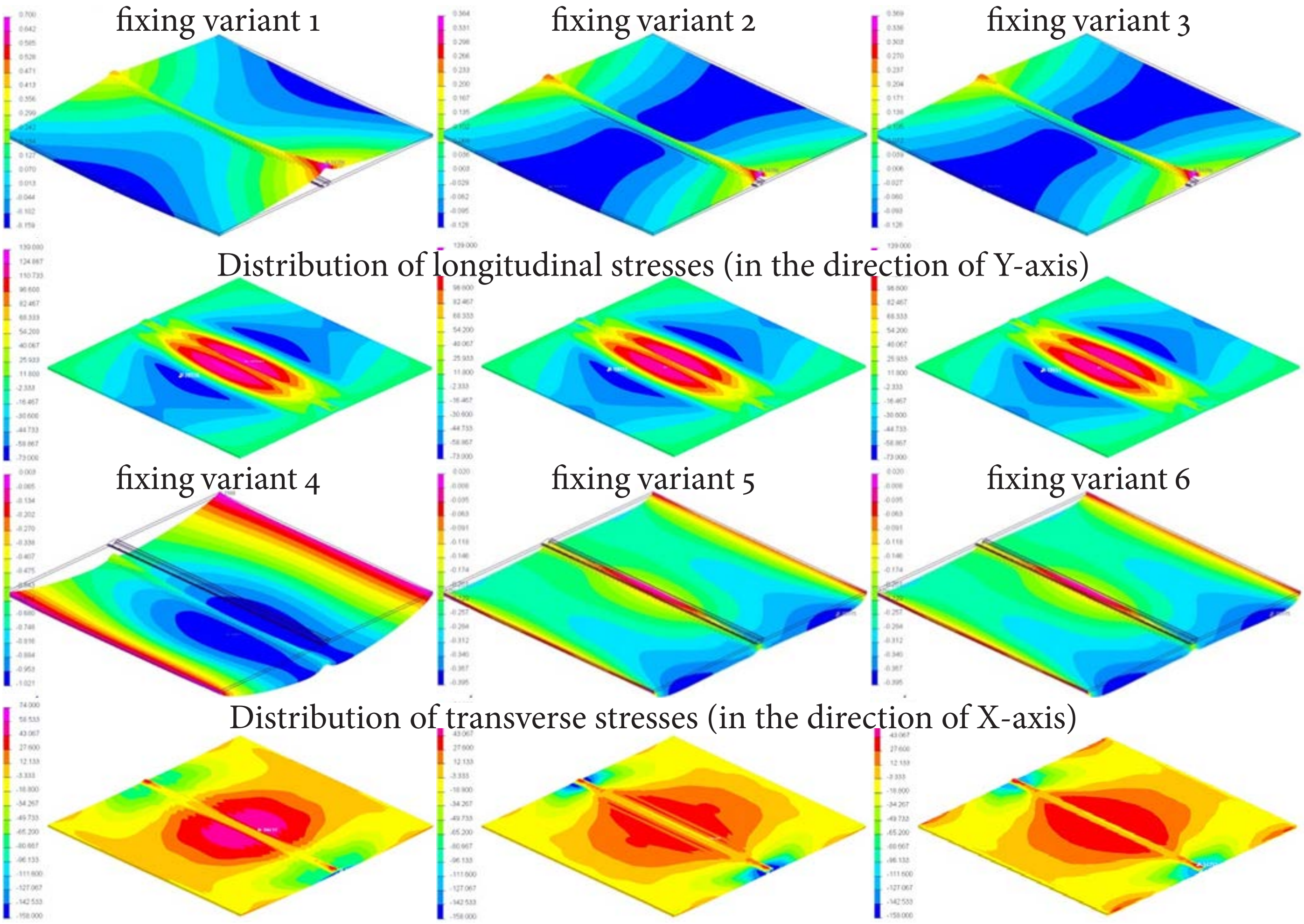

Fig. 11. Strains in the direction of Z-axis for various manners of element fixing during welding and corresponding distributions of longitudinal and transverse stresses, Table 2

mainly from the distribution of stresses in a welded joint (Fig. 11),
- numerical analysis enables faster and cheaper selection of the optimum manner of fixing elements for welding as well as the precise analysis of stress and strain distributions resulting from fixing variants analysed,
- as a result, numerical analysis makes it possible to significantly reduce prototyping costs and to consider a greater number of possible solutions without risking additional costs. This method also enables the analysis of difficult and expensive issues as regards necessary testing equipment.

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