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FATIGUE DESIGNING OF WELDED AGRICULTURAL WHEELS

PROJEKTOWANIE TRWAŁOŚCIOWE SPAWANYCH KÓŁ POJAZDÓW ROLNICZYCH*

Each introduction of new or modified products into production requires conducting a series of calculations and experiments which would verify the desired quality. In case of agricultural wheels it is necessary to estimate their fatigue life and durability at a possibly low cost. This paper presents a method of fatigue design of agricultural wheels on the example of a welded wheel type 9.00x15.3. A previously designed numerical model FEM was used, which enables to identify the potential weak spots of the construction which could determine its total durability and allows to assess the critical parameters. Based on the results of model studies, construction changes were introduced, which were experimentally verified on a fatigue machine during durability testing for radial forces.

***Keywords**: disc wheels, fatigue design, Hot-Spot.*

Wprowadzenie do produkcji nowych lub zmienionych pod względem konstrukcyjnym wyrobów wymaga wykonania obliczeń sprawdzających oraz doświadczeń potwierdzających uzyskanie ich założonej jakości. W przypadku kół pojazdów rolniczych konieczne jest wcześniejsze oszacowanie ich wytrzymałości i trwałości zmęczeniowej możliwie niskim kosztem. W pracy przestawiono metodę projektowania trwałościowego kół pojazdów wolnobieżnych na przykładzie spawanego koła typu 9.00x15.3. Wykorzystano opracowany wcześniej model numeryczny MES, który umożliwia identyfikację potencjalnie najsłabszych miejsc konstrukcji decydujących o jej trwałości oraz pozwala określić wartości parametrów krytycznych. Na podstawie wyników badań modelowych wprowadzono zmiany konstrukcyjne, które zweryfikowano doświadczalnie na stanowisku badawczym w testach trwałościowych na obciążenia promieniowe.

***Słowa kluczowe**: koła tarczowe, projektowanie trwałościowe, Hot-Spot.*

1. Introduction

The creation of new constructions or modification of existing ones must stem from an economic analysis and market requirements. In the case of agricultural wheels the necessity of increasing the quality of construction is caused by a relatively high share of material costs in the final product and a relatively low durability with regards to expectations. During usage, wheels undergo various types of strain, which may result in damage to the wheel. Due to constant operation, typical usage damages are a result of material fatigue and appear in some characteristic spots referred to as *theoretical critical zones TCZ* [12, 17]. During usage unique situations may occur, such as wheel collisions with an obstacle or a sudden puncture or tearing of the tyre, which may cause a permanent deformation of the wheel. Such cases will not be taken into account in this paper.

The fatigue life of every individual construction should be initially determined at the designing stage. The basic task of a constructor is then to identify the location of *TCZ*s and to assess their fatigue life for assumed usage conditions and with known material parameters. The appropriate norms, such as [4, 13] require the wheel durability to be verified in experiments with the use of fatigue machines. Obtaining the expected improvement in quality with a trial and error method is time-consuming, and prolonged analysis of wheels may be costly. It is therefore crucial to introduce construction analysis on models with use of computer technology, conducting fatigue tests in the last stages of work.

In this context *fatigue design of wheels* means a process of conscious and purposeful creation of a product characterised by the required fatigue life, based on the assumptions made, with use of theoretical knowledge in the field of material technology, methods of numerical modelling, fatigue life, fracture mechanics, as well as practical knowledge, while taking into account the influence of the technological process on durability.

The aim of this paper is to present the method of *fatigue design* used in welded agricultural wheels, aiming at obtaining more beneficial fatigue life with no increase in mass and with maintaining the same production technology. The method is presented on the example of a welded wheel type 9.00x15.3 with an *Implement* brand tyre [8], commonly used in agricultural vehicles.

2. Numerical modelling of the wheel and its experimental verification

The numerical model of agricultural wheels was developed earlier and described in [19]. The tyre played a key role in this model [9], which was described with the use of the hyperelastic Mooney-Rivlin material [11, 15], taking into account the five construction zones of different material properties. An example of the modelled wheel's geometry with an *Implement* type tyre and the division into individual zones is presented in figure 1.

In the correct wheel description, the various zones of the tyre presented in Fig. 1 need to be included, such as: the tread 1a, sidewall 1b, bead 1c, layer elements 1d and the steel-rubber bead bundle 2. The picture also presents the elements of the metal part of the wheel: rim 3, disc 5 and the weld 4. The values of the material parameters characterising the individual zones of the tyre were defined in accord-

(*) Tekst artykułu w polskiej wersji językowej dostępny w elektronicznym wydaniu kwartalnika na stronie ***www.ein.org.pl***

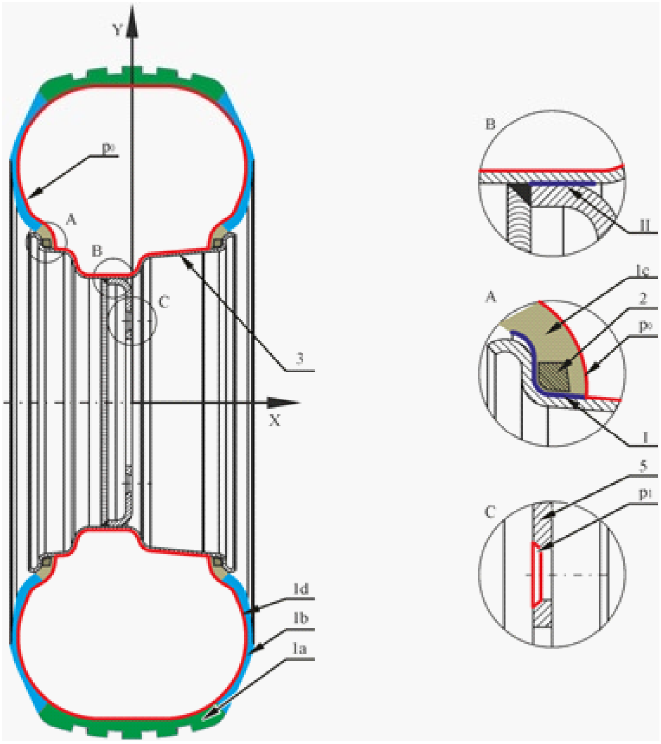

Fig. 1. Graphic scheme of the wheel model divided into the basic zones with characteristic construction properties. Description in the text

ance with the source data found in [5], and in case of the steel-rubber element (No. 2 in Fig. 1) the replacement parameters were determined as the harmonic mean of the material constants of the bead bundle and rubber, taking into account their percentage amount in the cross section.

The accuracy of the numerical calculations, proving the model's correctness, was verified in experiments with the use of the strain gauge method. Fifteen strain gauges were placed on the inner and outer part of the wheel's rim as well as on the outer part of the disc. After fitting the tyre and resetting the measuring device, the wheel was filled with air, fastened with screws on the workstation and gradually strained radially until the desire d force was obtained. During this time, the measuring device indications were being registered continuously. The maximum differences in deformation value calculated numerically and those acquired in strain gauge tests did not exceed 5%.

In Fig. 2 we can see the rim of the wheel with the strain gauges in place before the tyre was fitted. They were located in crucial places

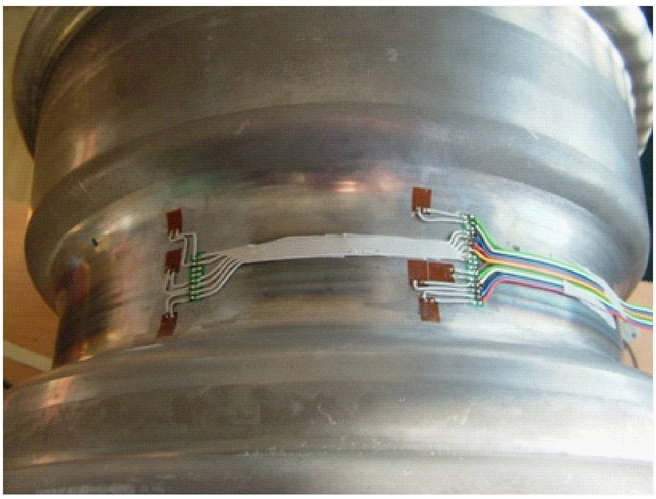

Fig. 2. The rim of the wheel with strain gauges in place from the tyre side

from the construction durability point of view, after an initial analysis of the numerical calculations results obtained by *FEM* for the designed model of a wheel strained radially.

3. Identification of *TCZ* zones and their parameters

The results of fatigue tests of the wheels, conducted on a full scale at a fatigue machine (a running machine) and model numerical tests allowed to identify the actual location of construction damages and enabled to verify the used *FEM* models. Examples of fatigue damage and stress values acquired from the *FEM* solution are presented in Fig. 3. In the computer simulation, the wheel with a four-arm disc was pressed down to the surface with a force of *P*=26 kN in the radius direction, which corresponded to the conditions of fatigue tests conducted on the fatigue machine. The fatigue fracture visible in Fig. 3a) was located in the end zone of the weld, where a local increase in stress was noted, caused by the notch effect.

From the point of view of stress concentration and fatigue durability, the key role was that of the local geometrical qualities of the con-

a) b)

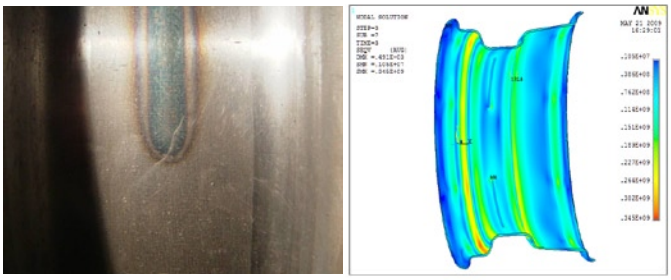

Fig. 3. a) Fatigue fracture at the end of the weld, b) distribution of stress in the FEM model of the rim with radial force applied

struction, such as: thickness, radius of curve and angles of the metal sheets, welded joints and notches located in the area of the weld cap and root.

Basing on the numerical calculations, resulting from model analysis, three zones of increased concentration of stress were identified, which are a potential weak durability links (Fig. 4), namely: the curving of the wheel rim (*TCZ1*), the boundary of weld cap and rim material (*TCZ2*) and the area of the weld root joining the rim and disc (*TCZ3*).

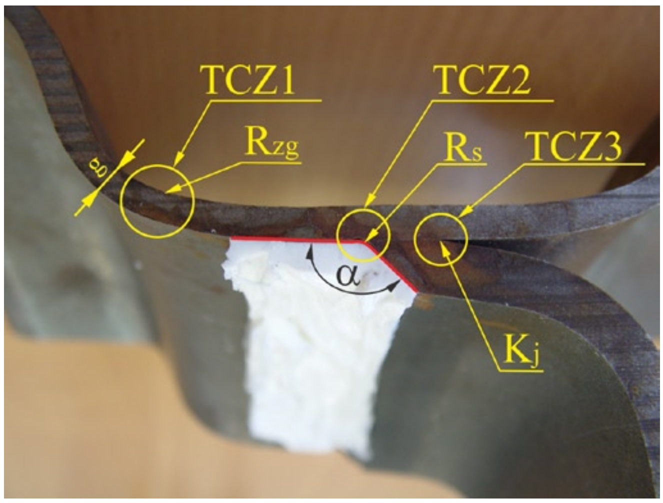

Fig. 4. A cross section of a weld joint with the characteristic values, areas of increased stress concentration marked and a layer of silicone enabling the identification of the local parameters of the notch

The characteristic local geometric features of the rim may be measured on real objects, whereas the parameters of weld joints may be conveniently identified for example using the method of silicone surface replicas.

Fig. 4 represents a cross section of a welded joint connecting the disc with the rim of the wheel. The characteristic values have been marked, such as the thickness of the sheet *g*, shape and radius of the curve R_{zg} and potential critical zones identified for the wheel model under radial load. The white silicone cast visible in the picture enabled the identification of the R_s value and the *α* angles. The results of these measurements are represented in figures 5 and 6.

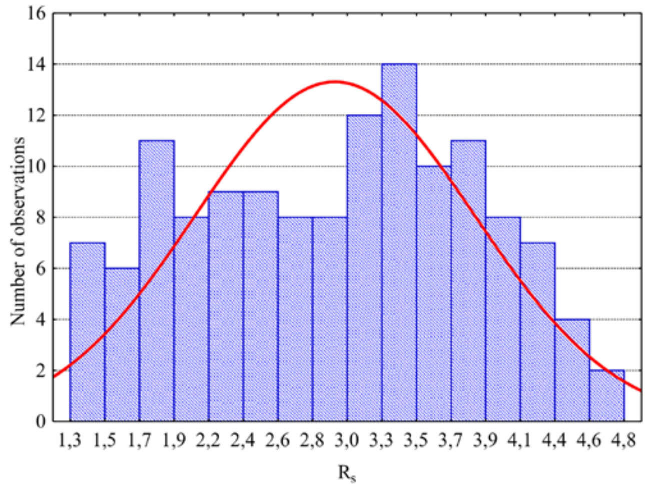

Fig. 5. Distribution of measured values R_s in a wheel with a four-arm disc

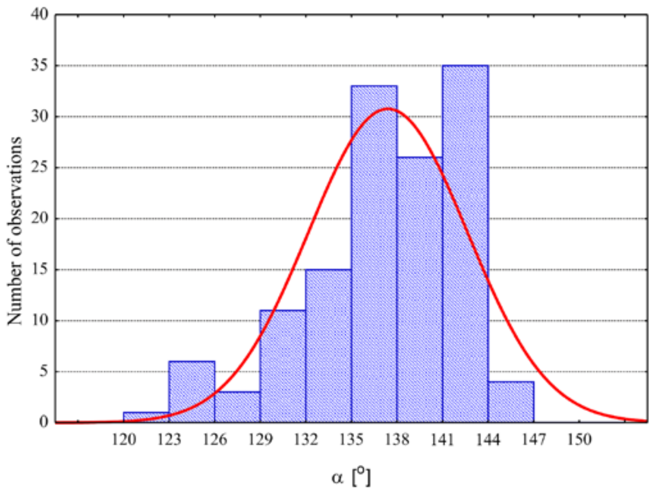

Fig. 6. Distribution of measured values of α angle in a wheel with a four-arm disc

In both presented cases the results of measurements may be described statistically by means of normal distribution. The average value of Rs radius was app. 3.0 mm with a standard deviation of 0.8 mm, whereas the average value of the α angle was 137° with a standard deviation of 6°.

The size of the R_{zg} radius and the thickness of the rim g are decisive in the value of local stress in the area *TCZ1* of the rim. By means of the Finite Elements Method the value and evolution of critical stress was determined in this area with a circumferential shift of the location of the reference point, starting from a location closest to the area of application of the radial force *P*. The character of these changes in points lying along the circumference is shown in Fig. 7. A characteristic feature of these stresses is their symmetry to the plane of force applied (coordinates '0' and '0.5' on the graph) and that the minimal stresses do not occur on the rim directly opposite to the area of application of the external force, but are located at an angle equal to appr. 1/3 of the wheel's revolution. This has a crucial meaning while calculating the number of cycles of stress changes in these areas, as well as the range and level of mean fatigue stresses in this area during a full revolution of the wheel around its axis.

In the location marked as *TCZ2* the value of stress needs to be calculated on the border of weld cap and rim material. In this case the Hot-Spot method is often used [6, 10, 14, 16], which is presented in Fig. 8.

This method is based on determining the values of stresses in strictly designated points in front of the weld cap, depending on the

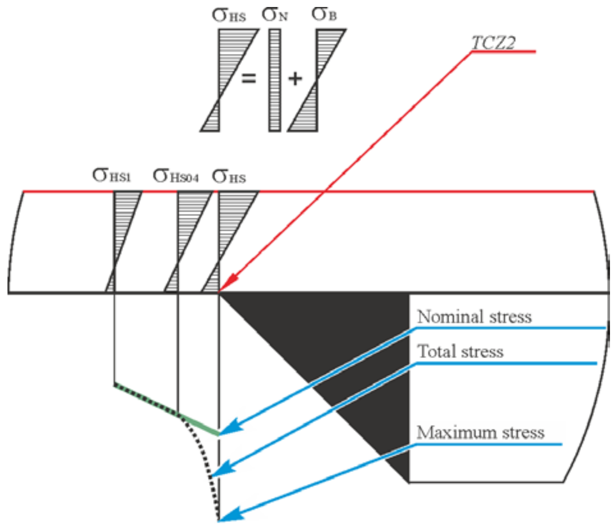

Fig. 8. Method of determining the nominal and maximum stresses at the front of the weld cap by using the Hot-Spot method and the interpretation of bending, normal and nominal stresses

thickness of the element, and calculating the hypothetical values of nominal stresses at the edge of the weld, in the location of the base of the concentrator. Next, the value of the coefficient of stress concentration is determined, based on the identified geometrical parameters of the weld R_s and α, and the maximum stresses are determined taking into account the nominal stresses calculated previously. In case of the existence of bending and stretching simultaneously, as is the case in the discussed example presented in Fig. 8, the coefficient of stress concentration should be determined independently from the bending and stretching. The values of reference stresses σ_{HS1} and σ_{HS04}, serving the purpose of calculating the nominal stresses σ_N and σ_G, can be acquired from the numerical solution *FEM*, for example in accordance with the procedures described in [14] and [16] or they can be determined experimentally with the strain gauge method.

The values of the stress concentration coefficients and maximum stress, for stretching and bending respectively, may be calculated from the equations published in [6, 10] or determined by numerical methods, such as conducting a separate calculation for plane problems. One of the methods of calculating the stress concentration coefficients, using nominal stresses in the Hot-Spot approach, was suggested by Monahan [10]. For pure stretching these coefficients' form is in accordance with the equation:

$$K_{t,hs}^{m} = 1 + 0{,}388\,\tilde{}^{\;0{,}37}\left(\frac{t}{r}\right)^{0{,}454} \quad (1)$$

whereas for bending – the equation is:

$$K_{t,hs}^{m} = 1 + 0{,}512\,\Theta^{0{,}572}\left(\frac{t}{r}\right)^{0{,}469}. \qquad (2)$$

The interpretation of the t, r and Θ parameters (in radians) is presented in Fig. 9. Other, more general equations, were suggested by Iida and Uemura [6]. These are less conservative [2] than the ones given by Monahan, but they consider the geometry of the welded joint to a greater extent, which is presented in Fig. 9. For stretching, the stress concentration coefficient is calculated in accordance to the equation:

$$K_{t,n}^{t} = K_{t,hs}^{m} = 1 + \frac{1-\exp\left(-0{,}9\,\Theta\sqrt{\frac{W}{2h}}\right)}{1-\exp\left(-0{,}45\,\pi\sqrt{\frac{W}{2h}}\right)}\left[\frac{1}{2{,}8\left(\frac{W}{t}\right)-2}\,\frac{h}{r}\right]^{0{,}65} \qquad (3)$$

and for pure bending – the formula is:

$$K_{t,n}^{b} = K_{t,hs}^{b} = 1 + \frac{1-\exp\left(-0{,}9\,\Theta\sqrt{\frac{W}{2h}}\right)}{1-\exp\left(-0{,}45\,\pi\sqrt{\frac{W}{2h}}\right)} 1{,}9\sqrt{\mathrm{tgh}\left(\frac{2t_p}{t+2h}+\frac{2r}{t}\right)}\;\mathrm{tgh}\left[\frac{\left(\frac{2h}{t}\right)^{0{,}25}}{1-\frac{r}{t}}\right]\frac{0{,}13+0{,}65\left(1-\frac{r}{t}\right)^{4}}{\left(\frac{r}{t}\right)^{1/3}} \qquad (4)$$

where $W = 0{,}3(t+2h)(t_p+2h_p)$.

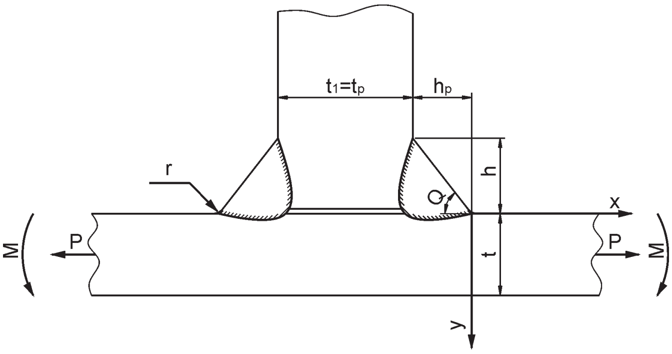

Fig. 9. Characteristic parameters of a welded joint [2] used in equations (1) – (4)

In the presented construction of a welded wheel, the third potentially critical spot was the sharp notch located in the area of the weld root, created after joining the disc and rim, marked in Fig. 4 as *TCZ3*. In this case, the durability criteria may be used based on fracture mechanics, which is to determine the values of the stress intensity factors K and their ranges ΔK in time of a full rotation of the wheel with applied radial force. The most useful tool allowing to determine the K value is the finite elements or the boundary elements method.

In the case of a wheel with a multi-arm disc, the area of rim damage is consistent with the location of *TCZ3*, which is located at the end of the weld, at the edge of the disc arm (Fig. 3).

4. Modification of the wheel construction

Based on the conducted model calculations and theoretical analyses, the construction of the welded wheel was changed in order to reduce the stresses in the critical zones. These modifications were to eliminate the areas of the highest concentration of stresses, located at the ends of the welds, by replacing the multi-arm disc with a full disc and the fragmented welds with a continuous circumference ones. In this way the concentration of stresses in the areas *TCZ2* and *TCZ3* was reduced, increasing the fatigue durability of the wheel, as shown by the results of later tests.

Fig. 10 presents the radial stress in the *TCZ1* zone during a full rotation of the modified wheel with a full disc around its axis, with applied force of $P = 26$ kN.

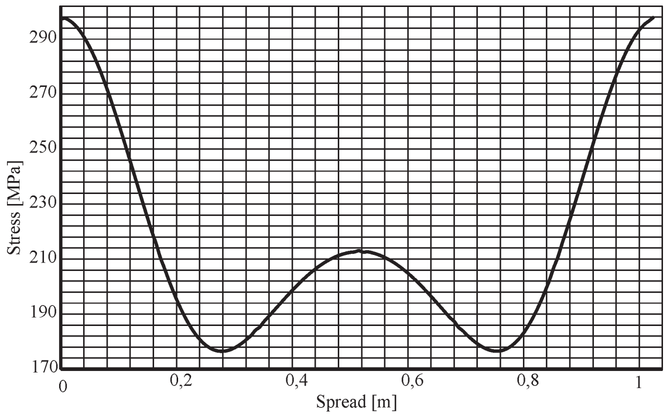

Fig. 10. Radial stress in the TCZ1 area during one full rotation of the wheel with a full disc 6mm thick, for force of P = 26 kN

As in the case of the wheel with a multi-arm disc, maximum stresses were occurring in the area closest to the appliance of radial force, and minimal values appeared in points corresponding to app. 1/3 of the wheel's circumference. In Fig. 10 two cycles of stress changes are seen during one full rotation of the wheel. A nearly 15% decline in the stress values was obtained relative to the wheels with a multi-arm disc, which is shown in Fig. 7.

The relation between the type of the wheel's construction and the value of weld parameters was also investigated. Collective results of local measurements of geometrical values of welds for different types of wheels are presented in Fig. 11. They point to the angle of the weld cap being independent from the wheel construction type, whereas the radiuses R_s are changing along with the thickness of the joined elements.

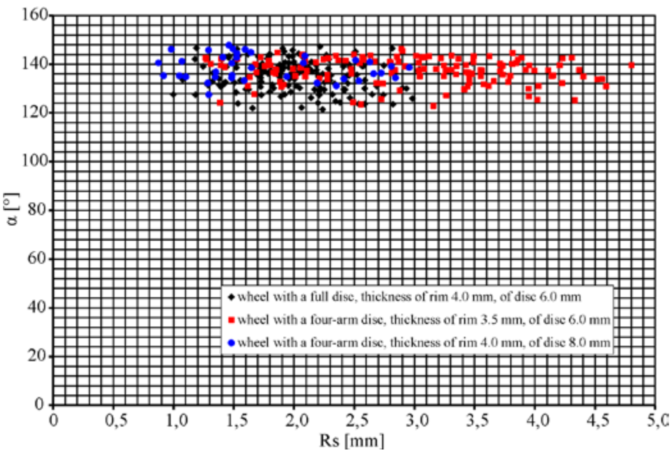

Fig. 11. The measured values of the weld cap angle in reference to the radius of weld/rim material border for different agricultural wheels construction solutions

The modified wheel constructions were tested on fatigue machines in a test for radial loads [18]. In Fig. 12a) fatigue crack is presented in the area of the rim bend, formed during a fatigue test of a wheel with a full disc. The origin location of the fatigue crack was located on the inner surface of the rim corresponding to the area of increased strains marked as *TCZ1* and identified with the *FEM*. A corresponding representation of the stresses calculated numerically is presented in Fig. 12b).

a) b)

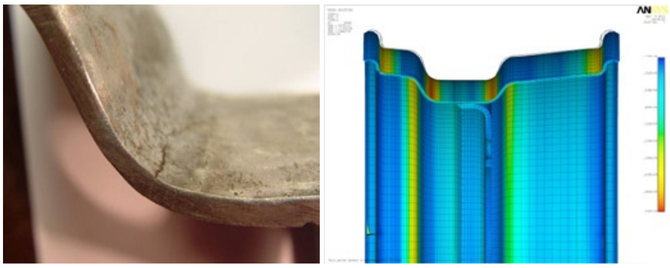

Fig. 12. a) The location of the fatigue crack in the bend of the rim, b) the corresponding distribution of stress in the FEM model, identified as TCZ1 (Fig. 4)

These wheels are characterised by significantly longer durability in comparison to the wheels with a multi-arm disc and a different location of fatigue cracks. The replacement of the multi-arm disc with a full disc and the fragmented weld with a continuous one allowed to eliminate local concentrations of stress at the ends of welds and remove the origin of fractures from the weld area. This changes also allowed to reduce the weight of the wheel itself by changing the thickness of the disc.

Fig. 13 presents the relation between durability and radial force for different types of wheels, obtained from fatigue tests [19]. The crosshatched area covers the location of the fatigue characteristics of wheels with multi-arm discs, whereas a continuous line marks the characteristic for a wheel with a full disc. A significant move to the right of the experimental curve is visible, which means an improvement in strength and increase in fatigue life. Another important feature of this new construction is the narrow spread of results for different levels of force applied, which allows to estimate more precisely the credibility range while predicting the durability of wheels.

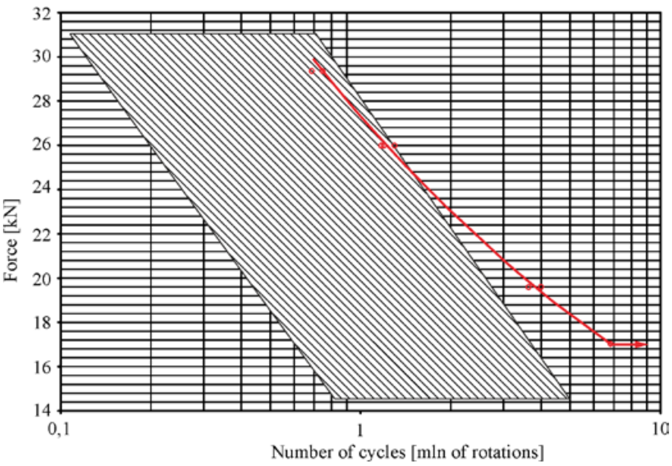

Fig. 13. A comparison of fatigue life of wheels with multi-arm discs with various disc and rim thickness (crosshatched area) and wheels with a full disc and circumferential weld (continuous line)

5. Procedure of fatigue designing of agricultural wheels

Fatigue design is connected to the shaping of the desired features of the product and therefore must involve many stages. The suggested algorithm of procedures in the case of wheels is shown in Fig. 14. The main elements here are the stages of *Assumptions* and *Prototypes,* which enable to achieve the desired goal.

The first stage of the process of shaping the utility features of wheels is the *Assumption Stage* which is defined after conducting the analysis of market requirements. In the case discussed here it is the need for designing a wheel of previously defined parameters, i.e.: weight, predicted durability, dimensions, method of mounting, construction type, type of tyre used, production cost also connected with the used technology etc. The process of creating the construction of designated durability is described in literature as *fatigue dimensioning of a product* [17].

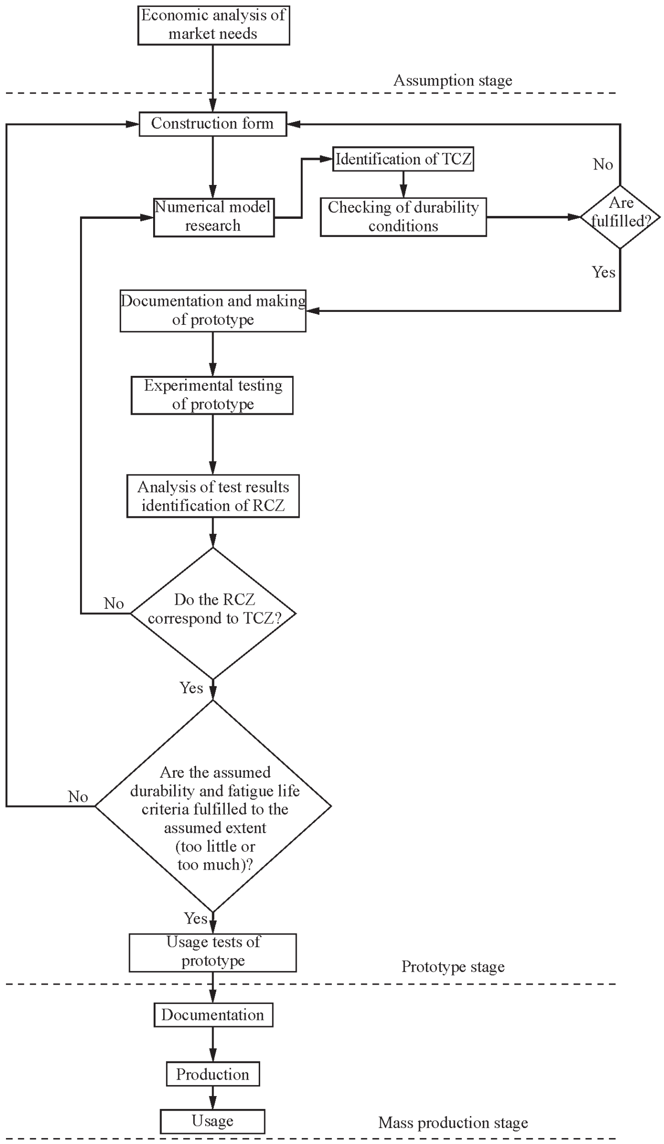

Fig. 14. The suggested procedure algorithm during fatigue design of welded wheels

The most developed, complex and time-consuming part of the algorithm is the *Prototype Stage,* which comprises of: conceptual work, numerical modelling aiming at identifying the areas of the wheel of greatest material stresses and the identification of *TCZ*, creating the prototype and testing it, which would verify the assumptions made, and any necessary modifications of the construction followed by testing, eventually leading to finding the optimal solution.

A key information obtained as a result of the conducted tests is determining the correspondence between the verified locations of fractures, i.e. the real critical zones *RCZ,* and the theoretical zones *TCZ*. If these areas overlap, the numerical model can be considered as qualitatively correct. However, in case of fractures appearing in places other than the theoretically estimated ones, the numerical model needs to be corrected for its accordance and precision. In the discussed case of the agricultural wheel the conformity of *TCZ* and *RCZ* was verified in experimental tests.

6. Summary and conclusions

The paper presented the method of *fatigue design* of a wheel used in agricultural vehicles, on the example of a welded wheel type 9.00x15.3. The local approach was used in fatigue design, where main effort has been made on the verification of zones of stress concentration and determining their local durability properties. The basis for theoretical analysis was the *FEM* model of a wheel with an *Implement* type tyre, which was positively verified with the use of the strain gauge method. As a result of the conducted numerical calculations three potential zones of an increased stress concentration were assessed, which determine the durability and fatigue life of the wheel. Their geometric qualities were identified and their local characteristic parameters were determined.

It was noticed that in welded wheels with multi-arm discs, the locations for the critical zones were the ends of the weld joints connecting the disc and rim, where a local increase in stresses occurred caused not only by the presence of the notch, but also by an uneven distribution of nominal stresses along the weld. These stresses initiated fatigue fractures which then propagated across the rim, causing the loss of the wheel integrity. It was also noticed that the value of the existing stress was determined by the thickness of the rim and that the thickness of the disc was of a smaller influence.

Based on the obtained results changes were made in the wheel construction, which were the replacement of a multi-arm disc with a full disc welded circumferentially with a decrease of its thickness, which in turn allowed to increase the fatigue life of the whole construction and lower its weight. Verification through experiment was conducted in a full scale test under radial loading. A significant quality improvement of the new construction, apart from the increase of fatigue life, was a high repetitiveness of the results of tests on every level of applied force, enabling more precise assessment of fatigue life of the structure.

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