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NON STANDARD SAMPLES BEHAVIOUR LAW PARAMETERS DETERMINATION BY INVERSE ANALYSIS

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Abstract

Electrical contact crimping is a process commonly used in aeronautical and aero spatial applications. One requirement to perform a resistant assembly is to master crimping parameters. Numerical simulation is then an efficient tool to limit tedious experimental test campaigns. Nevertheless, the numerical model accuracy depends on input data determination, such as material behaviour law parameters.

This paper deals with study done to determine material behaviour law parameters of component involved on electrical crimping process. The two samples, a strand and an electrical contact, have both small dimensions and specific shapes. For that reason, normalised tensile or compression tests could not be perform. Indeed, inverse analysis is a powerful tool to determine the behaviour laws parameters. The goal is to precisely model the sample mechanical solicitation. A series of computations is launched with various rheological parameters. By comparing experimental and simulated results, the goal is to minimize a cost function.

Thus, the first step of the study has been to determine experimental tests to perform in order to gather the force/displacement experimental data. The copper strands have been studied in compression, with a micro indentation device. A 60N force sensor has been used to acquire force data, whereas an inductive displacement sensor has been used for displacement acquisition data. The 60N force sensor is too weak to crush completely a copper contact. For that sample, we decided to use an instrumented crimping plier. A series of crimping tests has been performed on empty barrel, and the equivalent simulation has been done.

With the best copper strand material parameters set, relative errors between experimental and simulated copper strand data finally amount to 6.9% (lower than the 8% experimental data scattering). On the other side, with the best copper contact material parameters set, the cost function amounts to 4% (lower than the 7% experimental data scattering). This study allows to determine material parameters sets which are use to simulate efficiently the crimping process.

Key words: crimping, finite element computations, inverse analysis, automatic optimization

1. INTRODUCTION

Safety in the air transport is directly linked to the wiring harness quality. The reliability of the assembly is an overriding concern. These links are performed by crimping, which is a process based on the compression (no weld) of two items: the wire and the contact. Figure 1 shows parts at the beginning and at the end of the crimping process.

Generally, the holding quality is determined by testing the assembly resistance through tension tests. The link should resist to a minimal force defined in standards. These tensile tests allow to determine the most efficient crimping parameters, such as indentation depth for example. Today, the industrial partners would like to use numerical simulation tools to shorten experimental campaigns and evaluate mechanical efficiency of different crimping geometries or configuration.

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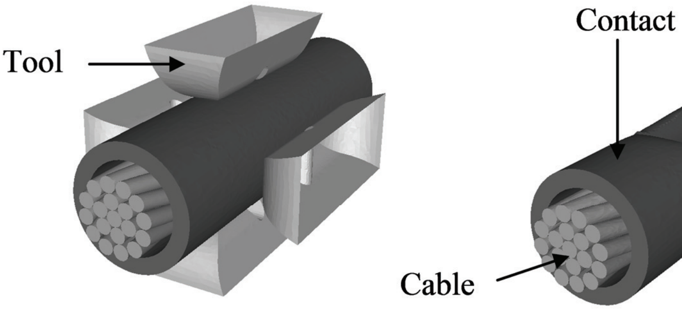

Fig. 1. Crimping model (initial and final state of the matter).

After modelling various crimping configurations, tension tests simulations will be done. Geometries and physical fields will be exported from crimping simulations to wrenching simulations. The goal is to predict the crimping force and the breaking load. Furthermore, the use of numerical analysis allows to study the impact of uncontrollable parameters during an experimental study: contact dimensions, materials grades, stripping defects, etc. Understanding and prioritization of factors impacting the mechanical strength performance will be performed.

2. CRIMPING MODEL AND RELATED INVERSE ANALYSIS

2.2. Computational software applied to crimping model

Many numerical studies of electrical crimping have been conducted since 1995. S. Kugener (1995) studied for the first time the crimping process in 2D. This assumption limits the number of degrees of freedom. It allows to deal with reduced computation time. However, the material flow in the third direction is completely neglected. Zhmurkin et al. (2008) made the first three-dimensional study of this assembling process. However, none of this work defines precisely the type of used rheological law. The only mention of elastoplastic behavior is found.

The computational software used for this study is the commercial version of Forge®. This software is specialized in forming process simulation such as forging or rolling for example (Chenot, 1989). It has also been used to simulate assembling processes such as riveting, self-pierce riveting (Fayolle et al., 2007) and clinching. Forge® computations are based on tetrahedral meshes (in the 3D version used here). This kind of mesh allows the use of an efficient automatic remeshing method (Coupez et al., 2000). It allows then to simulate large material deformations. The use of parallel computing for 3D models is also possible. Indeed, the software uses the MPI library coupled with a powerful partition calculator (Digonnet & Coupez, 2003).

A mixed finite element formulation is used on these meshes. Velocity and pressure are the discrete unknowns of the mechanical problem. To ensure computation stability, P1+/P1 elements with a bubble component are used (Chenot, 1989).

K. Mocellin et al. (2010) performed a simulation study on the crimping process and the mechanical holding of crimped contacts. In this article, the copper rheological parameters are gathered from a database, for both contact and wire. The study concludes that both the kinematics and the material behavior are correctly predicted. Nevertheless, the simulated force curves do not match to the experimental crimping force curves. It is important to determine the parameters values of the behavior laws as precisely as possible. Both the good prediction of crimping force values and the breaking mode determination (breakage or slippage) depend on it.

2.2. Inverse analysis with Forge®

The small sample sizes is one of the challenges of our study (less than a millimeter). Then, it is impossible to extract samples of components to perform mechanical standard tests in tension or compression. It is also impossible to consider samples of the same material in bigger billets because of specific properties coming from different heat treatments, hardening, etc. To overcome these difficulties, tests devices has been adapted to the size and geometry of components. Moreover, inverse analysis has been applied. This approach has already been used in assembly processes study (Fayolle, 2008).

The inverse analysis is based on the minimization of the gap (indicated by a cost function) between experimental and computed data (extracted from a simulation equivalent to the mechanical test). The different computed cases are generated using an algorithm based on neural network approach. The used cost function is the relative error in least squares sense. It should therefore achieve:

- experimental results from instrumented industrial or laboratory tests,
- a corresponding simulation of these tests to generate the same type of data (curve, sensor, ...).

In our study, force/displacement curves are taken into acount. Meticulous testing and proper analysis of the experimental data have been achieved.

Automatic optimization with Forge 2009 is an innovative approach to work. The software uses a meta-model algorithm with an assisted evolution strategy (MAES) (Emmerich et al., 2002). The capability of the algorithm associated with Forge has been particularly demonstrated by Ducloux et al. (2010) on several identification configuration.

The MAES algorithm is coupled with finite element software. It automatically generates the successive sets of parameters. The evolutionary algorithm is divided in three operations: selection, recombination and mutation. The MAES algorithm has been combine with a Kriging meta model, which has been studied by Emmerich et al. (2002). It has allowed to reduce the number of assessments and the analysis cost itself.

3. COPPER STRANDS STUDY

The first sample is a 0.15 mm diameter copper strand. It is used in a 19 twisted strands cable. Even if the anisotropic behaviour of strands is not taken into account in our models, it may be different in the longitudinal or transverse direction. In a tensile test, the strand break occurs at a deformation level (40%) lower than the deformation level in compression tests (over 100%) or during the crimping process. Considering this truncated deformation range may lead to an inaccurate prediction of behavior law. A specific testing device has been then developed. It has been designed by taking into account our samples and the stresses encountered during the process.

A radial compression test has been done to sollicitate the matter as a crimping. Considering the sample size, conventional devices are not suitable in terms of force sensors and control displacement. A micro indentation device has been adapted. The Vickers jaw has been replaced by a 0.5 mm radius half cylinder. The cylinder radius of curvature is approximately the same order of magnitude than a crimping tool jaw. The micro indentation is equipped with a 60N force sensor and an inductive displacement sensor. The second one allows to control one micrometer order displacements. It is therefore perfectly suited to the compressive stress of copper strands. Figure 2 shows the developped device.

Ten compression tests have been performed on the strands to demonstrate the measurements reproducibility. Figure 3 is a graph showing all the experimental curves and the average experimental curve (black). The discrepancy between the lowest and the highest curves is around 8%.

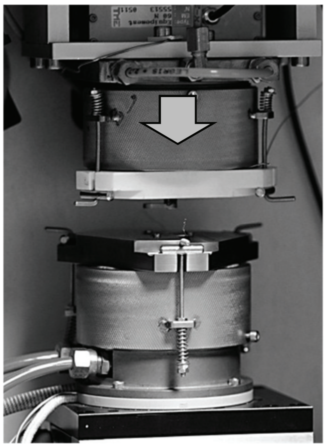

Fig. 3. *Modified micro indentation device.*

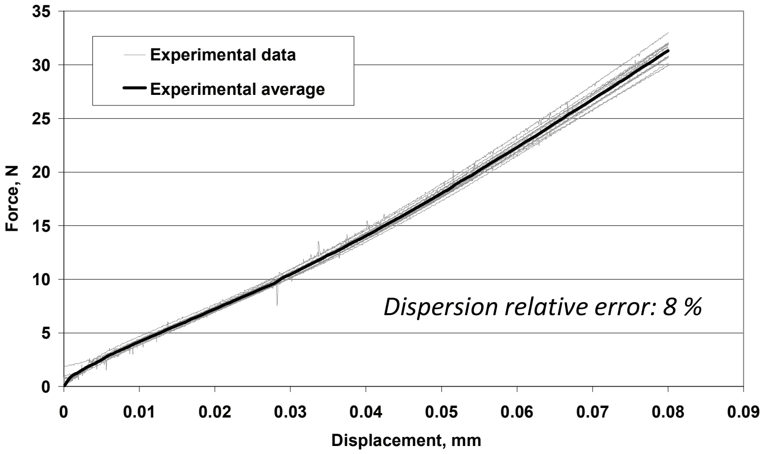

Fig. 2. *Experimental results of copper strands compression tests.*

The simulation of the experimental compression test was the next step. An elastoplastic behavior with linear power law was considered, following the equation 1:

$$\sigma = \sqrt{3}K(1 + a.\varepsilon_p{}^n) \qquad (1)$$

with the consistency K, and hardening parameters a and n. K is assimilated to a threshold stress in MPa. As the power law (Swift law), the linear power law is used to model the behavior of mild cold metals (Fayolle, 2008).

Figure 4 shows the model used for the inverse analysis. The use of a symmetry plane in the transverse direction reduces significantly the computation time. The number of nodes is around 10300 whereas the number of elements is around 42000.

In figure 5, the strand at the end of compression is shown. A mirror effect is applied to view the entire strand, even if only half of the problem is modelled.

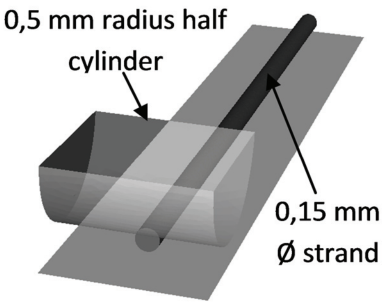

Fig. 4. *Strand compression inverse analysis model.*

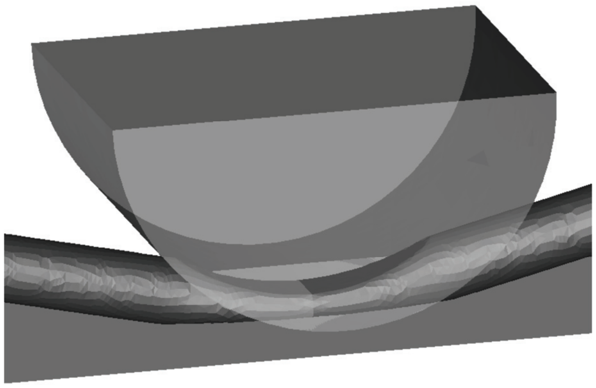

Fig. 5. *Strand shape at the compression end.*

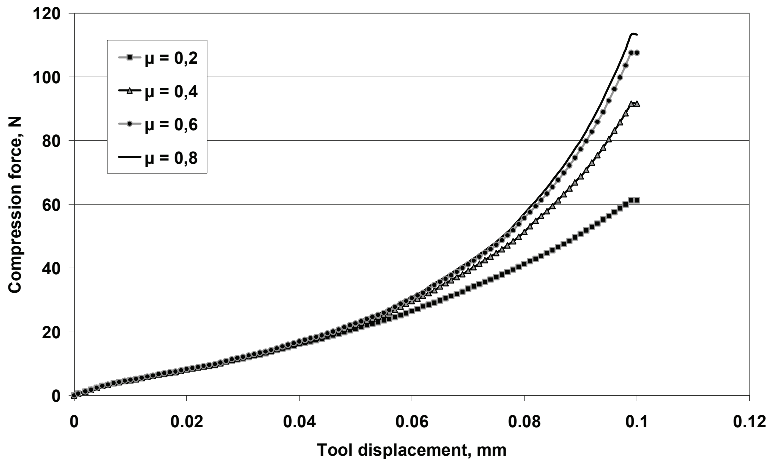

Fig. 6. *Comparison of strand compressive forces for different values of μ Coulomb coefficient.*

By optimizing only with K, a and n parameters, the inverse analysis do not provide good results. Another parameter has to be determined to improve the model: the Coulomb friction coefficient μ between the tools (steel) and the copper wire. Dozens values can be found in the literature. Zambelli and Vincent (1998) explain that the Coulomb coefficient between two metals varies generally from 0.3 to 1.5. However, they define the friction coefficient copper/copper from 0.4 (for force lower than 10^{-2}N) to 1.8 (for force greater than 10^{-1}N). These levels generate the breakdown of the surface oxide layer, hence the increase of the μ value. Under the same conditions, F.P. Bowden and D. Tabor (1964) vary this coefficient from 0.7 to 1.2. To evaluate the sensitivity of our problem in this setting, the compression force curves for four values of μ has been compared. Figure 6 shows the study results.

The μ friction coefficient impact is important according to the figure 6 force/displacement curves. The add of the μ coefficient as an optimized parameter has provided an accurate solution. Table 1 contains the best determined parameter set (K, a, n and μ) for the strand study.

Table 1. *Rheological parameters and friction coefficient values obtained by inverse analysis for the copper strand.*

Parameters	K (MPa)	a	n	μ
Values	98	1.28	0.46	0.37

CPU time for each computation is around 18 minutes on 4 processors. Figure 7 allows to observe the average experimental curve and simulated curve obtained with this parameter set at the end of inverse analysis.

The relative error between experimental and simulated curves is about 6.9.%. The percentage is lower than the experimental tests dispersion. Young's modulus E was not included as a variable. It has been communicated by the cable providers. For this sample, E is equal to 50.000 MPa. The value of the μ coefficient (0.37) is consistent with typical friction coefficient values between two non-lubricated metals.

4. COPPER CONTACT STUDY

The second component we have studied is a copper contact. This contact has a hollow cylindrical shape. The strippered wire is inserted before performing the crimping with the appropriate plier. Due to its millimeter range size and shape (see figure 10), the study of copper contact was difficult. Performing tests with the micro compression machine is impossible because the effort is too high. Moreover, the conventional testing machines are, conversely, oversized. The identification study by inverse analysis has been based on instrumented crimping tests. These tests has been done without any wire inside the contacts. An instrumented crimping plier provides experimental force/displ. curves on the plier jaws.

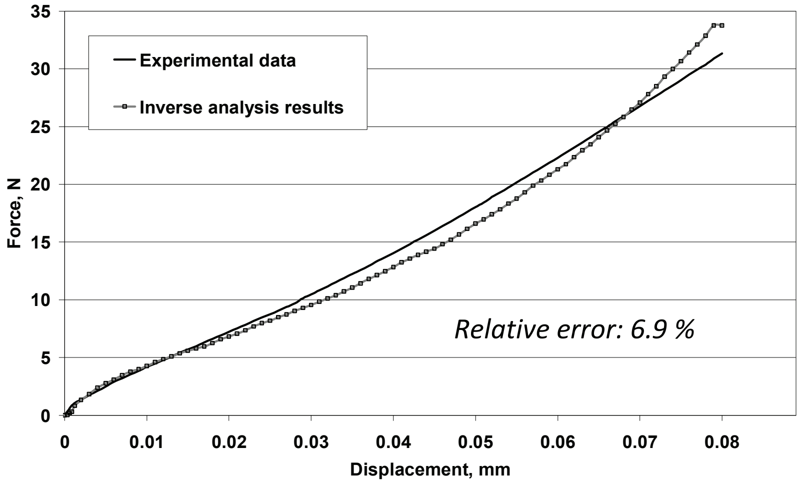

Fig. 7. *Comparison of experimental and simulated curves for a copper strand compression test.*

Figure 8 is a graph which superimposed all the force/ displacement curves obtained by crimping on empty barrel. The average experimental curve is also drawn. The relative error between the two extreme curves is around 7%. The tests dispersion is also relatively low.

Figure 9 is a contact picture after crimping on empty barrel. Figure 10 shows simulation pictures of the inverse analysis model. To reduce the computation time, a quarter barrel is designed and the studied contact length is limited to the deformed area. The number of nodes is around 13000, whereas the number of elements is around 58000.

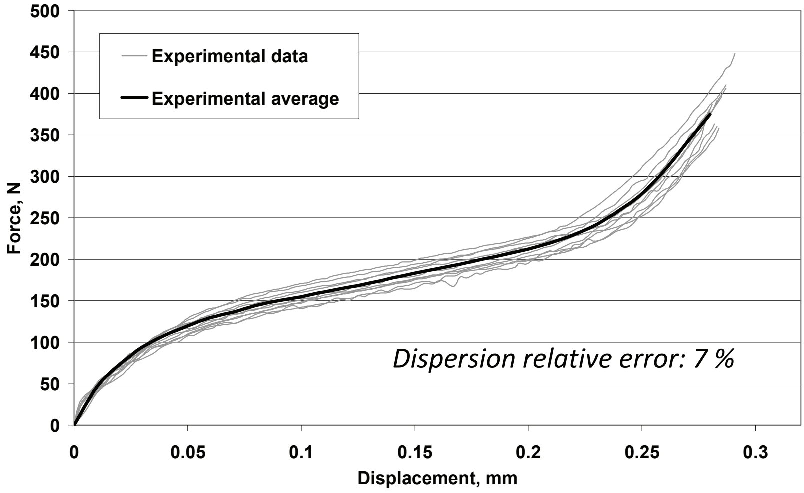

Fig. 8. *Experimental tests results of crimping on empty contact.*

Fig. 9. *Contact shape after crimping.*

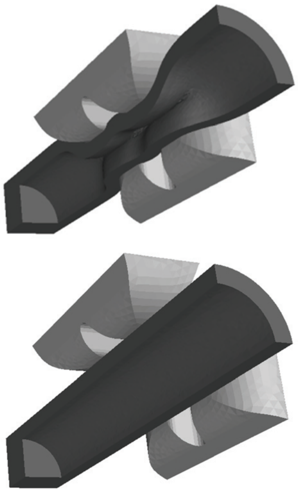

Fig. 10. *Inverse analysis model of a crimping on empty barrel test.*

Figure 11 is a graph which superimposed the average experimental curve and the simulated curve obtained with the inverse analysis model. The simulated curve was also obtained by using an elasto-plastic behaviour with linear power law strain hardening. The μ coefficient was introduced as an optimized parameter. CPU time for each computation is around 30 minutes. Final parameter values are given in table 2.

The inverse analysis provides a good correlation between the average experimental curve and the simulated curve. The relative error (4%) is lower than the experimental tests dispersion error (7%). The behaviour law parameters are determined and will be added into crimping models for the future assembly process studies.

Figure 12 is a graph superimposing the cost function evolution during the 80 computations, for both the strand and the contact inverse analysis. As a conclusion, the cost function is sharply enough stabilized. In both cases, after 30 computations, cost function is approximately the same than after 80 computations. The algorithm which creates the parameters sets is efficient.

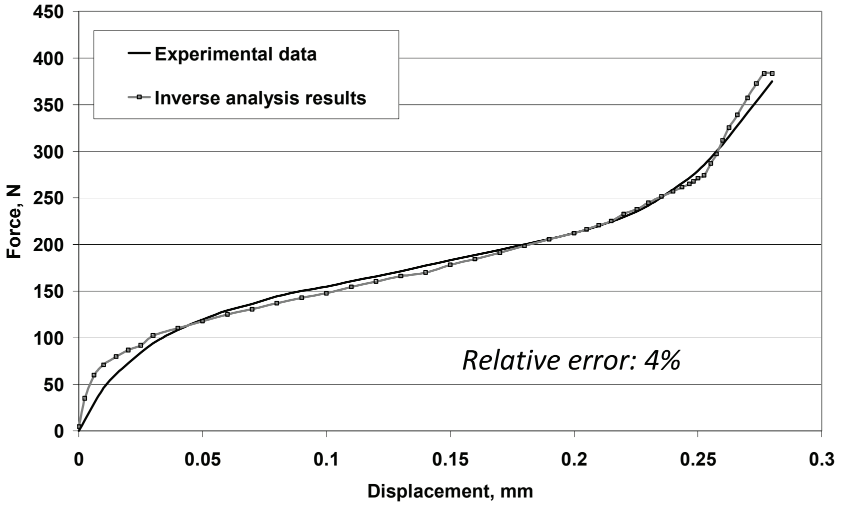

Fig. 10. Experimental and simulated force/displacement curves comparison for the contact study.

Table 2. Rheological parameters and friction coefficient values obtained by inverse analysis for the electrical contact.

Parameters	K (MPa)	a	n	μ
Values	216	0.52	0.35	0.24

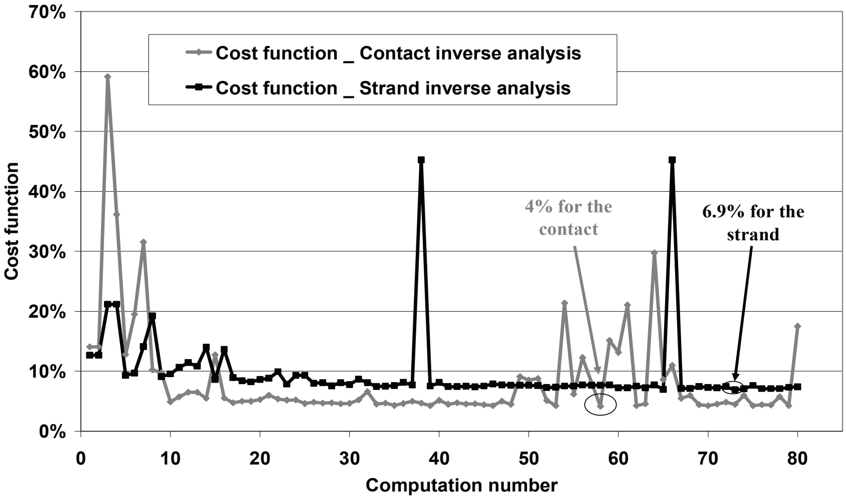

Fig. 11. Cost function evolution along both inverse analyses.

5. CONCLUSION

Inverse analysis is a powerful method to determine behaviour law parameters from unreliable experimental data. As part of our study, this type of analysis allowed to overcome the problems associated with samples small sizes and shapes. In this paper, two non-standard experimental acquisition ways have been presented. On one hand, the micro indentation device modification has enabled to load copper strands with a radial compression. On the other hand, an instrumented crimping tool has provided data from crimping on empty barrel tests.

A first numerical study has been performed to get the behaviour law parameters of the strands constitutive copper. The cost function between experimental and simulated data, which means the relative error in least squares sense, is around 6.9%. This error is lower than the 8% dispersion tests relative error. The second study, linked with contacts, has also allowed to determine the constitutive law parameters. The 4% final cost function (regarding to the 7% dispersion tests error) illustrates that the final results are satisfactory. All these data will be used in crimping models to determine the crimping force/displacement curves. It will enable to conduct a full study on this mechanical assembly process.

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ZASTOSOWANIEM ANALIZY ODWROTNEJ DO OKREŚLENIA PARAMETRÓW MATERIAŁU NA PODSTAWIE ODKSZTAŁCANIA NIESTANDARDOWYCH PRÓBEK

Streszczenie

Proces łączenia przewodów elektrycznych poprzez zaciskanie jest powszechnie stosowany w przemyśle lotniczym i kosmicznym. Poprawne przeprowadzenie zaciskania wymaga dokładnego zdefiniowania parametrów tego procesu. Symulacje numeryczne mogą znacznie zmniejszyć liczbę doświadczeń potrzebnych do wyznaczenia optymalnych parametrów zaciskania. Niemniej jednak dokładność obliczeń numerycznych zależy od prawidłowego określenia parametrów wejściowych procesu, w tym własności materiału.

W pracy przedstawiono wyniki badań nad określeniem własności materiałów używanych na zaciski przewodów elektrycznych. Ze względu na niewielkie rozmiary przewodu oraz nietypowy kształt złącza (styku), wyniki standardowych prób rozciągania i spęczania nie mogą zostać wykorzystane. Alternatywnym podejściem jest zastosowanie analizy odwrotnej do wyznaczenia własności materiałów, pozwalającej na dokładne określenie własności w analizowanym procesie. W tym celu przeprowadzono serię symulacji procesu zaciskania dla różnych modeli materiałowych. Funkcja celu, zdefiniowana w analizie odwrotnej jako różnica pomiędzy wynikami symulacji a wynikami otrzymanymi doświadczalnie, była minimalizowana właśnie ze względu na parametry materiału.

W pierwszym etapie prac określono warunki testów doświadczalnych, w których rejestrowana była siła w funkcji przemieszczenia. Dla przewodu miedzianego przeprowadzono próbę twardości metodą wciskania mikro wgłębnika. W testach wykorzystano czujnik siły do 60N oraz czujnik indukcyjny do rejestracji przemieszczenia. Czujnik siły okazał się za słaby aby całkowicie zgnieść styk miedzi, wobec czego dla tego elementu zastosowano szczypce ściskające. Przeprowadzono zarówno serię doświadczeń oraz symulacji numerycznych ściskania próbki rurowej wzdłuż promienia.

Dla najlepiej dopasowanego zbioru parametrów określającego własności przewodu miedzianego, błąd względny pomiędzy doświadczeniem a wynikami obliczeń był na poziomie 6.9% (mniejszy niż 8% rozrzutu danych doświadczalnych). Natomiast dla najlepiej dopasowanego zbioru parametrów określającego własności miedzianego styku, funkcja celu miała wartość 4% (była mniejsza niż 7% rozrzutu danych doświadczalnych). Przeprowadzone w ramach pracy obliczenia pozwoliły na określenie zbioru parametrów niezbędnych do efektywnej symulacji procesu zaciskania.

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