MODAL FREQUENCY ANALYSIS AND DIAGNOSTIC OF FRICTION-WELDED BIMETALLIC ELEMENT WITH CYLINDRICAL ROD DESIGN

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ABSTRACT

The modal frequency analysis is based on registration of the system's natural frequencies. The purpose of this work is to research and to justify the possibilities for diagnosing the equivalent amount of imperfections in friction-welded joints in a bimetallic cylindrical part by frequency modal analysis. The part is made of austenitic steel 1,4404 according to EN 10088-3 and high-carbon steel 1,0601 (C 60) according to BS EN 10083-2:2006. The strength of the friction-welded joints is comparable with the strength of steel 1,0601 (C 60). The static strength testing evidence that the bimetallic element manufactured using the proposed technology breaks through the parent metal next to the welded portion. In case of unilateral discontinuity the frequency of transversal modes in orthogonal directions is uneven. It is appropriate to introduce a new information parameter - Frequency Difference between transversal modes with deformations in Orthogonal Directions (FDOD). The degree of accuracy of diagnosis of depth is increased by the frequency factor, defined through the ratio between frequencies of modes obtained by experimental and theoretical research of parts without imperfection.

The discussed algorithm for diagnosis of imperfections by frequency modal analysis is applied for welded bimetallic element with cylindrical rod design. The results obtained using the different transversal modes are grouped in relatively close values for the depths of the imperfections.

Keywords: Diagnostic of Imperfections by Frequency Modal Analysis, Bimetallic Element

I. INTRODUCTION

The modal frequency analysis has many advantages for fast and efficient evaluation of the technical condition of manufactured products. It is used for registration of the system's natural frequencies. The deviations within the system are the reason for the alteration of the frequencies of the modes, and these are used as information parameters for diagnostics. The method is fast and highly efficient and enables to diagnose the products on different stages of their manufacture and operation, such as incoming inspection of blanks, evaluation of the technological process for preparation of some product, as well as evaluation of its condition during operation. In this study the modal frequency analysis is applied for evaluation of an intermediate technological process, i.e. friction welding of bimetallic rotary detail.

For the purpose of labeling by the customer the research team has developed technology for friction welding of bimetallic steel element with cylindrical rod design. The welding is realized through plasitfication of the joined surfaces due to the friction forces between them from pressing during their relative motion. Thereby the increase of the growth of grains in the high-strength thermo-mechanically processed steels is prevented. Generally, precise preparation is not required since the dirt is removed during the relative movement. The pieces for welding have heads with diameter 16 mm. The parameters of the welding mode are: rotational speed 1400 min^{-1}, time for welding 5-7 s. The pressing effort is induced by a hydraulic cylinder with controllable pressure. After welding, the surface around the weld joint is roughly turned and then the piece is finally grinded. Upon customer's request, the working part of the piece is made of austenitic steel 1,4404 according to EN 10088-3 and the gripper is made of high-carbon steel 1,0601 (C 60) according to BS EN 10083-2:2006. It was found during our preliminary studies on the welding technology that some samples have non-welded portions which remain undetected after turning due to the impossibility to identify visually the discontinuities in welded layers of thickness less than 10 μm . This is the reason for scrapping the pieces despite the considerable manufacture costs.

Due to variations in the technological mode, it is possible that some portions may remain not welded yet any visible evidences may be missing. Such imperfection of the welded piece is the spill within the contact area that does not come out to the surface and cannot be detected using the means for visual control.

On intermediate stage of manufacture the workpiece does not allow any access to the welded layer due to the technological allowances for the centering of the samples. Therefore, the vibro-acoustic method is preferred for quick evaluation of the condition of the welded layer.

The purpose of this work is to analyze the condition of the friction welded joint in order to create bimetallic machine element for labeling and to justify the possibilities of the vibro-acoustic method to diagnose the equivalent amount of imperfections in cylindrical rod design.

II. PRELIMINARY STUDY OF THE PRODUCT

The drawing of the typical intermediate product (without technological allowances) is shown in Fig. 1. The workpiece have simple shape and consists of hollow cylinders symmetrical in respect to x axis, regardless of the orientation of y and z axes.

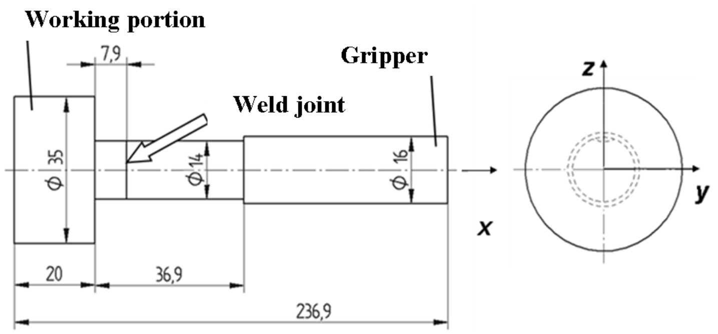
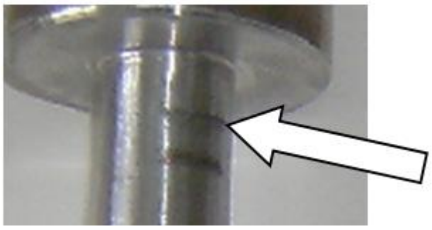
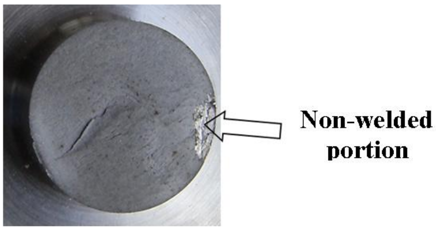


Fig. 1. Drawing of the manufactured product

The static strength of the welded joint is studied. In Fig. 2 is shown a discontinuity detected after surface machining (Fig. 2a), and image of the fractured cylindrical stem (Fig. 2 b). The fracture has fine-grain structure from the side of the gripper and a smoothed part of a poorly welded portion. The fracture initiates from the non-welded portion and proceeds within the base metal close to the weld seam. Its depth is in the range from 1 mm to 1.4 mm found in the middle of CAD. The shape of this discontinuity has been used for to model such defects in computer environment. The present study and the testing that the user carried prove that the friction welding of two elements provide sufficient mechanical strength. It is necessary to check the welded details in advance and to select the ones potentially suitable for manufacture of quality products. The criterion for assessment can be the depth of the discontinuity after turning: the admissible depth is at least equal to the tolerance for grinding; the inadmissible depth is larger than the allowance for grinding.



a)

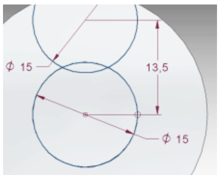


b)

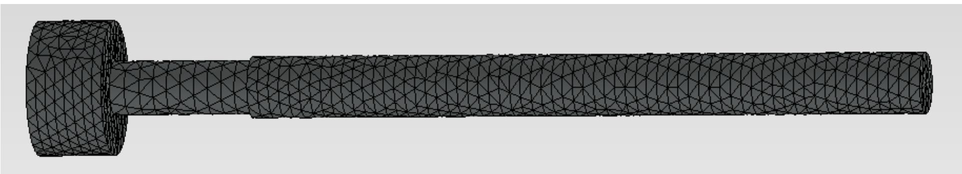
Fig. 2. View of Discontinuity (A) And Fracture After Static Strength Testing of the Welded Portion (B)

III. STUDYING THE NATURAL FREQUENCIES OF THE SAMPLE

To evaluate the capabilities of the vibro-acoustic method for the assessment of the presence of discontinuities at intermediate stage of the manufacture process, a bimetallic sample is 3D modeled in the environment of specialized software. In the zone of welding a flat discontinuity is modeled shaped as circular sector (similar to the discontinuity in Fig. 2 b), which is unilaterally positioned on the stem. The two types of discontinuities are formed with depths of 1 mm and 1.5 mm, and thickness 0.02 mm. Fig. 3 shows the assembled unit of the sample (a) and a point in the modeling of discontinuities shaped as circular sectors with depth 1.5 mm (b); annular discontinuity (c); and locally non-welded portions in the welded layer. Table 1 shows the dimensions of the modeled local non-welded portions.



a)

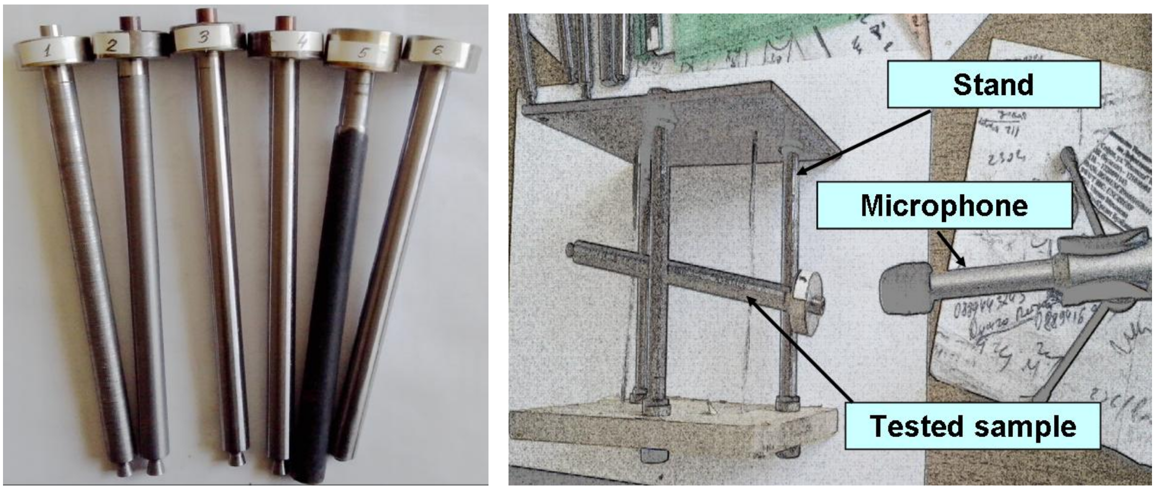


b)

Fig. 3. Modeling of Sample And Elements of the Study on Intermediate Manufacture Stage: A) Unilateral Discontinuity; B) A Point in the Division of the Sample into Finite Elements

The effect of the size of the discontinuity on the value of the natural frequency of the sample is evaluated using engineering software upon the method of finite elements (FEA). For the purpose, for the generated 3D model is specified material and is then divided into finite elements with maximum size 3.94 mm. A point in the division of the sample into finite elements is shown in Fig. 3 (b). Both the value of the modes and their shapes are obtained automatically. As per [1], the machine element shown deforms in a plane, which defines the minimum energy for deformation in orthogonal direction too. This approach is embedded in different algorithms for theoretical determination of the natural frequencies. The presence of discontinuity in the layer evokes a total alteration of the frequencies of the modes. Meanwhile, there is an asymmetry in the variation of the moment of inertia of bending in the plane y-z, and hence the frequencies of the oscillations in the transversal modes in orthogonal planes. Therefore, the introduction of an additional information characteristic based on the frequency difference of oscillations in orthogonal directions for a mode will allow in reverse to determine the depth of the discontinuity. It is convenient to evaluate this characteristic theoretically with consideration of the difference between the theoretical and the experimental results for the frequencies of the modes.

This work discusses the experimental study of six samples (Fig. 4a) numbered from 1 to 6 with similar shape. The samples are tested in laboratory conditions after placing on soft threads involved in the specialized test set. Some imperfections are visually detected in part of the samples. Free vibrations are excited within the samples through application of impulse effort on the head. The dynamic behavior of the samples is measured through registration of the sound pressure using acoustic microphone with linear characteristics in the range 20 Hz – 18 kHz. The results are computer-recorded through 16 bit analog-to-digital converter. Statistical surveys of the confidence interval for determination of the modes are carried out. The registered values are within 1-4 Hz over the entire frequency range.



a) b)

Fig. 4. Tested Samples (A) And Laboratory Test Set (B)

In Table 1 are shown the values of the frequencies of the modes of a detail without imperfections, both the measured (f_E) and analytically obtained by FEA (f_{FEA}). In Fig. 5 are shown the elastic deformations of the detail at different modes. For modes 1, 2, 4, 5, 8, and 9 there are bending (transversal) deformations of the cylindrical stem. Therein the detail deforms in identical manner in the planes x-y and x-z (Fig. 1). For the modes 3, 7 and 10 the deformations stretch in radial direction of the cylindrical stem, and for 6 and 11 they are in axial direction. Available is data that experimentally prove all modes except 7 and 10. There are some discrepancies between the theoretical and the experimental frequencies of the modes. The reason for this discrepancies is attributed to some deviations between the elastic properties and the density of the incoming data for simulation studies and to some particularities in the application of numerical method, such as lack of consideration of all geometric dimensions, the size of the elements, the anisotropy of the materials, and others [4].

Table 1. Frequencies of the Modes of a Detail without Discontinuity

Mode No,	Frequency Hz										
	1	2	3	4	5	6	7	8	9	10	11
Simulation f_{FEA}	1024	2829	4204	5333	8394	8555	10264	12539	17368	17753	17944
Experiment f_E	1066	2923	3919	5439	8529	8712	-	12789	17529	-	17644
Δf	42	94	-285	106	135	157		250	161		-300
η	3.94	3.22	-7.28	1.94	1.58	1.80		1.95	0.92		- 1.7

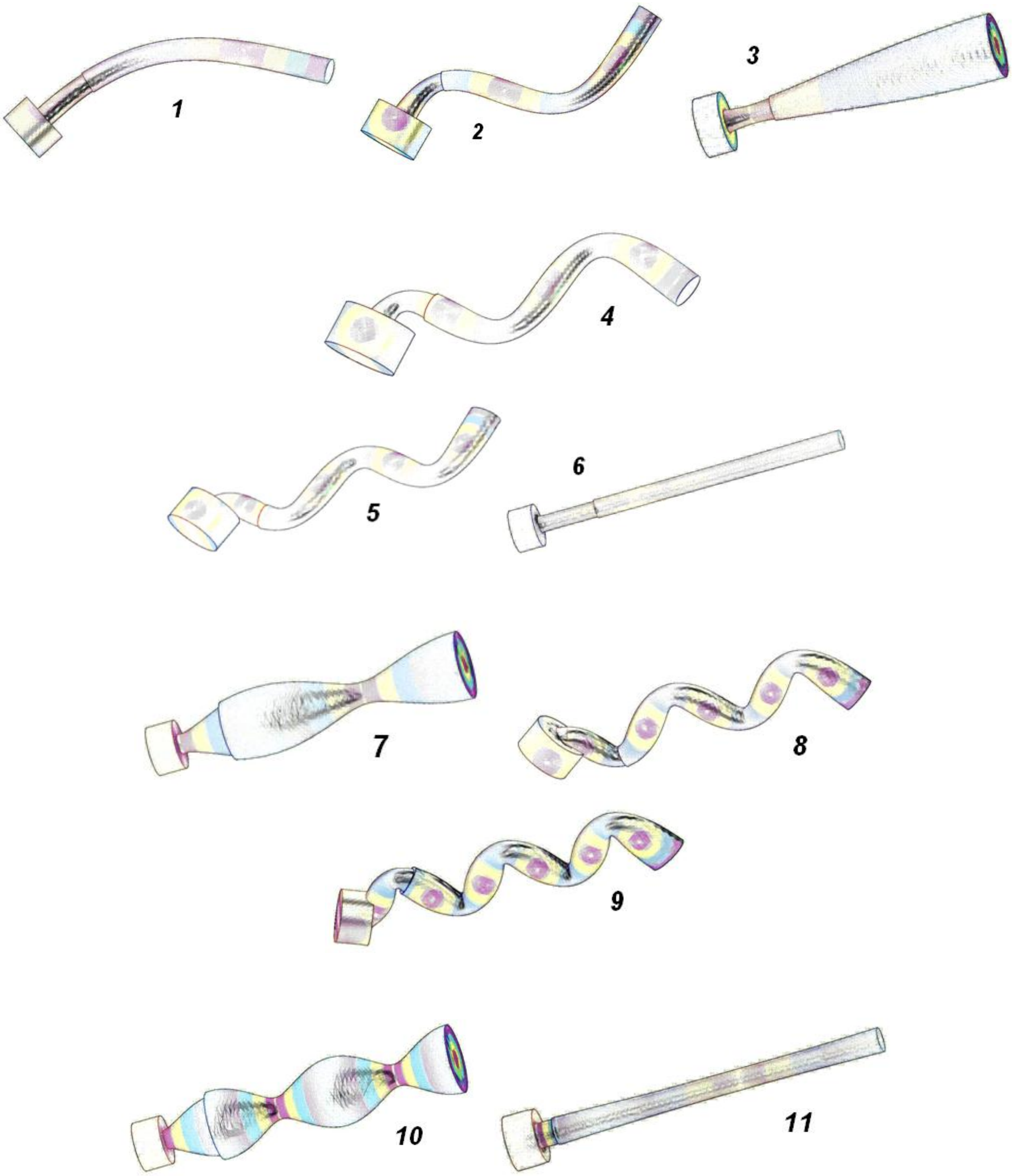


Fig. 5. Elastic Deformations at Modes 1 To 11 (the Numbers Correspond to those in Table 2)

The values of the modes of the bimetallic element on condition for absence of discontinuity $f_{n,0}$ and at modeled discontinuities $f_{n,\delta}$ for mode n are obtained through simulations. The difference for the corresponding mode n is estimated upon the equation:

$$\Delta f_n = f_{n,0} - f_{n,\delta} \quad (1)$$

Numerical results are obtained for Δf_n (Fig. 6). The maximum variation of Δf_n is found within the range 2 – 4 Hz for some modes at depth 1 mm of the non-welded portion, within the range 13 – 16 Hz at depth 1.5 mm, and up to 110 Hz at depth 3 mm. The variation is not steady over the modes. The maximum variation of Δf_n is obtained for modes 4, 5, 8, and 9, which generate transversal vibration in the detail.

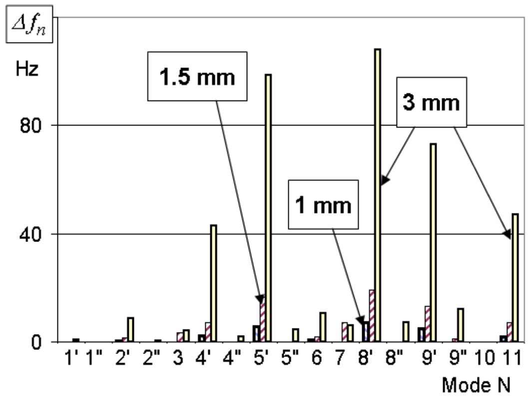


Fig. 6. Typical Results for Δf_n for non-Welded Portion with depth 1 mm; 1.5 mm; and 3 mm.

IV. AN APPROACH TO DIAGNOSE THE SIZE OF THE DISCONTINUITY IN THE LAYER

In presence of discontinuities, there is a deviation of the moment of inertia of the cross section in the area of the discontinuity and the requirements for validity of the above relationships are not observed. The expectations are that the variation of the frequency of the mode will depend not only on the size of the discontinuity but on its position in the detail too. Since the frequencies of the modes in the two mutually perpendicular planes are independent, in the case of unilateral discontinuity we expected a difference between the frequencies of vibrations in the different planes. The deformation behavior of the detail will depend on the size and the position of the discontinuity for and will be different in the different directions for the same mode. These more general conclusions are used to carry out the following studies.

4.1. Comparison Between Frequencies of Modes Obtained Using Different Research Approaches

Obtained are theoretical values f_{FEA} of the modes through analytical expressions as per (2) and using FEA. The resonance frequencies f_E excited through the application of impulse on the detail of the same geometrical dimensions are measured experimentally. Both ways of estimation of the modes are based on the assumption that that the material is the same, i.e. tool steel 1.0601 (C 60) under BS EN 10083-2:2006, and the structure is isotropic. The frequency differences Δf are estimated and their relative value η between the modes are determined both experimentally and theoretically (including through FEA), as well as the theoretical valued as per the dependencies:

$$\Delta f = f_E - f_{FEA} \text{ and } \eta = \frac{\Delta f}{f_E} \quad (2)$$

The results for Δf and η obtained are shown in Table 1. the convergence achieved during the calculation of the modes' frequencies through FEA of the values within the range from 0 Hz to 0.4 Hz for modes 1 and 2, and from 1 Hz to 3 Hz for modes 4 and 5. The experimental values of the frequencies are obtained with accuracy of ± 2 Hz over the whole range of measurement.

The results indicate that there is a frequency deviation Δf of the modes obtained under the different approaches. There is a certain consistency observed in the variation of Δf for all comparative assessments. The similar conclusion may be drawn for the relative variation η of the frequencies. A significant difference in the values of Δf and Δf_{FEA} is observed and it is larger than the frequency of variation of the modes due to the presence of non-welded portion. Consequently, the theoretical approaches shall be applied in a more general sense for assessment of the variation of the modes due to the presence of discontinuities, but not directly to estimate the size of the discontinuities. It is necessary to consider the difference both in absolute and relative units in order to enhance the accuracy with which the characteristics evaluated using FEA are specified. This consideration may be carried into effect by means of the coefficient $K_\eta(f)$ of discrepancy between the frequencies of the modes obtained either experimentally or using FEA, and namely:

$$K_\eta(f) = \frac{f_E}{f_{FEA}} . \quad (3)$$

4.2. Behavior of the Transversal Modes in Presence of Discontinuity

The presence of surface discontinuity evokes a substantial alteration of the moment of inertia in the different directions of deformation, which alters the frequency of the transversal modes. In the case of an axially symmetric detail, the resonance generated in the area of the transversal mode n will results in registration of resonance with frequency f_n (Fig. 7 a). In the case of unilaterally positioned discontinuity, a second amplitude will occur. The two amplitudes will have frequencies f_n' and f_n'', and frequency difference $\Delta f_{n,t} = f_n' - f_n''$ (фиг. 7 b) will occur between them. The discontinuity changes the moment of inertia of the cross section in both directions, thus the vales of f_n' and f_n'' will differ from the frequency f_n of the mode n before the disruption of geometric integrity. What they have in common is that both amplitudes occur in a narrow frequency range and depend on similar factors, e.g. elastic and geometric characteristics of the detail, including such with accounting for possible deviations from the anisotropy of material on general and local level, securing of the detail, and to a large extent, on the method for calculation the results too.

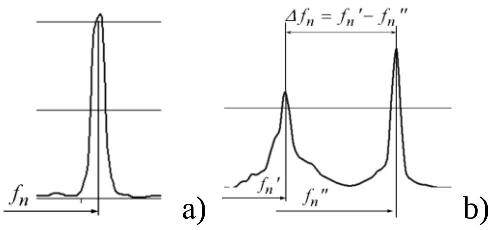


Fig. 7. Image of the Mode for a Rod with Cylindrical Cross Section Without (A) and with Discontinuity (B).

The calculations show that there is a direct correlation between the depth x of unilaterally positioned crack in the welded layer and the frequency difference between the transversal modes $\Delta f_{n,t}$ of the type:

$$\Delta f_{n,t} = a.x^2 - b.x + c \quad (4)$$

In Fig. 8 is shown the variation of $\Delta f_{n,t}$ for the transversal modes from the depth of the discontinuity x in the welding zone of the studied sample. These dependencies are described through the approximating equations (5). Here R^2 is the square of the coefficient of correlation. The variation $\Delta f_{n,t}$ of the modes is more significant in presence of discontinuities of depths 1.5 mm and 3 mm. For discontinuity with depth less than 1 mm, $\Delta f_{n,t}$ is found to vary within 1 Hz. The frequency difference $\Delta f_{n,t}$ depends on the number of the mode, therefore it is appropriate to chose a mode with significant variation $\Delta f_{n,t}$ in order to improve the accuracy with which the depth x is evaluated. It is appropriate to compare the results for the depth of the imperfection obtained through different transversal modes.

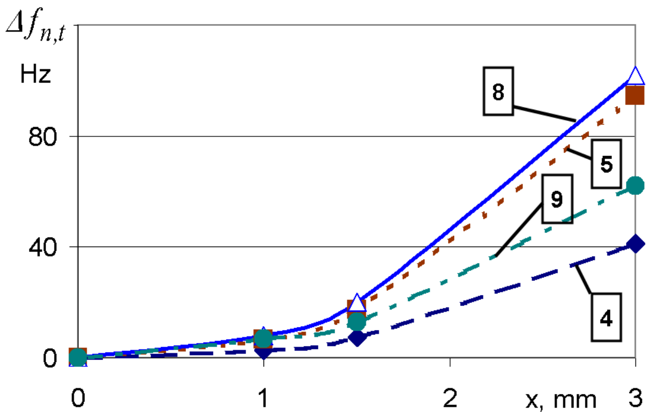


Fig. 8. Dependencies of $\Delta f_{n,t}$ on the Depth x of the Discontinuity for Modes No 4, 5, 8, and 9

The approximating curve for mode 1 is obtained too but is not shown here since it doesn't have any significant application for the determination of the discontinuity. According to the probability theory, the values for R^2 may be defined as "good" and "very good" correlation.

$$\Delta f_4 = 5.6867.x^2 - 3.4073.x + 0.0947 \text{ at } R^2 = 0.9997 \quad (5)$$

$$\Delta f_5 = 12.96x^2 - 7.472x + 0.184 \text{ at } R^2 = 0.9998$$

$$\Delta f_8 = 13.467.x^2 - 6.4933.x + 0.1867 \text{ at n } R^2 = 0.9998$$

$$\Delta f_9 = 7.5333x^2 - 2.0733x + 0.28 \text{ at } R^2 = 0.9988$$

The correlations for modes 1, and 2 obtained are not shown because of their lack practical significance.

The difference between the theoretical and the experimental frequency is accounted for by the factor $K_\eta(f)$, which means that the adjusted value $\Delta f'_{n,t}$ of the theoretical value is determined towards the experimental one upon the dependence:

$$\Delta f'_{n,t} = K_\eta(f).\Delta f_{n,t} \,. \quad (6)$$

The inverse function of this expression gives the dependence of x on $\Delta f_{n,t}$ as follows:

$$x = a.\Delta f'^{2}_{n,t} + b.\Delta f'_{n,t} + c \text{ , at } R^2 = d \quad (7)$$

V. DIAGNOSTIC OF IMPERFECTION IN THE WELDED LAYER

The approach described for estimation of the depth of the imperfection is applied for the samples shown in Fig. 4 a). The samples are tested through identical impulse excitation. The typical experimental results for samples with or without discontinuity are shown in Fig. 9 a) and b). The theoretical results obtained through FEA are confirmed. The frequency difference $\Delta f_{1,t}$ for mode 1 is minimal and is note registered by the experiment. The frequency difference $\Delta f_{n,t}$ for modes 4 and 8 (as well as others not shown herein) is easily noticeable through experiment.

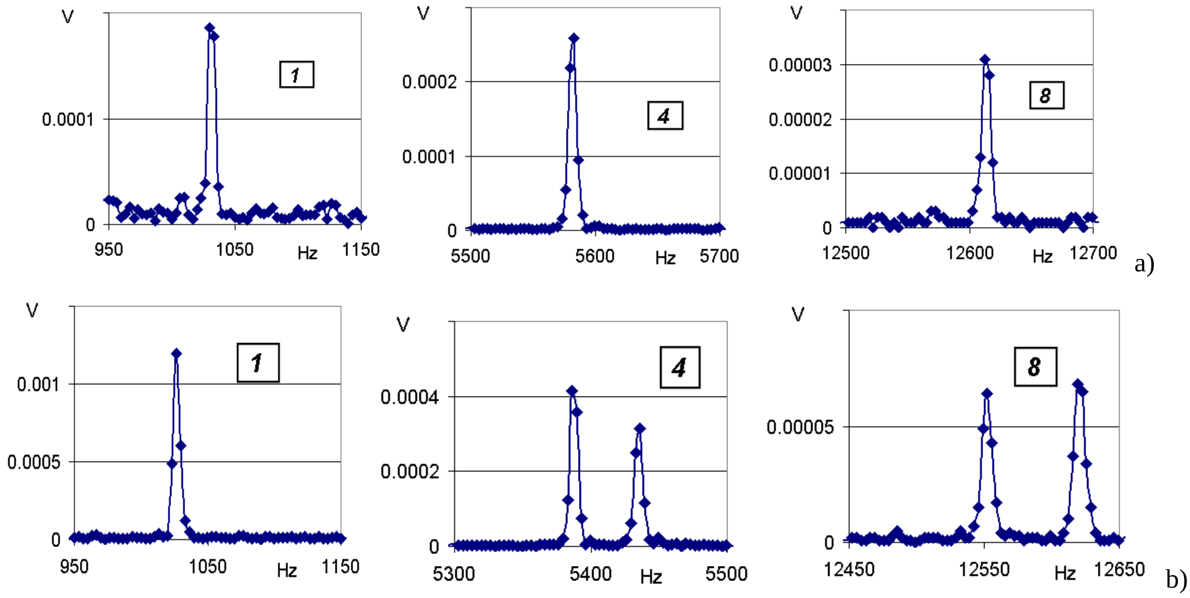


Fig. 9. Typical Experimental Results for Sample without (a) and with (b) Discontinuity

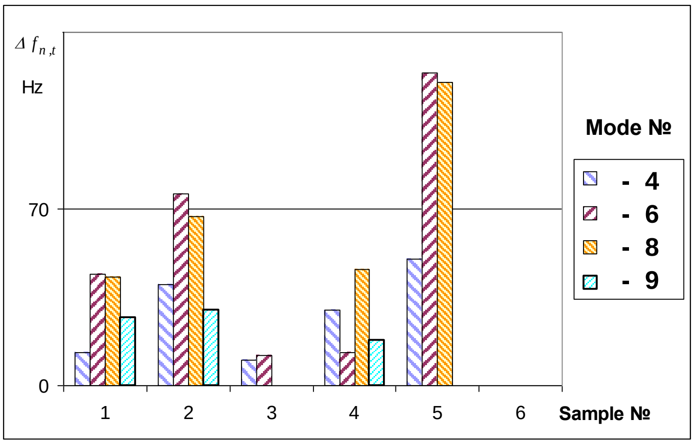


Fig. 10. Results for $\Delta f_{n,t}$ from Experimental Studying of Samples No 1, 2, 3, 4, 5, and 6

Table 3. Results for Equivalent Depth of Discontinuity Estimated Using the Values of Δf_n for the Transversal Modes

Mode No	Depth of the discontinuity, mm					
	Detail					
	1	**2**	**3**	**4**	**5**	**6**
4	1.7	2.9	1.5	2.5	> 3*	0
5	2	2.8	1.4	1.4	> 3*	0
8	1.9	2.7	-	1.8	> 3*	0
9	1.9	2.6	-	1.7	-	-

* Too high values, including such exceeding the expected size range of the discontinuity.

The results obtained using the different transversal modes are classified in groups with relatively close depths of the imperfections. The deviations in the depth of the imperfections obtained using different transversal modes are attributed to the different shapes of the non-welded sections.

VI. CONCLUSIONS

Based on the theoretical and experimental studies of bimetallic machine detail for labeling consisting of austenitic steel 1,4404 according to EN 10088-3 and high-carbon steel 1,0601 (C 60) according to BS EN 10083-2:2006, the following more significant conclusions may be drawn:

The strength of the friction-welded joints between steels with different mechanical properties is comparable with the strength of steel 1,0601 (C 60). The static strength testing evidence that the bimetallic element manufactured using the proposed technology breaks through the parent metal next to the welded portion.

In case of unilateral discontinuity the variation of the modes is uneven. It is appropriate to introduce a new information characteristic $\Delta f_{n,t}$ for evaluation of the depth of the discontinuity, which is the frequency difference between identical modes with transversal deformations in orthogonal directions (FDOD). It can be determined through analytical calculations (for example using FEA) when the depth of the imperfection consistently increases.

The degree of accuracy of diagnosis of depth is increased by the frequency factor $K_\eta(f)$, defined through the ratio between experimental and theoretical frequencies of identical modes, which do not change substantially by the presence of the imperfection. This factor accounts for both the specificity of the method of calculation of the modes, and the mechanical properties of the elastic medium. Therefore the actual value $\Delta f'_{n,t}$ of FDOD accounting for the factors of deviations is determined by the dependence $\Delta f'_{n,t} = K_\eta(f).\Delta f_{n,t}$.

The depth of the imperfection x is evaluated through an inverse function of the type $x = a.\Delta f'^{2}_{n,t} + b.\Delta f'_{n,t} + c$, as more than one transversal mode can be used for more credible results, and respectively to register more values for $\Delta f'_{n,t}$ during a single testing.

The discussed algorithm for diagnosis of imperfections by frequency modal analysis is applied for welded bimetallic element with cylindrical rod design. The results obtained using the different transversal modes are grouped in relatively close values for the depths of the imperfections. The deviations of the depths evaluated using the different transversal modes are attributed to the different shapes of the non-welded portions.

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