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# Welding in Vibration Conditions – Critical Approach

**Abstract:** Vibratory stabilisation has been used in production practice for a relatively long time now. The use of vibratory stabilisation provides technical and economic advantages where high dimensional stability of welded structures is required. For many years, research magazines have been reporting of attempted welding in vibration conditions. The article provides the overview of reference publications concerned with this issue as well as presents related tests performed by the author. The publications cited in the article inform about the effect of vibration on the distribution of welding stresses, strength-related properties and on the manner of weld formation. However, varying views presented in the above-named publications do not unequivocally confirm the efficiency of welding on vibration conditions. The foregoing inspired the author to carry out research including welding tests involving ferritic steel s355 and performed in various conditions of vibration having specified frequency. The tests involved the determination of the distribution of welding stresses as well as included metallographic examinations, toughness tests and hardness measurements. The research revealed the lack of the effect of vibration on the distribution of welding stresses, hardness and toughness of welds. No changes in the microstructure of welds were observed either. The conclusions formulated on the basis of the research did not recommend, generally, the welding of ferritic steels in vibration conditions.

**Keywords:** vibratory stabilisation, welding in vibration conditions

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## Present State

The vibration-based method used to increase dimensional stability has found applications in the making of welded machinery structures. The most favourable effect as regards dimensional stability is obtained when vibration is of resonant frequency. Vibration-induced stresses accelerate processes of microrelaxation and phase transformations at ambient temperature and, as a result, delayed strains. Vibration, as it were, "provokes" strains so that, after mechanical treatment, structures do not undergo unallowed deformations. When selecting structures to be subjected to vibratory stabilisation it should be noted that the vibration-triggered reduction of welding internal stresses is insignificant [1-5].

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The procedure of vibratory stabilisation should be applied in the making of structures which after welding are subjected to thorough machining. Vibratory stabilisation should not be used in cases of structures requiring the reduction of internal stresses (e.g. pressure vessels, pipelines or structures, where the reduction of internal stresses conditions an increase in fatigue service life or corrosion resistance). The use of vibration procedures leads to the obtainment of dimensional stability close to that obtained through (natural) stabilising.

Vibratory stabilisation has fully established itself as regards machine building technologies, yet information concerning the use of mechanical vibration during welding is relatively new, arousing both interest and doubts and, as a result, requiring necessary clarification. Available scientific reference publications present the use of vibration technique in welding processes. The process of welding in vibration conditions is referred to as vibration welding (VW). Vibration welding should, allegedly, affect the process of weld solidification and, consequently, the size of grains. It was noticed that vibration supposedly increased the rate of crystallisation, decreased the size of subgrains and increased impact energy [6]. It was confirmed that the vibration welding of thick-walled steel cylinders led to an increase in impact energy during an impact strength test (only in the weld material) and to the obtainment of a greater bend angle (during a bend test) [7]. The confirmed vibration welding-triggered increase in impact energy was ascribed to more favourable thermal conditions in the heat affected zone [8]. The process of vibration welding performed at a frequency of 80 Hz led to the refinement of grains in the weld zone, thus improving mechanical properties of the area [9]. The use of vibration having a frequency of approximately 18 kHz during repair welding reduced welding stresses by approximately 20% [10]. Vibration performed at ultrasonic frequency was responsible for the refinement of the structure of a weld made of austenitic steel 316L. It was noticed that the content of columnar dendrites decreased from 95% to 10% [11]. The vibration welding of structural steel performed at frequency restricted within the range of 0 to 300 Hz and displacement amplitude restricted within the range of 0 to 30 μm led to the refinement of grains. The greater efficiency of the process was observed in relation to lower frequency values [12]. The casting of aluminium alloys performed using mechanical vibration was accompanied by the favourable refinement of the structure [13]. The effect of mechanical vibration was tested during the welding of alloy Inconel 82. The process of vibration welding was performed at a frequency of 48 Hz (subresonant) and that of 58 Hz (resonant) at an amplitude of 38 μm and 89 μm respectively [14]. The post-weld changes included differently directed dendrites in the structure and a decrease in hardness of the specimens subjected to the process of vibration welding. A significant amount of information is available in the form of Internet publications, provided particularly by companies offering vibration systems. One of more active is the Bonal company (USA) [15] presenting, among other things, the technology of vibration welding in extensive, undoubtedly promotional, materials which, for the above-named reason, should be treated with duly sceptical care. Mostly, the cases presented in the materials are concerned with applications of vibration welding in relation to various elements and materials. For instance, after 30 days, vibration welded joints made of steel A36 (S275) are characterised by a significant increase in tensile strength. Sadly, the reason for the above-named improvement remains uncommented. Similarly, vibration welded joints made of aluminium alloy 6061 also demonstrated higher resistance than those made using traditional welding and subjected to treatment T6. The aforementioned facts might imply that vibration could replace heat treatment. An alloy composed of copper and nickel subjected to vibration welding revealed clearly visible structural refinement resulting in a different arrangement of dendrites. Vibration welding involving unalloyed ferritic steel performed using dynamic excitation at a frequency of 50 and that of 500 Hz in the direction transverse in relation to the weld did not result in any relaxation of welding stresses along or across the weld axis [16]. The welding of austenitic steel 304 performed using a frequency of 39.4 Hz decreased the precipitation of ferrite $\delta$ and reduced residual stresses by approximately 20%. It was also possible to notice changes in the mechanism of metal bath solidification [17].

The test results and conclusions presented in this study are concerned with various structural test materials including aluminium alloys [6, 10], nickel alloys [12], austenitic steels [18] and structural steels [7, 16]. Materials of each of the above-presented groups are characterised by various thermomechanical properties, various crystallisation mechanisms and, undoubtedly, various behaviour during the transition from the liquid to the solid state, which in turn may lead to varied effect on the properties of welded joints. Because of the foregoing, there are no grounds for any generalisations with reference to results of vibration welding, which is well illustrated by publication [18] describing tests involving the use of MAG method-based vibration welding performed on structural steel. During welding, the test elements were put into vibration using a dedicated station. The frequency of forced vibration amounted to 50 Hz and 500 Hz. The time of the process was adjusted so that the test element remained exposed to vibration during the entire process of welding and cooling. The welding process was followed by x-ray diffraction-based measurements of internal stresses in the longitudinal and transverse directions. The tests did not reveal the effect of vibration on the distribution of internal stresses.

## Vibration Welding Tests

Various opinions concerning the effectiveness of the vibration welding process inspired research, the effect of which should provide basis for the application of vibration welding in practice [20]. The tests were performed on a popular structural material, i.e. (15 mm thick) unalloyed steel S355J0 (EN 10025-2).

Figure 1 presents the fixtures used to perform the process of vibration welding. The vibration station was composed of a base, plate and four helical springs. The plate was provided with an eccentric vibrator, the purpose of which was to put the plate with the test element into vibration. The location, specific operation of the motovibrator and the degrees of freedom of the support (helical springs) made the plate with the test element move over the elliptical trajectory presented in Figure 1. Figure 2 contains a photograph of the vibration welding station.

During the process of vibration welding, the parameters of station vibration were technological variables. Taking into consideration harmonic motion triggered by vibration,

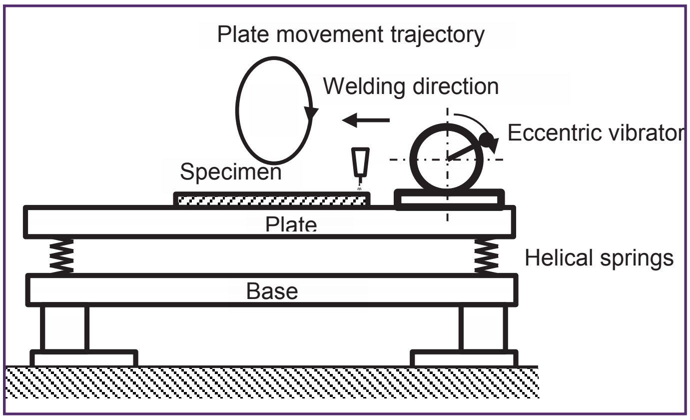

Fig. 1. Scheme of the vibration welding station

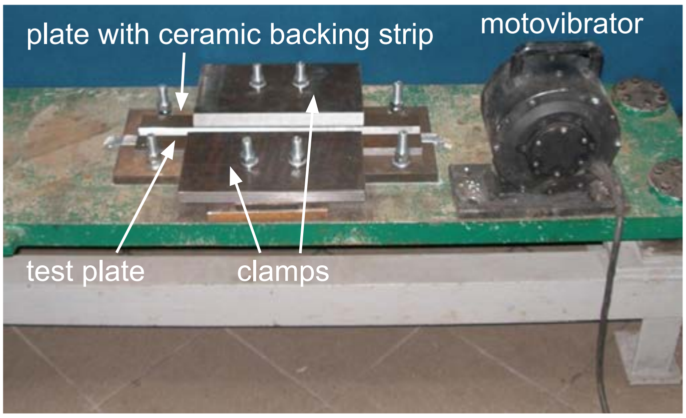

Fig. 2. Vibration welding test rig

in a general case the parameters included frequency, displacements resulting from the trajectory of motion in the rotation plane as well as components of velocity and acceleration. It was assumed that the primary effect of vibration during welding would reveal itself during the solidification of the weld pool. In the above-named case, the primary parameter was acceleration, which, when affecting the mass of the molten and solidifying metal, would exert primary dynamic effect. Certain dynamic effect could occur in the liquid–solid transition state and would grow weaker along with progressing solidification (an increase in the solid cohesion along with a decrease in temperature). To summarize, it was assumed that vibration would be effective primarily during the transition from the liquid to the solid state during the crystallisation of the weld. Welding was performed using the above-named station presented in Figure 2 and a robotic unit composed of a Rotrol II G industrial robot (Cloos) and welding module 553mc3r (Cloos).

The tests involved the making of five test plates, the first of which designated as P0 was welded without vibration (using the station and maintaining all stiffening conditions), whereas the remaining four plates were welded in vibration conditions. The dynamic parameters of vibration welding are presented in Table 1, whereas the shape and dimensions of the test plate are presented in Figure 3.

## Performed Tests

To confirm the effect of vibration, if any, on the process of welding, welded joints made in vibration conditions were tested for their properties. The results of the aforesaid tests were compared with those obtained in tests involving test elements welded without vibration. The scope of the tests involved the determination of welding stresses as well as the performance of hardness and toughness measurements as well as metallographic tests.

The first stage of the tests involved the determination of distributions of internal stresses in relation to reference plate P0 (not subjected to vibration) and after the process of vibration welding (P1-P4). Welding stresses were determined using the trepanation method [19]. Measurements consisted in making uniformly arranged measurement bases having an assumed length of 40 mm, where measurement points were metal balls having a diameter of 1.588 mm (1/16") and mechanically pressed against the material (Fig. 4a, b). Afterwards, a mechanical extensometer was used to measure distances between individual measurement

Table 1. Dynamic parameters of vibration welding

| Test plate | Eccentric | Frequency [Hz] | Acceleration [m/s²] |
|---|---|---|---|
| P1 | Min | 93.8 | 168 |
| P2 | Min | 73.5 | 72 |
| P3 | ½ Max | 60.4 | 19 |
| P4 | Max | 57.1 | 38 |

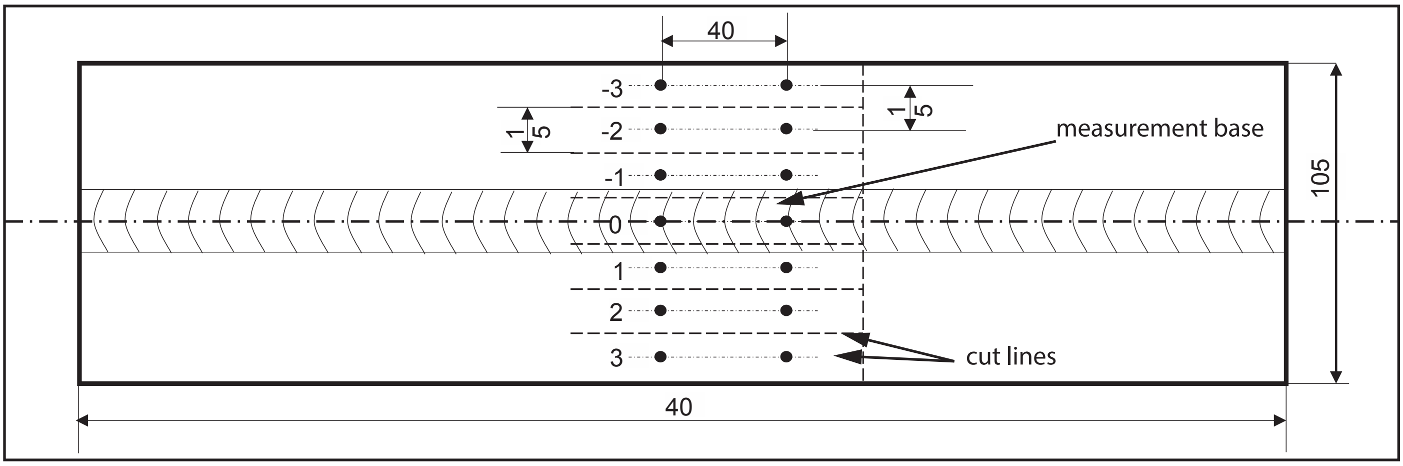

Fig. 3. Shape and dimensions of the test plate

points of the measurement bases. The extensometer provided with measuring stems was placed on the balls and results were read out of a provided sensor (Fig. 4c). The device enabled measurements of base lengths at an accuracy of $10^{-4}$ mm on bases of 20, 40, 60 and 100 mm.

During the reading, the pointer is blocked so that a photo of the device from measurement bases does not trigger changes in sensor indications (Fig. 4c). Because of high accuracy ($10^{-4}$ mm), each measurement involving a given element must be compared with a measurement on the bases of a standard plate made of invar. Because of temperature differences, all readouts are compensated and reduced to a "normal temperature" of 20°C. Result measurement $L$ is the difference between a value measured on test element $P$ and a value measured on standard plate $B$ increased by the value of correction $\Delta L_t$ resulting from the difference of the temperature of the test element and that of the standard plate.

To reveal internal stresses it is necessary to make cuts between measurement bases (Fig. 3, 4b). Once the cuts are made, another measurement concerning the distance between the base points is performed. The difference of lengths between the bases before and after the releasing of stresses enables the identification of their components along the measurement axis. Because of the fact that measurements can be performed at various temperatures, extensometer readouts must be appropriately corrected after reducing them to a normal temperature of 20°C.

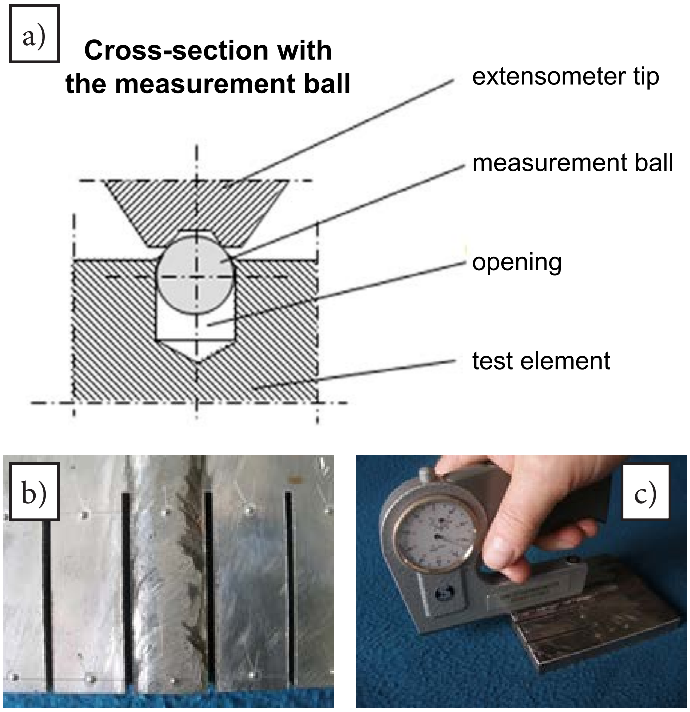

Fig. 4 Measurement of strains enabling the determination of internal stresses; a) Scheme of measurement ball fixing; b) Test element with measurement bases (balls); c) Extensometer

$$L = P - B + \Delta L_t \tag{1}$$

$$\Delta L_t = \left[\alpha_P\left(20 - t_P\right) - \alpha_W\left(20 - t_W\right)\right]L_W \tag{2}$$

where:

- $L$ [mm × $10^{-4}$] – difference between the length of the base on the test element and the length of the base on the standard plate,
- $\Delta L$ [mm × $10^{-4}$] – correction allowing for difference of temperature,
- $P$ [mm × $10^{-4}$] – readout on the base on the test element,
- $B$ [mm × $10^{-4}$] – readout on the base on the standard plate,
- $\omega_W$ – $1{,}6 \times 10^{-6}$ $^1\!/_{^\circ C}$ – linear expansion coefficient for the standard plate material (invar),
- $\omega_P$ – $11{,}0 \times 10^{-6}$ $^1\!/_{^\circ C}$ – linear expansion coefficient for the test element material (steel),
- $L_W$ [mm × $10^{-4}$] – length of the measurement base,
- $t_W$ [°C] – temperature of the standard plate,
- $t_P$ [°C] – temperature of the test element.

The component directed along the axis of the measurement bases is calculated using the following dependence (3):

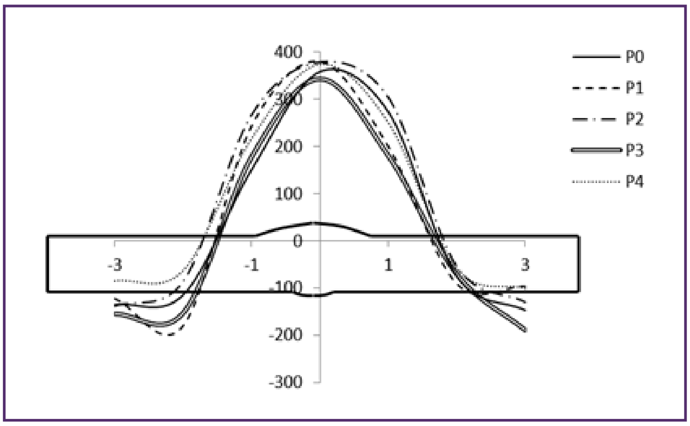

Fig. 5. Distributions of internal stresses in the test elements

$$\sigma_W = \frac{\Delta L}{L} E$$

where $E$ [MPa] – coefficient of longitudinal elasticity [N/mm²]

Brittle crack resistance is one of the most important parameters specifying operational properties of steel welded joints. Related standards and specifications precisely specify requirements with reference to each material, technology and the intended use of a welded structure. For this reason, the determination of the vibration welding effect on the above-named parameter might be of significant importance as regards the making of welded structures. In practice, brittle crack resistance is determined through impact strength tests, where, in turn, impact energy is identified. The test elements were sampled for standard specimens to be subjected to impact strength tests. The manner of cutting is presented in Figure 6.

The notch of the specimen for impact strength tests was placed in the weld axis, i.e., in the area which during the vibration welding process remained in the liquid state for the longest time and in the conditions where the effect of vibration on the bath of liquid metal was the most intense. The effect, if any, on the metallurgical process in in such an area should be the most intense. Table 2 presents the results of impact strength tests performed at a temperature of -20°C.

Table 2. Impact strength test results

| Test results | Test plates | | | | |
|---|---|---|---|---|---|
| | P0 | P1 | P2 | P3 | P4 |
| Impact energy [J] | 104 | 76 | 74 | 92 | 82 |
| | 96 | 70 | 64 | 92 | 84 |
| | 116 | 94 | 84 | 136 | 54 |
| | 108 | 92 | 100 | 114 | 102 |
| | 96 | 112 | 128 | 100 | 102 |
| | 108 | 90 | 102 | 120 | 96 |
| Average | 104 | 89 | 92 | 109 | 86 |
| Standard dev. | 7 | 14 | 22 | 17 | 18 |

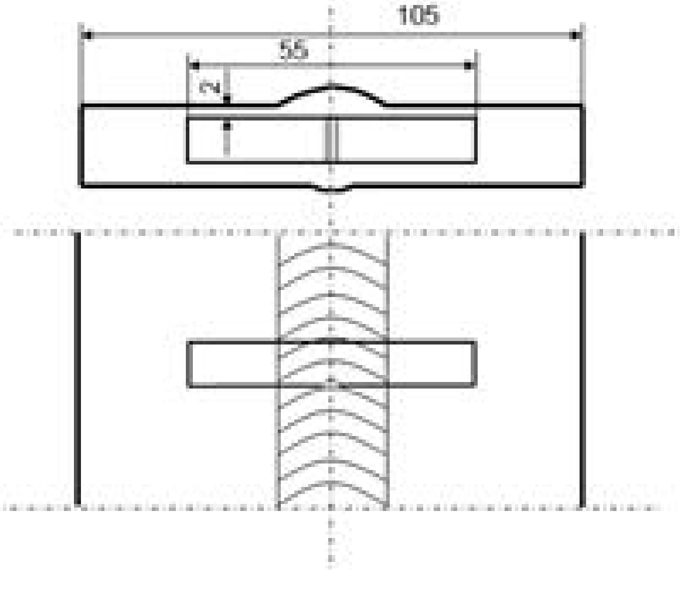

Fig. 6. Manner of the cutting of specimens for impact strength tests

Hardness is another important parameter identifying strength-related properties of welded joints. Hardness measurements involved areas in the weld axis, i.e. areas characterised by the greatest segregation resulting from the direction of crystallisation. It was assumed that the most intense effect (if any) of dynamic phenomena occurring during vibration would reveal themselves during the solidification in the weld axis, i.e. in the area which remains in the liquid state for the longest time, where the process solidification comes to an end and where the effect of vibration processes can be visible most clearly. Figure 7 presents measurement areas. On each cross-section of the specimen, 10 measurement lines spaced at 2 mm intervals were made. The first measurement line (1) was located 2 mm away from the weld root edge.

Because of the significant number of measurements (90 measurements on one specimen), their results are presented in the form of

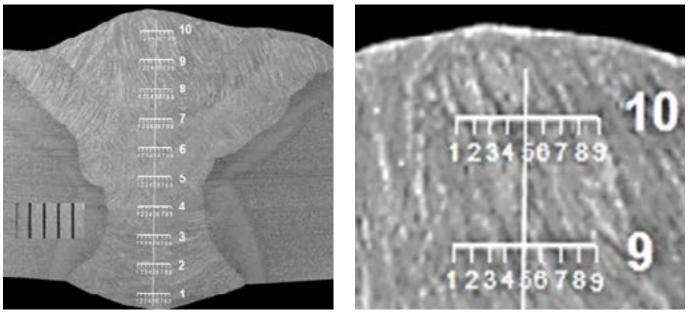

Fig. 7. Scheme of hardness measurements

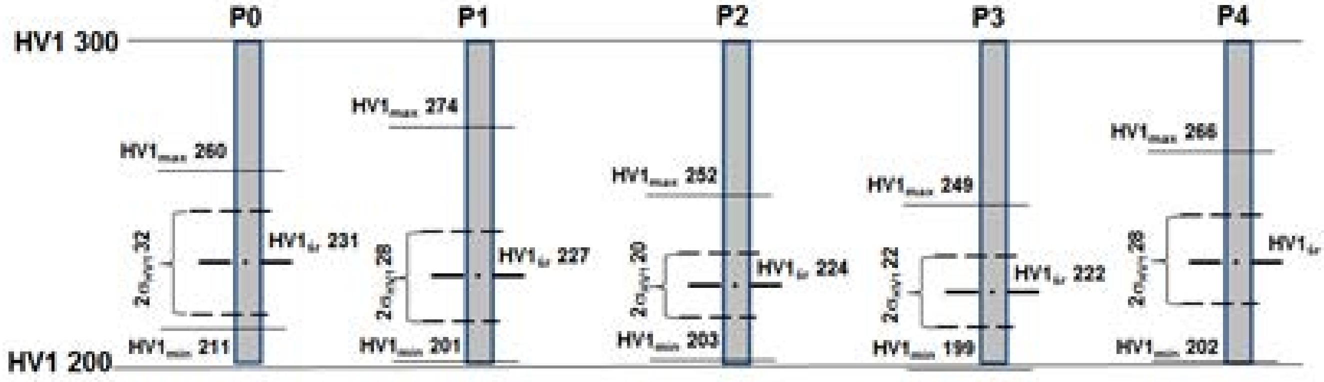

Fig. 8. Hardness measurement results in the static approach

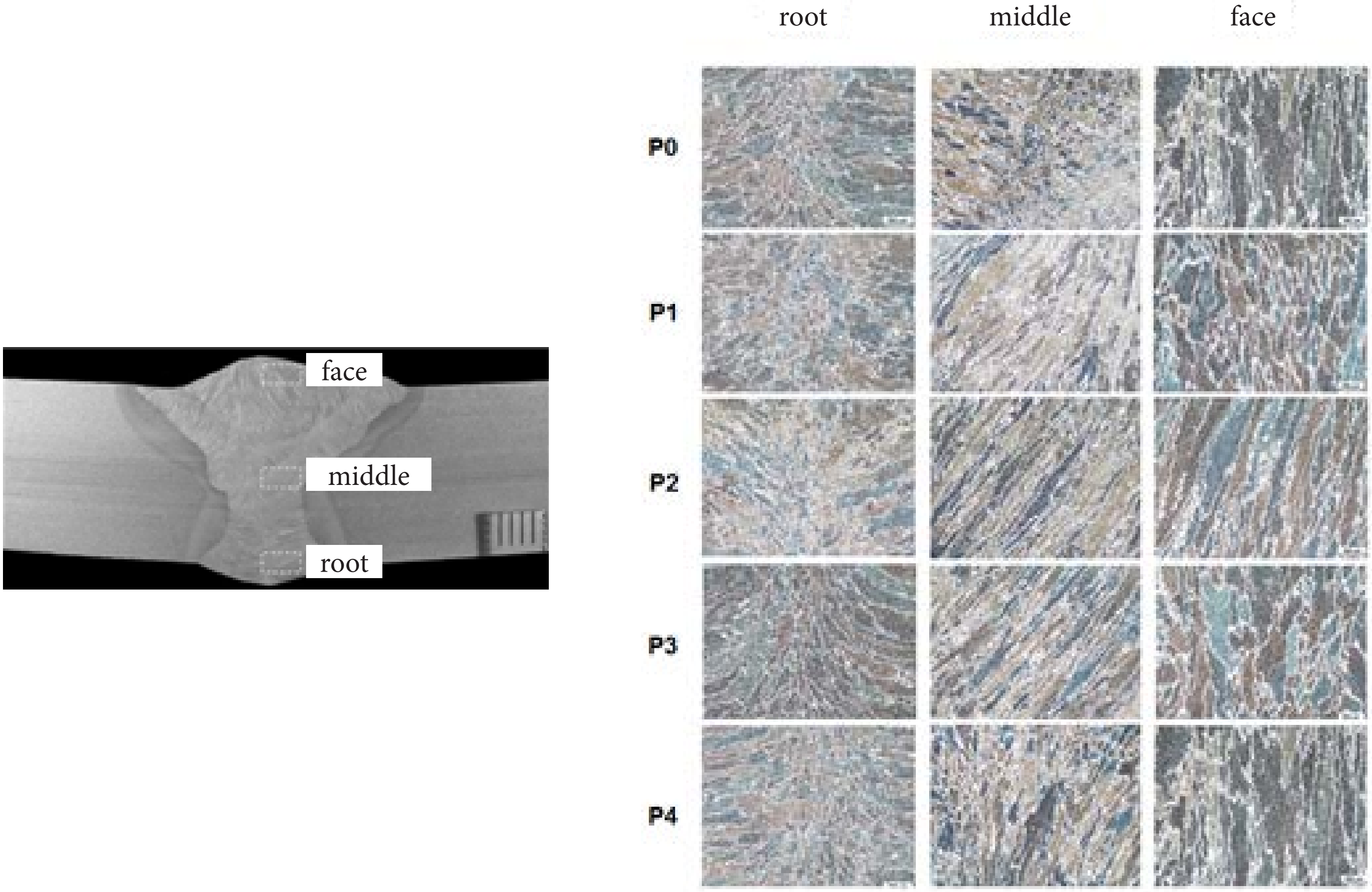

Fig. 9. Results of metallographic tests; a) weld cross-section with marked areas subjected to microscopic tests; b) Micrographic structures in the test welds

a statistical diagram in Figure 8. The diagram contains the maximum, minimum and average of hardness values as well as the standard deviation (±$\sigma$) in relation to each test element.

The process of solidification constitutes and important stage in the formation of the weld structure and, consequently, its properties. The directions of crystallisation, the size and shape of the dendritic structure as well as the size and shapes of grains depend on the heat flow during crystallisation. Dynamic phenomena responsible for the additional motion of the bath may affect the above-named quantities. For this reason, the investigation, involving the performance of metallographic tests, was focused on the effect of mechanical vibration on the solidification of welds made in various dynamic conditions (Table 1). Figure 9 presents areas subjected to microstructural tests and the results of the structural tests.

The micrographic tests aimed to identify differences, if any, in the structures of weld metal after solidification in various dynamic conditions and their comparison with the structures of the welds solidified without vibration. The microscopic photographs were made at 50x magnification, i.e. most favourably revealing dendritic structures. The etchant used during the tests was Nital.

## Analysis of Test Results

The scope of research and related tests aimed to determine the effect of the vibration welding process on quality-related properties of welded joints. Welding stresses resulting from a thermal cycle often affect operational properties of welded joints and as such should be minimised to, among other things, increase the brittle crack resistance or the fatigue service life of structures and elements. Stress relief annealing performed to obtain the-above named result is very time and energy-consuming. Therefore, the use of vibration welding leading to the reduction of welding stresses could be of great importance. However, the measurements performed within the scope of the research revealed almost no effect of element vibration during welding. The distributions of welding stresses presented in Figure 5 were the same in relation to the element welded without vibration and to that welded in vibration conditions. Differences in values of maximum stresses in the weld axis were restricted within the limits of measurement errors. Consequently, it is possible to conclude that the dynamic conditions of the vibration welding process do not affect thermal processes during welding. Another result of the above-presented situation is the lack of vibration effect on such quality-related parameters as the toughness and hardness of welds. The extended impact strength tests performed involving each test element (of six specimens) revealed a typical scatter in each case, which implies that the vibration welding process does not affect the above-named parameter (Table 2). Likewise, as was revealed in the view of the structures in the microscale (Fig. 9), the hardness in the weld axis, i.e. the area remaining in the liquid state for the longest time, was not affected by vibration dynamics (Fig. 8). In all of the cases, the shapes and dimensions of the structures were similar, thus failing to confirm any effect of dynamic processes during solidification.

The above-presented studies and research do not provide an unequivocal reply to the question concerning the effect of mechanical vibration accompanying welding processes on properties of welded joints. As no such influence was identified in relation to structural unalloyed ferritic steels, it can be concluded that the use of vibration welding (vw) is not justified as regards the above-named group of materials.

## Conclusions

The results of the above-presented tests and their analysis enable the formulation of the following conclusions to be allowed for in practice:

1. Welding performed in vibration conditions known as vibration welding (vw) can be performed on appropriately prepared technological stations featuring the controlling of frequency and amplitude.
2. The effect of vibration processes on welding stresses during the welding of ferritic structural steels was not identified.
3. The vibration welding of ferritic steels does not trigger changes in the structure of welds nor does it affect mechanical properties such as toughness and hardness.
4. In view of the obtained research results, the purposefulness of the use of vibration welding when joining elements made of ferritic steels should be considered thoroughly.

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