UDK 621.791.05:539.42
Izvirni znanstveni ~lanek

ISSN 1318-0010
KZLTET 33(6)443(1999)

APPLICATION OF LASERSPECKLEINTERFEROMETRY TO FRACTURE MECHANICAL INVESTIGATIONS OF BONDS AND NON HOMOGENEOUS MATERIALS

UPORABA LASERSPECKLEINTERFEROMETRIJE ZA LOMNOMEHANSKE RAZISKAVE SPOJEV IN NEHOMOGENIH MATERIALOV

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Prejem rokopisa – received: 1999-11-19; sprejem za objavo – accepted for publication: 1999-12-06

With commonly used testing procedures, like measuring the average displacement with clip-gauges or measuring displacement qualitatively with field measuring techniques over a selected specimen surface, only limited information can be obtained for a welded joint. Therefore, the influence of notch position and weld geometry on deformation initiation and further deformation is not sufficiently well known. As a consequence, an enhanced defect assessment of welded components i s not possible. Due to recent developments in field-measurement techniques, in computer technology and specific programs i t is now possible to obtain detailed information about the quantitative deformation in base and weld metal in an effecti ve and economic manner. In this contribution the analysis with laserspeckleinterferometry is described. Furthermore, computer- assisted laserspeckleinterferometry is applied to SENT specimens with different notch positions in the highe r strength weld metal. With laserspeckleinterferometry the quantitative deformation performed in base and in weld metal under t he influence of the 45°-yielding starting from the crack tip, was measured. The possible evaluations for laserspeckleinterferometry in terms of total deformation, partial deformation and deformation performed during single steps of the experiment ar e demonstrated. From the results the influence of notch position and weld geometry on the deformation behaviour could be eva luated. The consequences for the analytical determination of the yield load for welded joints, as input for defect assessment, are derived.

Key words: material testing, fracture mechanics, laserspeckleinterferometry, welded joints

S klasi~no tehniko preizku{anja, kot je merjenje povpre~nega pomika z merilnikom ali pa kvalitativnim merjenjem pomika s pomo~jo povr{inske metode na izbrani povr{ini preizku{anca, se lah ko pridobi samo omejene informac ije o zvarjenem spoju. Zaradi tega je informacija o vplivu polo`aja zareze in geometrije zvara na iniciranje in nadaljni potek deformacij nepopolna, kar onemogo~a podrobnej{o oceno napak zvarjenih spojev. Zahvaljujo~ sodobnemu razvoju povr{inske tehnike merjenja, ra~unalni{ki tehnologiji in programski opremi, je sedaj mo`no na gospodaren in u~inkovit na~in dobi ti podrobne informacije o kvantitativni deformaciji v osnovnem materialu in zvarjenem spoju. V tem prispevku je opisana anali za z laserspeckleinterferometrijo. Na SENT preizku{ancih z razli~nimi polo`aji zarez v visokotrdnemu zva ru je uporabljena metoda ra~unalni{ko podprte laserspeckleinterferometrije. S to tehniko je kvantitativno merjena deformacij a v osnovnem materialu in zvaru pod vplivom 45° linije te~enja iz konice razpoke. Prikazano je vrednotenje z laserspeckleinte rferometrijo v obliki skupne in delne deformacije ter deformacij dobjenih v posami~nih korakih experimenta. Na osnovi rezultatov vpliva polo`aja zareze in geometrije zvara je mo`no oceniti deformacijske lastnosti. Zasledovane so posledice za analiti~no dolo~anje sile te~enja za zvarjeni spoj kot vhodni podatek za ocenitev napak.

Klju~ne besede: preizku{anje materiala, lomna mehanika, laserspeckleinterferometrija, zvarjeni spoj i

1 INTRODUCTION

Over the last few decades many new materials and new bonding techniques have been developed. Nowadays, composites such as fibre matrix, and laser-welds are in common practise and widely used in industry. In order to evaluate these new techniques, known defect assessment procedures have been improved and new assessment procedures developed. As a result, more adequate and accurate assessments can be achieved in order to ensure safety and save costs.

However, some information which is necessary for a satisfactory defect assessment is still missing:

– appropriate input data such as mechanical properties for a welded joint are difficult to determine;
– a better understanding of the failure and deformation behaviour is necessary in order to generate analytical solutions in accordance with engineering defect assessment methods.

The reasons for this can be found in the experimental state of the art: in comparison to the above mentioned developments, relatively little development had been made in the field of experimental fracture mechanics until recently.

As a consequence, insufficient input information leads to a loss of accuracy for defect assessment.

In this contribution it is shown how with the help of further developed experimental procedures, like laserspeckleinterferometry, the quality of defect assessment can be enhanced.

2 DEFECT ASSESSMENT

The aim of defect assessment is to determine whether a component containing a defect will be safe in service

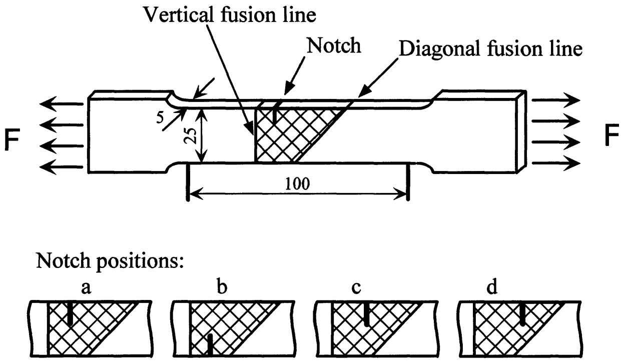


Figure 1: Single edge notched specimen: notch positions
Slika 1: Preizku{anec z enostransko zarezo: polo`aj zareze

or not, and how much safety remains for the given defect.

In order to assess the cracked component input information is required relating to the component's geometry, material, loading, and about the defect's geometry and its position in the component.

Well-known is the FAD (Failure Assessment Diagram) which is applied when assessing according to R6 or PD 6493.

By comparing the fracture toughness, K_{Ic}, of the material which contains the defect with the applied stress intensity, K_I, in the component, the possibility of brittle failure is assessed. By comparing the yield load F_Y, determined with the yield stress σ_Y and the ligament size, with the actual applied load, the possibility of ductile failure/plastic collapse is assessed.

In comparison to a component consisting of pure base metal, a welded joint consists of 1 or 2 base metals, 1 or 2 HAZs (Heat Affected Zones), and the weld metal. The HAZ and WM (Weld Metal) themselves have relatively inhomogenous microstructures. This is what makes the determination of mechanical properties and the defect assessment difficult: without proper input information concerning the mechanical properties and the interaction behaviour of the welded joint with the surrounding material, no proper defect assessment is possible.

3 EXPERIMENTAL CONFIGURATION

The following experimental configuration was used for the investigation. A welded joint with HV-geometry was produced from HSLA steel. The yield strength of the weld metal (σ_{YW} = 635 MPa) is higher than the yield strength of the base metal (σ_{YB} = 450 MPa) which is defined as overmatching weld joint. From the welded joint single edge notched tensile (SENT) specimens were extracted. The notch was positioned in the upper part (cap) and in the lower part (root) of the weld joint. The position towards the fusion line was varied systematically, **Fig. 1**. During the experiment elongation and crack opening displacement were measured by conventional methods with clip-gauges and with laserspeckleinterferometry, **Fig. 2**.

4 DETERMINATION OF YIELD LOAD

The yield load of a cracked component is an important parameter for defect assessment. It is defined as the load at which the first plastic deformation initiates at the end of the elastic deformation. The yield load can be obtained by experiment, by finite element calculations or analytical expressions. By experiment, the yield load is determined from load-deformation curves as the change in slope after the elastic regime. For calculating the yield load, information about the specimen's geometry and yield strength σ_Y is required, as depicted in **Fig. 3**. It is known that the first plastic deformation initiates from the crack tip in a 45°-direction.

For components made of "pure base metal", i.e. which do not contain welds, sufficient information about the component is available. Solutions for the geometry dependent yield load F_Y and stress intensity, K_I, are contained in documents like, e.g. [1].

For welded joints the assessment is more complex. It is possible to determine the fracture toughness as a "stand-alone" property, but actually the fracture and failure behaviour is influenced by the interaction of base metal and weld metal properties and their geometries. Therefore, up to now for welded joints, finite element solutions for the yield load have been derived for only a few configurations.

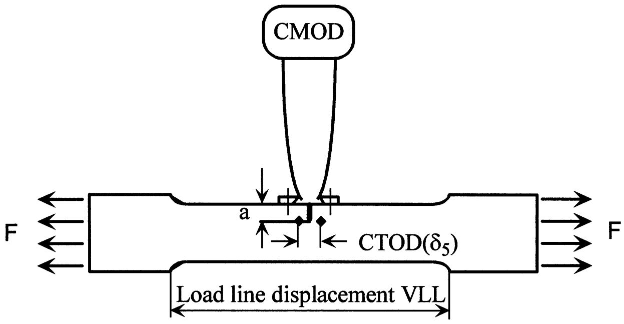
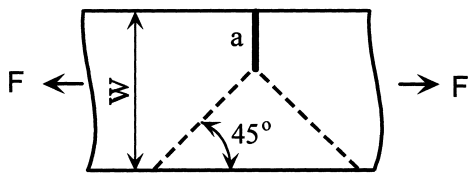


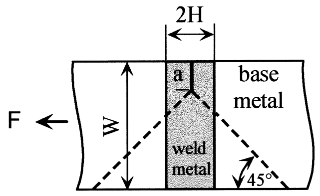
Figure 2: Instrumentation with clip-gauges
Slika 2: Instrumentiranje z merilnikom



Calculation of yield load F_Y:

$$F_Y = (W-a) * \sigma_{YB} * B$$

Figure 3: Calculation of the yield load for a base metal configuration
Slika 3: Dolo~anje sile te~enja za osnovni material



Yield Load for Mismatch:

$$F_{YM} = \{ H * \sigma_{YW} + (W\text{-}a\text{-}H) * \sigma_{YB} \} * B$$

base metal: σ_{YB}, N_B

weld metal : σ_{YW}, N_W

Figure 4: Calculation of the yield load for a welded joint according to the "penetrating slipline model" with idealised weld geometry

Slika 4: Dolo~anje sile te~enja za zvareni spoj na osnovi "penetrating slipline" modela za idealizirano geometrijo zvara

At the present time, only one analytical solution for the yield load is available for a welded joint: the "penetrating slipline model"[2] as used in the Engineering Treatment Model for Mismatch (ETM-MM) [3]. According to this model, for a crack situated in the weld metal, initial yielding starts in a 45°-direction emanating from the crack tip, penetrates the fusion lines and penetrates into the base metal, **Fig. 4**.

The problem of applying this model is that only a "rectangular" weld with width 2H can be assessed, **Fig. 4**, which means that real weld geometries like those shown in **Fig. 5** can not be considered. The ETM-MM gives no hint how the idealisation should be performed, i.e. whether the smallest weld metal width $2H_{min}$, the average width $2H_{av}$ or the largest width $2H_{max}$ should be used for calculation of the yield load F_{YM}, **Fig. 5**. Furthermore, it is not possible to determine the yield load F_{YM} for a defect which is not placed in the centre of the weld.

In order to generate analytical solutions for the yield load F_{YM}, it is necessary to obtain a better understanding about the deformation behaviour of a welded joint, especially how the crack position in the weld metal influences the initiation of plastic deformation and the further interaction with the base metal.

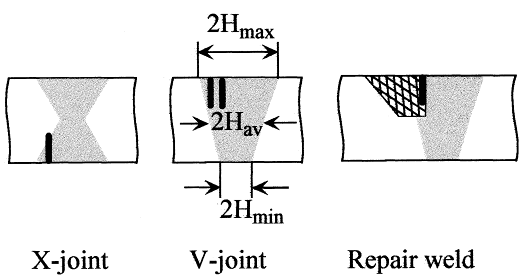


Figure 5: Real weld joint geometries and possible notch positions, possible idealisation of weld geometry with $2H_{max}$, $2H_{av}$, or $2H_{min}$

Slika 5: Realne geometrije zvara in mo`ni polo`aji zarez, mo`na idealizacija geometrije zvara z $2H_{max}$, $2H_{av}$, or $2H_{min}$

5 MEASURING OF THE DISPLACEMENT BETWEEN 2 POINTS

Measuring of the displacement between two points with clip-techniques is commonly used for obtaining mechanical properties or for observing the behaviour of a cracked component. Usually displacement in terms of e.g. elongation or crack opening displacement (COD) is measured and registered together with the applied load. For measuring the COD, the measuring base is supposed to be relatively small and it should be placed close to the crack.

In contrast to this, in a test to determine the specimen's yield load the elongation is measured over quite a large base, i.e. the gauge length of the specimen, e.g. with a linear variable transducer. There are problems associated with this type of measurement. By measuring elongation between 2 points information is obtained only for an average strain, as **Fig. 6** shows. For a "pure base metal" specimen, with a gauge length = 100 mm, an elongation of 10 mm results in 10% strain. For a specimen containing a weld metal strip in the centre, with much higher yield strength than the base metal, the performed elongation could be e.g. 0 mm in the weld metal and 10 mm in the base metal. The average strain observed by measuring between 2 points is again 10%,

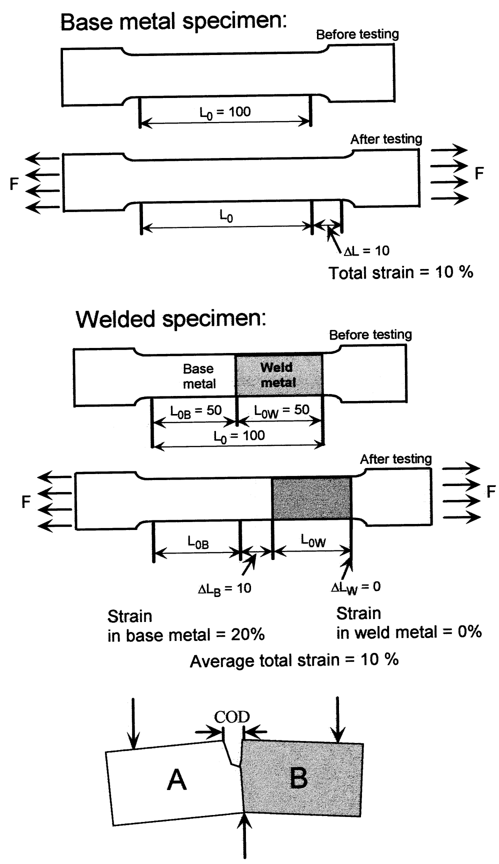


Figure 6: Influence of higher strength material on the obtained strain and crack opening displacement

Slika 6: Vpliv visoko trdnostnega materiala na dose`eno deformacijo in odpiranje razpoke but actually the base metal exhibited 20% strain. The measuring technique does not provide this information. The same phenomenon occurs when determining the material parameter COD for an interface as shown in **Fig. 6**: a softer material A exhibits more strain than the higher strength material B. As a result, an average COD is obtained. The prob lem is how to select an appropriate material parameter for further defect assessment.

Therefore, when determining the yield load from an experimental load-elongation curve obtained by measuring the displacement between two points by the change in slope no information is available about the amount of deformation performed in the weld metal or in the base metal. It is not possible to distinguish whether e.g. the weld metal did not exhibit any plastic deformation at all.

From the yield load, determined by the change in slope, no distinguishing characteristics could be obtained for the four different notch configurations, **Fig. 7**. A defect assessment would lead to the same result for the four notch configurations. It is obvious that this is not sufficient for a proper failure analysis. Therefore, in order to develop appropriate solutions for the yield load, it is necessary to obtain more information about the deformation behaviour of welded joints.

6 MEASURING ALONG AREAS

For the investigation of deformation initiation and further deformation behaviour other measuring systems are more suitable. Well-known methods are e.g. photoelastic foil and Moiré-fringe techniques[4]. In these techniques the interesting surface of the specimen has to be prepared thoroughly and is then illuminated with a light-source. The resulting optical interferences are usually registered by photographs. This time-consuming quantitative evaluation demands special optical instruments.

These methods are associated with several disadvantages:

– the preparation of the specimen’s surface demands a lot of effort and is time-consuming. The foils are expensive;
– when registering the interferency stripes with photographs, a picture has to be taken for every stage which seems to be important;
– before the evaluation of the results one has to wait until the film is processed;
– after the experiment it is not possible to obtain intermediate results between 2 photographs. If the evaluation reveals that a certain stage would have been interesting to separate from the other stages, this cannot be done afterwards;
– it is only possible to obtain "summarised" results, i.e. the pictures contain the deformation performed from the beginning of the experiment on up to the moment when the picture was taken;
– the pictures themselves show only qualitative deformation. In order to achieve quantitative results (in mm or %) a complex, high-effort, time-consuming evaluation with special instruments has to be performed.

Therefore, in practice, the quantitative evaluation in most cases is not performed, i.e. the results are only discussed in terms of high or low deformation, but not in absolute numbers.

7 COMPUTER-ASSISTED LASERSPECKLEINTERFEROMETRY

In the last few years, considerable progress has been made in the areas of computer capacity and speed, and in specific programs like image processing. As a result, it is now possible to record images from field measurements continuously and to evaluate the results at once. Computer assisted laserspeckleinterferometry makes use of these techniques. It allows the measurement of the displacement of every point in a selected area, the results are recorded continuously. Evaluation and further calculation of the results are quick and effective[5].

The specimen’s surface, which does not need any special treatment, is illuminated with two laser waves symmetrically to the observation direction. By illumination in the horizontal and vertical directions the displacement in the horizontal and vertical directions is observed, **Fig. 8a**. The laser waves are reflected by the specimen’s surface, interfere and produce the "speckle pattern" which is registered with a video camera and stored in the computer as a reference. By movement of the object, i.e. displacement, a new speckle pattern is produced, **Fig. 8a and b**. The difference between the patterns is represented by correlation fringes which are shown as "black-and-white" stripes, **Fig. 8c**. The number of fringes indicate the relative displacement registered with the video camera. Together with the relevant distances and angles of the laser device, plus the wavelength of the laser, the absolute displacement in mm is derived from the relative displacement. In order to obtain the relative deformation in %, the results are differentiated. The results may be shown as load-deformation curves, in 3D-diagrams or in 2D-diagrams in which colours represent the performed deformation, **Fig. 8c**.

In practice, the experiment is conducted in a stepwise manner, i.e. the experiment starts with a reference stage, i.e. no fringes can be seen. When a certain number of fringes have developed due to the specimen’s displacement, the stage is registered by the video camera and the stage is optically set to the next reference picture, i.e. no fringes can be seen. The displacement continues, again after a certain number of fringes the stage is registered and then set to the next reference stage. When the experiment is finished, the single stages

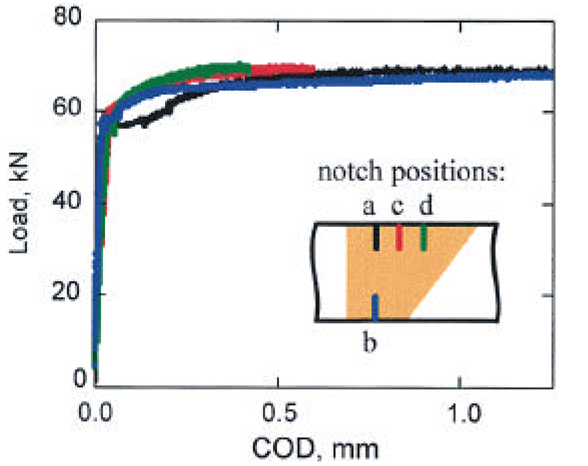


Figure 7: Load-COD-curves obtained for the different notch positions
Slika 7: Krivulje sila-COD za razli~ne polo`aje zarez

are summed by the computer. Various possibilities for evaluating the data are given, **Fig. 9**.

It is not only possible, in this type of experiment, to calculate the total deformation performed during the whole process. In addition, due to the stepwise progress of the experiment partial sums may be calculated, which is important if special deformation stages are of concern. For example, the performed deformation during the Lüders' plateau can be evaluated, sum A in **Fig. 9**. It is also possible to determine the amount of performed base metal yielding before the yielding at the notch in the weld metal initiated, sum B in **Fig. 9**. Processes which initiate "suddenly" or which are indicated only by very little deformation can also be distinguished due to the detailed registered information, e.g. the starting of the Lüders' regime at point 1 in **Fig. 9**, or the exact initiation of plastic deformation at the crack tip at point 2 in **Fig. 9**. When registering the performed deformation with a photographic film, such refined evaluations can not be performed, because when conducting the experiment it is not known when specific deformation processes start or end.

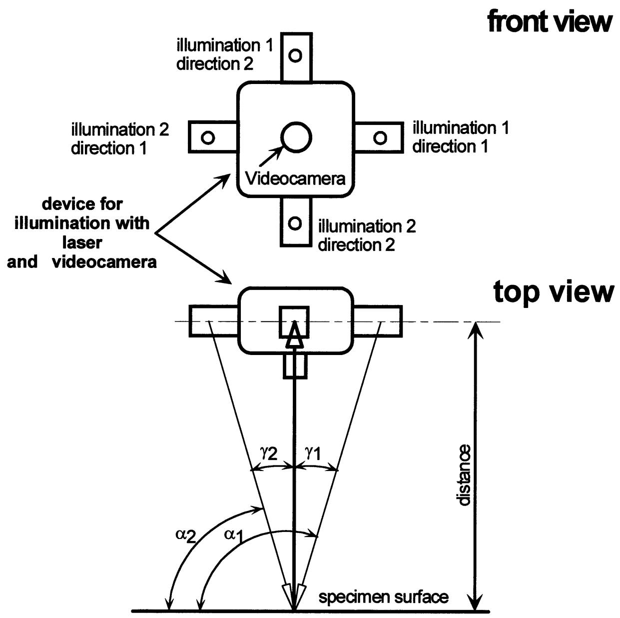


Figure 8a: Geometric relationships of laser- and video unit
Slika 8a: Geomerijska postava laser-video enote

8 RESULTS AND DISCUSSION

For the experimental configuration a selection of the obtained results is presented. **Fig. 10** contains the partial sums of deformation from the start to the first plastic deformation at the notch tip, stage A, and the total sums obtained for the whole experiment, stage B, for the various notch positions.

From the partial sums it can be seen that for notch position "a" the first plastic deformation at the notch tip takes place in the 45°-direction towards the vertical

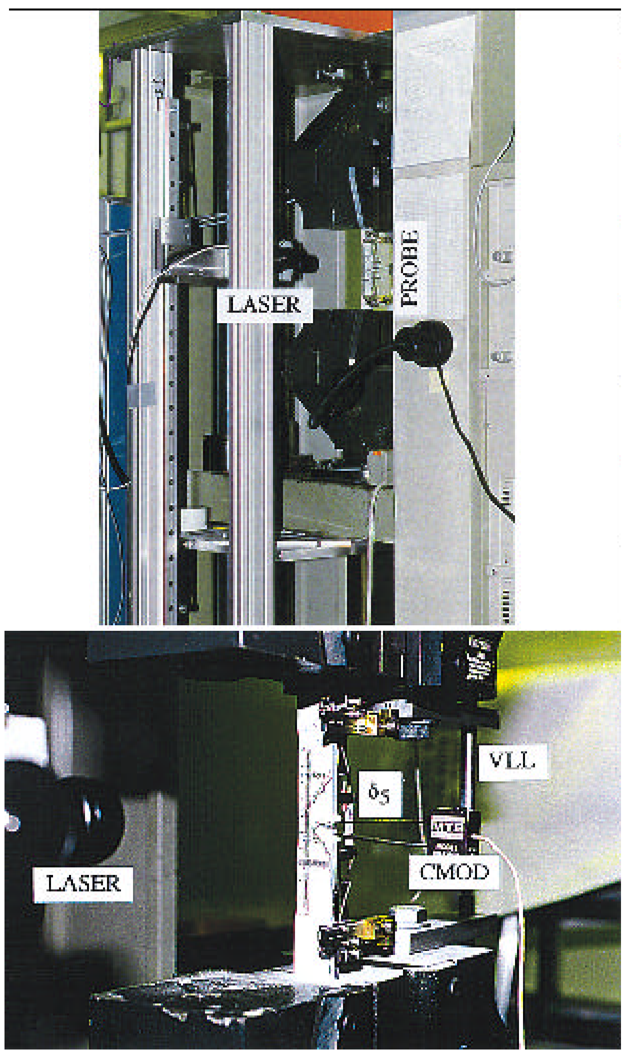


Figure 8b: a) Testing machine with laser- and video device and mounted specimen, b) Instrumented SENT-specimen
Slika 8b: a) Preizku{evalni stroj z lasersko in video enoto in preizku{ancem, b) In{trumentirani SENT-preizku{anec

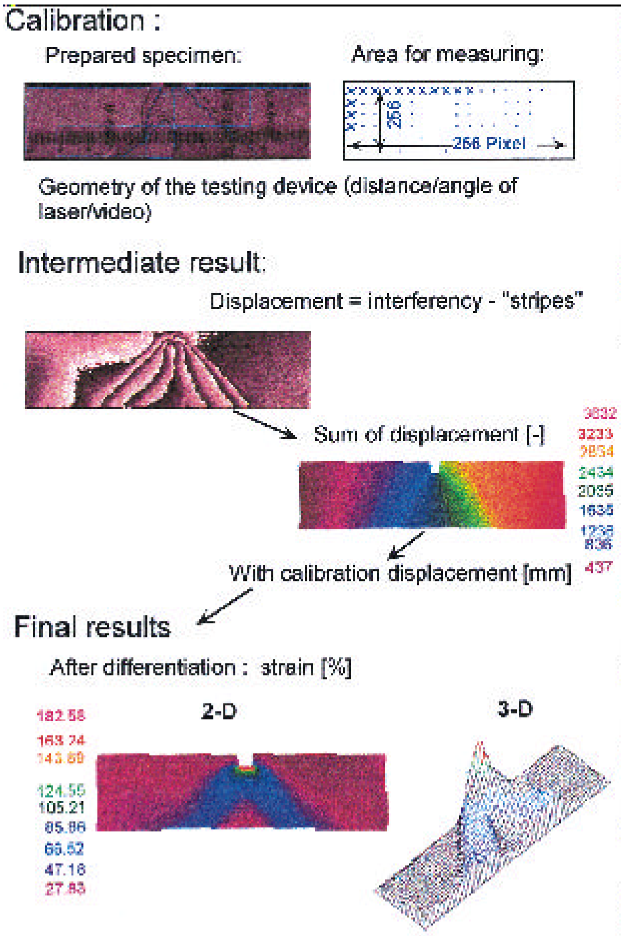


Figure 8c: Evaluation of results obtained from laserspeckle-interferometry
Slika 8c: Vrednotenje rezultatov dobljenih z laserspeckle-interferometrijo

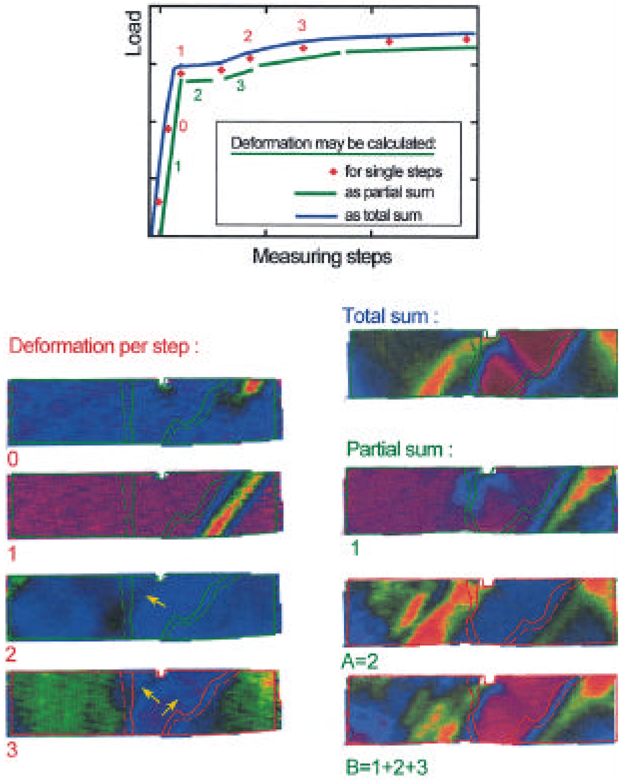


Figure 9: Possible range of evaluation of results obtained from laser-speckleinterferometry
Slika 9: Mo`na obmo~ja vrednotenja rezultatov dobljenih z laser-speckleinterferometrijo

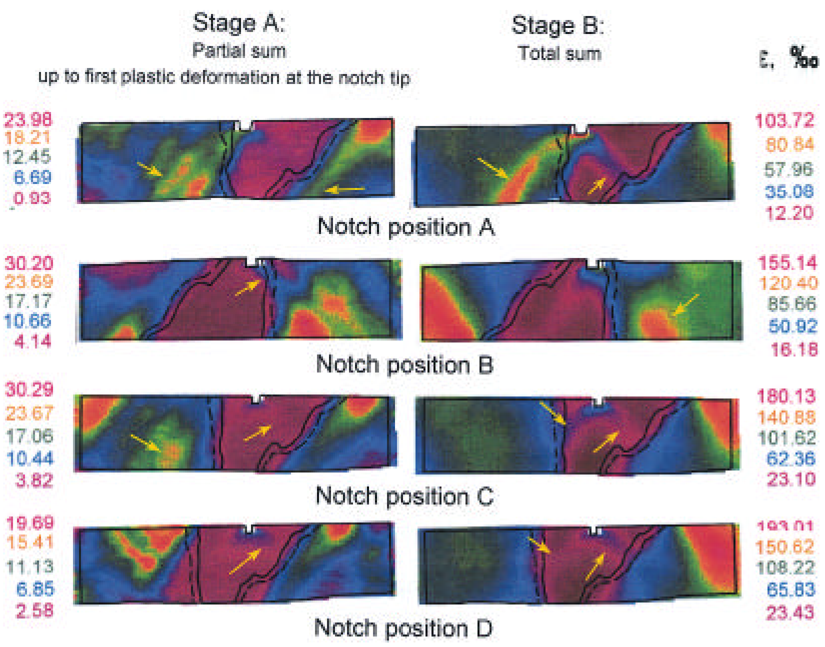


Figure 10: Sums of deformation for the various notch position
Slika 10: Suma deformacij za razli~ne polo`aje zarez

fusion line into the base metal. For notch position "b", which is placed opposite to the notch position "a" in the root part of the weld, the first plastic deformation at the notch tip also takes place in the 45°-direction towards the vertical fusion line into the base metal. For notch position "c", which is situated more towards the weld metal centre than notch position "a", the first plastic deformation at the notch tip is more or less symmetrically towards both 45°-directions. For notch position "d", which is closer to the diagonal fusion line, the first plastic deformation at the notch tip takes place in the 45°-direction towards the diagonal fusion line.

These results indicate that the first plastic deformation at the notch tip is influenced by the distance from the softer base metal. The first plastic deformation at the notch tip takes place into that direction in which the neighbouring base metal is closer.

From the total sums of deformation it is observed that for notch position "a" the highest deformation emanating from the notch tip in the 45°-direction is 8.1% for the base metal near the vertical fusion line. In comparison with this, for notch position "b" the region for the highest deformation in the 45°-direction is the same: the base metal near the vertical fusion line, but the peak value is about 12.0% and therefore much higher than for position "a". For position "a" a significant deformation in the second 45°-direction towards the diagonal fusion line is observed too, with an amount of about 3%. For notch position "b" the performed deformation in the second 45°-direction is only about 1.6%. It can be concluded from these observations that the presence of weld metal in the second 45°-direction partly shields the notch tip from deformation. Therefore, for notch position "b" more deformation is forced into the base metal and less deformation takes place at the notch tip. These processes have to be concerned when calculating the yield load for a welded joint.

For notch position "c" the total deformation at the notch tip is only about 6.2% and only very little deformation in the base metal related to the 45°-directions is present. The deformation is less pronounced towards the vertical fusion line than for notch position "a". The performed deformation is much less than for the positions "a" and "b". This indicates that due to the notch position, which is approximately in the weld metal centre, the notch is shielded from deformation. For notch position "d" the amount of deformation is about the same as for notch position "c", but now the deformation is more pronounced towards the diagonal fusion line.

As result it can be concluded that the closer the notch is positioned towards the softer base metal, the sooner the deformation at the notch tip will start. As a consequence, for the calculation of the yield load, the distance of the notch tip to the base metal has to be considered.

The quantitative results obtained from laser-speckleinterferometry will provide sufficient information for generating better models for calculating the yield load for welded joints. More results and further analysis are presented in[6].

9 CONCLUSIONS

With laserspeckleinterferometry it is possible to measure the deformation at every point of a selected area quantitatively. The different amounts of deformation resulting from the interaction of different materials, in this case, base and weld metal in a welded joint, are obtained. From the results the influence of the notch position in the weld metal on the degree of deformation can be deduced, which will enhance the models for calculating the yield load for welded joints.

Laserspeckleinterferometry is also suitable for obtaining mechanical properties such as the crack opening displacement for interfaces between two different materials.

The possibilities of laserspeckleinterferometry exceed those given by common measuring techniques significantly, especially for nonhomogenous configurations. As a consequence, this technique will become established for the characterisation of welded components.

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