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Experimental and numerical analyses of indentation in single piece and split type specimens

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Indentation tests using a spherical indenter for split-type two half specimens, or the bonded-interface specimens, have been proposed as a means to evaluate the deformation behaviour or the internal damage of materials during indenting the conventional single piece specimen. The purpose of this study is to assess the validity of the split type technique and to better understand the mechanics during the indentation of the split type specimens with respect to the effect of the interface condition between the two split type half blocks. Indentation tests of Al 6065-T5 alloy specimens are chosen to study the whole elasto-plastic stress-strain behaviour. The finite element method was also employed to investigate the deformation behaviour of the two (single piece and split type) test systems loaded with a spherical indenter. The simulated geometry of the specimens and load-displacement curves during indentations are compared with the experimental data of the Al alloy specimens. The similarity and difference in deformation behaviour and stress distribution between the single piece specimen method and the split type specimen method are investigated. The effect of the friction between the two half blocks in the split type specimen test is discussed.

1. Introduction

Indentation tests using spherical indenters have been widely used for measuring mechanical properties of materials since the time of Hertz in 1881 [1] due to its technical simplicity compared with tensile/compressive tests. The results of the indentation test provide **lots of** information not only for the deformation behaviour of the specimen, such as hardness, elastic modulus, yield strength and elasto-plastic responses, but also for the fracture behaviour of brittle materials. In addition, indentation damage bears profoundly on a wide range of other mechanical properties, such as strength, toughness and wear.

In order to examine the internal deformation behaviour or damaged state of the specimen during indentation test, the indented specimen is, in general, cut into two halves and the cut planes are examined using an optical microscopy or a scanning electron microscopy [2]. However, the cut planes can be easily damaged during cutting and machining the indented specimens, hence, examining the original interface plane itself without any damage is difficult. To avoid this difficulty in treating the indented specimen, the method of the pre-division of the specimen before testing, named as "bonded interface test", has been frequently used [3, 4]. The bonded interface specimens of ceramic coated metal substrates provided information on fractures in the ceramic coatings, plasticity in the metal substrates and delamination between layers [3]. Fig. 1 shows schematic diagrams of the single-piece test and the split-type test. A modified bonded interface technique [4] tightening the two half blocks using screws, as shown in Fig. 1b, instead of the conventional adhesive, has been proposed in order to provide a strong interface contact between the two half specimens.

The pre-division or split type specimen technique, although interfaces are not usually bonded, has been widely used for investigating the flow pattern of not only solid metals [5, 6] but also even powders [7] during the metal forming processes, such as forging, extrusion and drawing. The split type specimen technique also has provided varied useful information on deformation pattern, strain distribution and die design errors. Usually square grids are scribed using a height gauge on the plane surface of one of the half specimens before forming and then visioplasticity analysis [8] is employed

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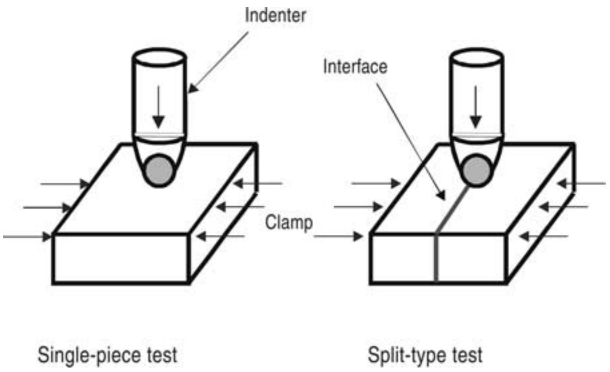


Figure 1 Schematics of indentation tests for a single piece specimen and a split type specimen.

by examining the flow pattern of the deformed square grids.

Whereas the split type specimen technique in an indentation test has been widely used in the fracture and damage research fields, the validity of this technique and the parameters affecting the results of the technique have not been nearly studied in detail. The purposes of this study are to assess the validity of the split type specimen technique and to better understand the mechanics of indentation with respect to the effect of the interface condition between the two split blocks. For simplicity, we performed indentation tests on Al alloy specimens with nearly perfect isotropic and elasto-plastic stress-strain behaviour. The finite element method (FEM) was also employed to investigate the deformation behaviour of both single piece and split type specimens loaded with a spherical indenter. These experimental and numerical results are compared so that the similarity and difference in deformation behaviour, stress distribution, and fracture response between the conventional single piece specimen method and the split type specimen method can be well understood.

2. Experimental procedures

Commercial Al 6065-T5 alloy was selected for the current investigation. To perform the compressive tests, cylindrical Al alloy specimens were machined to the size of 3 mm in diameter and 3 mm in height. Both top and bottom surfaces of the specimen were polished down to 1 μm and the graphite powders were applied between the compression plate and the specimen in order to minimize the friction effect between the die and the specimen. The cross-head speed of the Instron 4031 was 0.5 mm/min. The load-displacement diagram was obtained from the compressive test and used to measure the Young's modulus and stress-strain curve of the Al alloy specimen which are to be used as FEM data.

To perform the indentation tests, the Al alloy specimens were prepared to the size of $10 \times 10 \times 3$ mm^3. For the split type specimen test, the same piece as the single piece indentation specimen was cut into two parts with equal size of $10 \times 5 \times 3$ mm^3. The top surfaces of both test specimens and side surfaces of the bonded interface test specimens were polished down to 1 μm by using the diamond suspension to minimize the friction effect between the indenter and the specimen surface. The specimens were clamped in one direction during the tests, as shown in Fig. 1b. The same Instron 4301 machine was used to perform the single piece and the split type indentation tests. The load-displacement curves during the indentation tests were measured. An optical microscope was used to observe the outer profile of the indented specimen for comparison with FEM results.

3. Calculation

The ABAQUS [8] finite element package was used to perform all theoretical calculations. The Al 6060-T6 alloy was modeled as an elastic-plastic von Mises material. The constitutive flow curve of the Al alloy was obtained from the simple compression test as described in section 2 and input into ABAQUS as the stress-strain curve shown in Fig. 2. As shown in Fig. 2, deformation at small strain is elastic with modulus $E = 3100$ MPa. Poisson's ratio $\nu = 0.33$ [9] was used, which means the material is nearly incompressible. The material then yields at $\sigma = 180$ MPa, after which some work hardening is observed until the stress reaches the saturation value (about 225 MPa). The yield stress and ultimate stress almost coincide with the reference [10].

The indentation process was simulated by increasing the indenter displacement, h, relative to the initial surface in small increments to the total depth of 0.8 mm, and then incrementally withdrawing the indenter to the original position to reproduce the unloading behaviour.

Since the geometry of the indented specimen is neither plane strain nor axisymmetric, three dimensional analysis was employed. However, due to the symmetric condition in the geometry of the specimen and the loading condition during the indentation using a spherical indenter, only a quarter of the specimen was taken as a computing domain, see Fig. 3.

During indenting the split type specimen, the interfaces between the two half blocks interact with each other due to shear stress generated by the friction effect as well as due to normal stress. In order to consider the effect of the interface condition between the two half blocks, it is necessary to compare the deformation behaviour of specimens with different friction coefficients. One extreme case of the friction condition

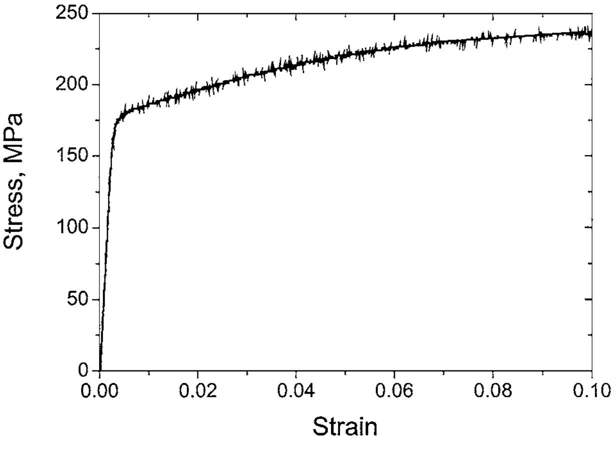
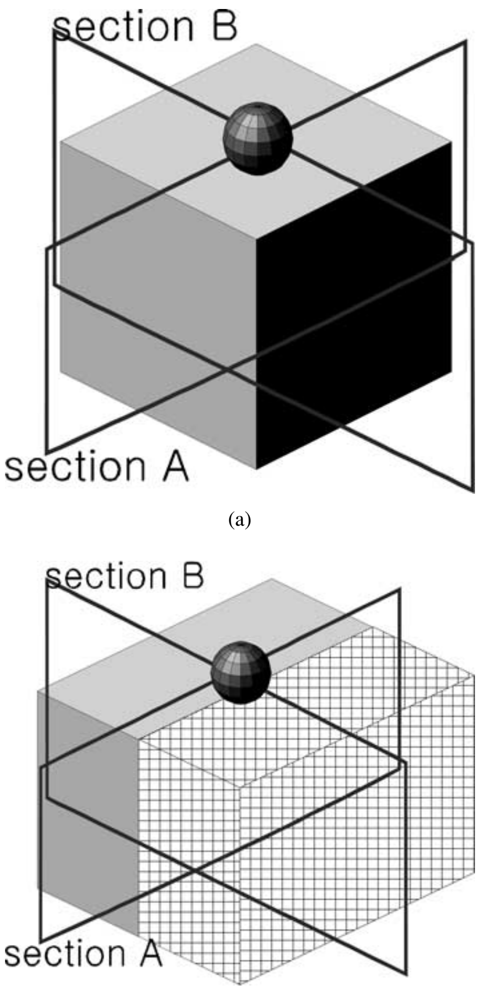


Figure 2 Stress-strain curve for 6065 Al alloy obtained from the compression test.



(a)

(b)

Figure 3 Schematics showing calculation domains for (a) single piece specimen and (b) split type specimen. Section A and section B are parallel and perpendicular to the two contact surfaces of the split type specimens, respectively.

between the two half blocks is a sticking condition, in which case the stress state is identical to that of the single specimen test. The other extreme case is a slipping (frictionless) condition between the interfaces. Here, calculations were performed for the single piece test and the frictionless split type specimen test. These two calculations cover all friction condition range and are enough to describe the difference in deformation behaviour between the single specimen test and the split type specimen test.

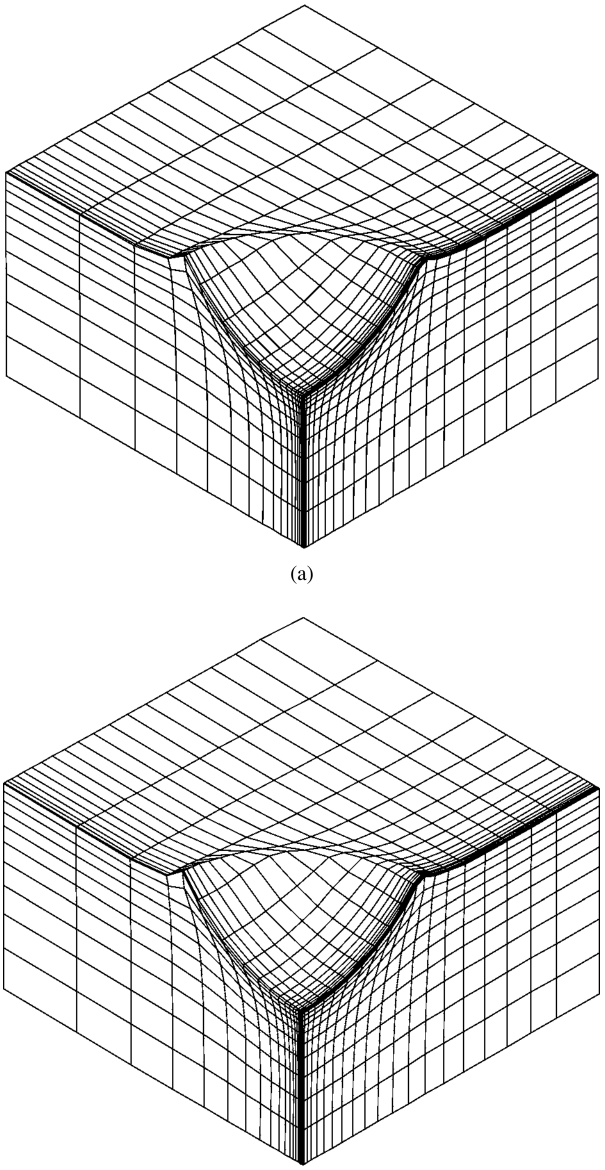
The computation utilized 2000 eight-node isoparametric brick elements and 2421 nodes. The contact condition between the indenter and the specimen surface was assumed to be frictionless. Only one quarter of the single piece specimen was calculated due to the two symmetric conditions as shown in Fig. 3a. On the other hand, one symmetric condition (section B in Fig. 3b) can be firstly applied in the split type specimen test. In addition, in order to fully utilize the symmetric condition between the two half blocks, an imaginary rigid surface at the symmetric plane was applied. By inserting the fixed rigid surface between the two half blocks, the interaction between the two half blocks is a substitute to that between a half block and the rigid surface. This technique of the imaginary fixed rigid contact surface makes it possible to reduce the calculation domain to only a quarter of the original specimen.

Unloading was simulated by removing the loading and contact conditions. The calculating time on the Alpha workstation was about 1 h.

4. Results and discussion

Fig. 4 shows the predicted grid distortions of (a) the single piece Al alloy specimen and (b) the split type Al alloy specimen after indenting 0.8 mm in depth and unloading. A narrow gap between the two split parts in the split type specimen test due to the elastic recovery of the indent region after unloading, was found although it is difficult to see in Fig. 4b. This elastic recovery at the contact surface between the two half blocks was attributed to the removal of the outer clamps which compressed the two blocks during indenting.

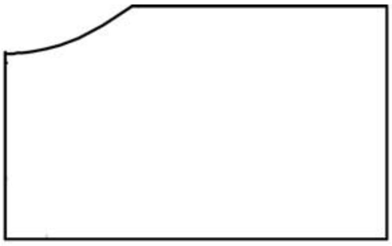
In order to investigate the difference in deformed shapes between single piece and split type specimens



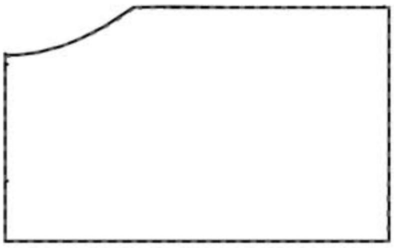
(a)

(b)

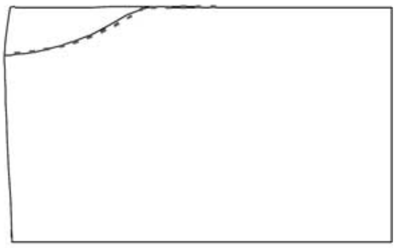
Figure 4 The predicted grid distortions of (a) the single piece specimen and (b) the split type specimen after indenting 0.8 mm and unloading.



(a) single specimen



(b) section A



(c) section B

Figure 5 Comparison of the experimental (dashed curves) and calculated (solid curves) outer profiles of the indented specimens for (a) single piece specimen, (b) section A of split type specimen and (c) section B of the split type specimen.

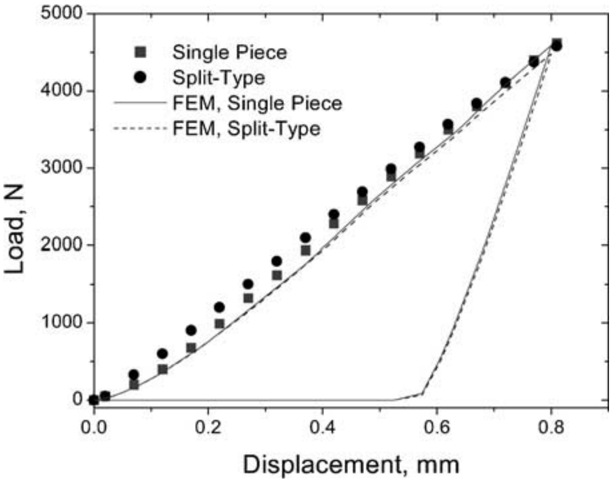


Figure 6 Comparison of an experimental load-displacement curve during loading of an indented specimen with that generated by the finite element analysis.

and between calculated and experimental results, the outer profiles of the indented specimens are plotted in Fig. 5. The experimental (dashed curves) and calculated (solid curves) outer profiles of the indented specimens are overlapped. Only the one directional view is plotted in Fig. 5a for the single specimen test because of the same conditions and geometry. For the split type specimen test, the boundary condition and specimen geometry are different at the interface plane (section A in Fig. 3b) and at the plane normal to the interface plane (section B). Hence, the outer profiles viewed from the normal to the interface plane (Fig. 5b) and from the parallel to the interface plane (Fig. 5c) are shown separately. As can be seen, the outer profiles viewed from each direction are different. An interesting observation is the curved interface shape between the two half blocks which appears in the split type specimen, Fig. 5c, while the interface is straight in the section A, Fig. 5b. It is attributed to the absence of the constraint after the unloaded state and the release of the compressive stress in the interface region by the outer clamps. It should be stressed that these two different outer profiles of the specimens in the two test methods appear after unloading not during loading. Therefore, it cannot be the evidence that the deformation behaviour of the specimens between the two methods is different at least during the indenting. The calculated deformed geometries are in good agreement with the experimental ones for both test methods. Is should be noted that the 'ridging' which is an upward extrusion of displaced metal near the indenter to form a raised crater can be found for all cases. The height of the ridge was about 0.017 mm for both the experimental and calculated measurements.

Fig. 6 illustrates the comparison of an experimental load-displacement curve during loading of indenter with one calculated by the finite element analysis. The experimental values are somewhat higher than the calculated results, which can be attributed to the ignorance of the friction between the indenter and the specimen upper surface. A little higher load in the split type test than in the single piece test of the experimental results can be attributed to the higher outer clamp constraint in the split type test. This difference in load between the single type test and the split type test dies not appear in the FEM results. The nearly identical responses between the measured and calculated curves in both single piece and split type tests confirms that the FEM calculations are satisfactory. It should be noted that the deformed geometry can be considered as strain and the load-displacement curve represents the overall stress behaviour. Therefore, the good agreements of the deformed geometry and the load-displacement curves between the measured and calculated results confirm the FEM as a useful tool for any further parametric investigation of the single type and the split type specimens indentation tests.

The friction between the two half specimens was taken to be zero in the FEM calculation. However, in real situations, the friction condition which depends on the surface state between them would not be zero and affect the deformation behaviour of the specimens. It should be noted that one extreme case with maximum friction coefficient (sticking friction) is identical to the case of the single piece specimen test, and the other extreme case is frictionless state. Since the load-displacement results obtained from both the FEM and the experiments showed almost the same curves from

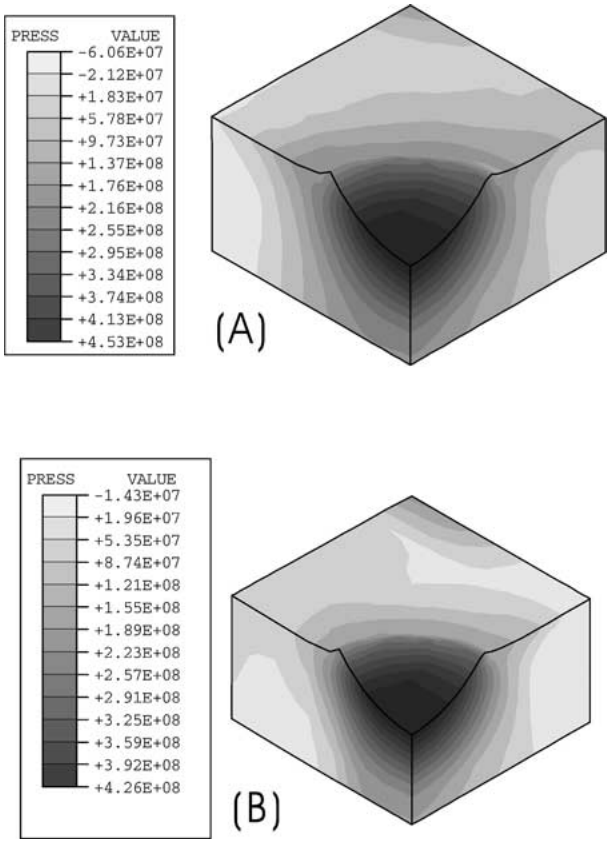


Figure 7 Comparison of the calculated hydrostatic stress (-mean stress) components between (a) the single piece sample test and (b) the split type sample test under indent displacement of 0.8 mm.

the single specimen test and the split type specimen tests, it can be concluded that the indenting load is independent of the friction condition between the two half blocks in the split type test. Therefore, the effort to have a strong bond at the interface as in the bonded interface test [4] is not necessary only if the opposite outer surfaces of the two samples are fixed during indenting.

The stress states during indenting and after unloading are examined in order to compare the deformation behaviour of the materials in detail. Fig. 7 illustrates pressure distribution under loaded conditions. The maximum pressure, i.e. compressive stress, is 330 MPa and 323 MPa for the single specimen test and the split type specimen test, respectively. The minimum pressure, i.e. tensile stress, is −47 MPa and −48.8 MPa for the single specimen test and the split type specimen test, respectively. These maximum and minimum pressure values show just a little difference between the two techniques, and the pressure distribution shapes are almost the same; i.e. axisymmetric distribution. Therefore, the internal stress response, that is the deformation behaviour, can be regarded as the same in the two methods during loading. It can also be observed from the pressure distribution after unloading (see, Fig. 8) that the shape of the pressure distribution is similar to that under loading in the single specimen, although the absolute values of the maximum and minimum pressure decreased. On the other hand, the residual stress (or pressure) which is the stress (or pressure) after unloading in the split type specimen is different from that under loading. In other words, the stress distribution is not axisymmetric and the maximum pressure (that is, the compressive residual stress) which appears at the symmetric region deviated from the indent center point. From the same pressure distribution under the loaded state and the different pressure distribution of the unloaded state between the single specimen test and the split type specimen test, we should remember that the split type specimen test is valid and can be a useful method for investigating phenomena induced during loading, for example damage, fracture and flow curve. However, it cannot be used as a main tool for residual stress related properties.

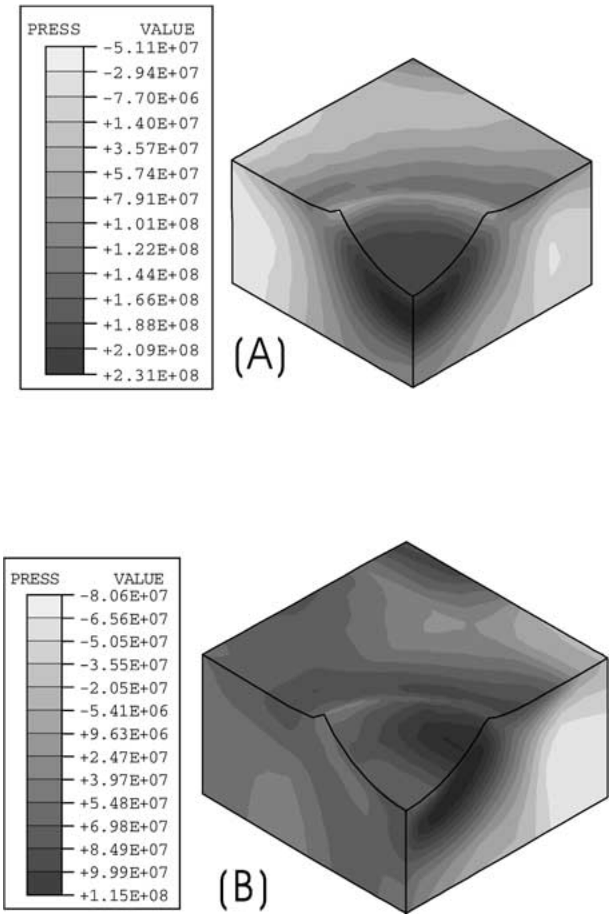


Figure 8 Comparison of the calculated residual stress components (hydrostatic stress) between (a) the single piece sample test and (b) the split type sample test.

5. Conclusions

In this paper the deformation behaviour of a split-type two pieces specimens and single specimen during the indentation tests using a spherical indenter has been investigated. The finite element method was also employed to investigate the deformation behaviour of the single piece and split type specimens loaded with a spherical indenter. The simulated geometry of the specimens and load-displacement curves during indentation are in good agreement with the experimental data of the Al alloy specimens. The similarity and difference in deformation behaviour and stress distribution between the single piece specimen method and split type specimen method are investigated. The indenting load is independent of the friction condition between the two half blocks in the split type test. The present study also gives a theoretical justification for the use of the split type indentation test as a good technique for the examination of the damaged section. However, when some properties related to the residual stress are examined, the situation of the two tests is different because of the difference in the loading conditions.

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