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Advanced Technologies for Fracture Prediction in Automotive Steel Sheets

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Abstract

In crash testing of automobile bodies, when material fracture and spot weld fracture occur, there is a possibility that the intended energy absorption cannot be obtained due to the change of deformation mode. Therefore, it is required to predict fracture of the spot weld using FEM analysis and take countermeasures in advance. We developed software that enables us to predict fracture of the material in conjunction with a general-purpose crash analysis solver. The feature of this software is the prediction of fracture considering the influence of element size in an FEM analysis model. In addition, we introduced the fracture prediction function from the heat-affected zone of spot welding.

1. Introduction

In crash tests of automobile bodies, on the occurrence of material fracture and spot weld fracture, it may be difficult to obtain the intended energy absorption. In recent years, application of ultra-high-strength steel sheet has been in progress and it has become more difficult to design automobile bodies than using conventional methods. Using FEM analysis, these fractures are predicted in advance and necessary measures are required. To this end, Nippon Steel Corporation developed NSafe™-SPOT (spot weld fracture prediction software) and NSafe™-MAT (material fracture prediction software), which operate as sub-routine programs of the general-purpose solver LS-DYNA® widely used in the crash analysis field of the automobile body. These software programs are developed based on use of the full-vehicle model. While supporting new steel types, functions have been improved and added to improve accuracy of prediction.

NSafe™-MAT predicts material fracture using stress FLD converting the strain-forming limit diagram (FLD) into the stress space.[1, 2] The fracture limit strain is created by using the Swift coefficient (n value), which can be obtained from the tensile strength characteristics of steel sheet based on S-R theory.[3] Since S-R theory is a theory predicting start of local constriction, it has the feature of determining a fracture on the safe side (early phase) in comparison with the test result of FLD. Also, in general, the finite element method calculates the strain for each element. If elements cannot be divided sufficiently finely for distribution of actual strain (gradient), a correct strain value cannot be obtained.

For the element size of the full-vehicle model for individual automobile companies, a rough size of about 2 to 5 mm is used in view of reduction of calculation cost. If a rough element size is used, there is no particular problem in the area where the material is uniformly deformed. In the area where local deformation is generated and strain is local (possible fracture), not only can the correct value of strain not be obtained, but the calculated strain value is also different depending on the element size used by the user. This may cause a problem of element size dependency.

For these issues, Nitta et al.[4] have proposed the gauge length (hereinafter referred to as GL) dependency prediction formula of the fracture limit strain. In the FLD test, the method to measure the fracture limit strain in various GLs and to formulate the relationship between the GL and the fracture limit strain is used. This can predict start of fracture, not start of local constriction. In addition, since the element size in FEM is almost equivalent to GL in the FLD test, use of this formula can support the issue of element size dependency. However, development has been conducted for high-strength (high-tensile) steel material with relatively low strength and it is known that it cannot support ultra-high-tensile-strength steel exceeding 980 MPa grade. To this end, an FLD test of ultra-high-tensile-strength steel was performed and the relationship between the GL and the fracture limit strain was obtained, and the formula structure was re-

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viewed so that the formula may support ultra-high-tensile-strength steel. The test was then implemented using the program of NSafe™-MAT. In addition, a JIS No. 5 tensile test piece model was prepared in various element sizes and fracture in the tensile test using NSafe™-MAT was predicted to verify the accuracy.

In contrast, in many cases, for ultra-high-tensile-strength steel, martensite is used to ensure tensile strength. If spot welding is performed, a heat-affected zone (hereinafter referred to as HAZ) is tempered and softened.[5] In automobile steel sheets, it has been reported that, since the tensile strength exceeded that of the 780 MPa grade, HAZ softening is found at the spot weld.[6] In the TSS test or CTS test, which is an evaluation method for spot weld joints, effects of HAZ softening are small.[7–9] In contrast, it is reported that, if in-plane tensile force is applied to 1500-MPa-grade hot-stamped steel sheet with a spot weld, strain is concentrated in the HAZ-softened area and total elongation is lowered compared to the base metal.[10] In the automobile side crash test, the flange of the B pillar may be in a deformation mode close to the above and it may cause fracture starting from the HAZ-softened area of the spot weld. Various measures are under consideration.[11]

The HAZ-softened area is caused by spot welding. As described above, the effect on joint strength of the spot weld is small. It is rather considered that it is one of the base metal fractures caused by tensile force inside the plane. Therefore, we estimated that addition of a function to NSafe™-MAT, not to NSafe™-SPOT, would be able to prevent fracture of the HAZ. Since the width of the HAZ-softened area is about 0.5 to 2.0 mm, it is necessary to make the element size of the HAZ-softened area smaller than the element size generally used. In addition, in the area where strain is concentrated like the HAZ-softened area, the issue is element size dependency. We consider that NSafe™-MAT reflecting the formula supporting the element size dependency above can solve such issues. In addition, the function that selects the spots causing HAZ softening from thousands of spot welds and that performs automatic setting for fracture prediction was added to the Pre-software (NSafe™-MAT Pre). With these development functions, fracture of the HAZ-softened area arising from a three-point bending test of the hat part or B pillar was predicted and the accuracy was verified.

2. Derivation of the Element Size Dependency Prediction Formula

In addition to the test performed by Nitta et al.,[4] an FLD test was performed for 270- to 1310-MPa-grade steel sheet including ultra-high-tensile-strength steel. The relationship between the GL and the fracture limit strain was investigated. **Figure 1** shows the representative relationship in plotting between each GL of JSC1180Y and fracture strain ε_{f1}. Also, the calculation value (solid line) fitted with the GL dependency prediction formula shown in equation (1) is also shown.

$$\varepsilon_{f1} = \alpha\,(GL)^{-\beta}.$$

To generalize α and β in equation (1) obtained for each steel type and each strain ratio ρ, α for each strain ratio ρ was arranged on the 270- to 1310-MPa-grade steel sheet. It was found that α had linear relationship with tensile strength TS. Then, using the theoretic FLD curve based on the test results or S-R theory, the FLD curve is determined in standard GL. From the FLD curve of the standard GL, ε_{f1} for any strain ratio ρ in a specific steel type can be determined. In addition, from these values and equation (1), β can be determined. Substitution of α and β determined like this in equation (1) can determine ε_{f1} for any GL. This is called the element size dependency prediction formula.

3. HAZ-softened Area Modeling Method

For example, in the case of 1500-MPa-grade hot-stamped steel sheet, the HAZ-softened area width is about 1.0 to 2.0 mm. It has been reported that, if the strength for the base metal is softened by 20% or more, fracture occurs starting from the HAZ-softened area.[10] To this end, when it is modeled with FEM, it is necessary to make the element size in the HAZ area smaller than the element size of the base metal, and to define the material characteristics of the softened HAZ area correctly. With a low-strength material, fracture was not found from the HAZ-softened area, and it has been reported that fracture starting from the HAZ-softened area is found in material exceeding 1180 MPa grade.[10] Thus, the target steel type for fracture of HAZ in NSafe™-MAT was determined to be 1180-MPa-grade steel sheet or higher.

As shown in **Fig. 2**, a new function was installed in the Pre-software of NSafe™-MAT. Elements of the base metal joined by each spot weld (beam element) were searched and the material characteristics and the average mesh size of the base metal were read. The circle of “nugget diameter + 0.4 mm” was drawn on the flange surface from the center position of the spot weld, and elements crossing with the circle were selected. The selected elements were reset to a new part different from the base metal, the average mesh size of the HAZ-softened area was obtained, and the same thickness as that of the base metal was defined. The material characteristics were also obtained from the tensile strength of the base metal by linear interpolating the Swift coefficient of the HAZ-softened area based on the micro-tensile test data of the HAZ-softened area.

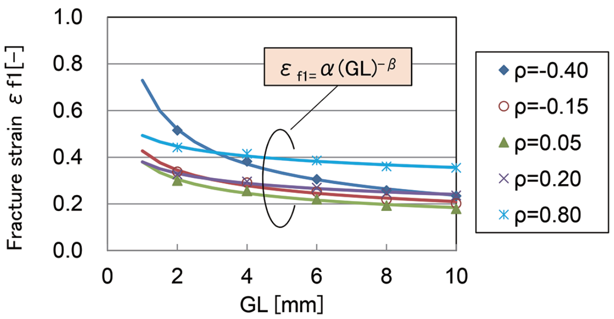

Fig. 1 Relationship between GL and fracture strain in JSC1180Y

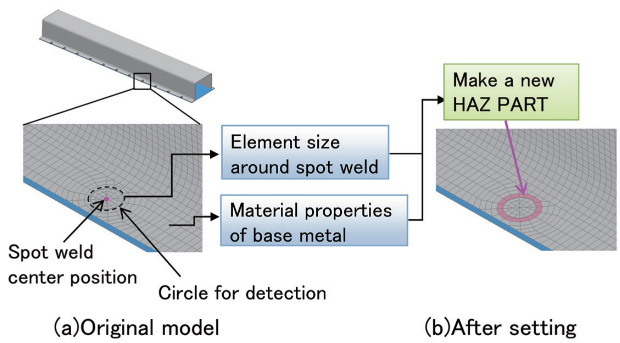

Fig. 2 HAZ softening part setting function by NSafe™-MAT Pre

4. Accuracy Verification Result of the Element Size Dependency Prediction Formula

As a typical example, **Fig. 3** shows the FLD prediction values in GL = 2, 6, and 10 mm obtained from the element size dependency prediction formula on JSC1180Y and the FLD experiment values for comparison. Accurate prediction of the test results in any GL was confirmed.

To verify the fracture prediction accuracy for the element size, a JIS No. 5 tensile test model with element sizes of 2, 3 and 5 mm was prepared (JSC980Y, thickness: 1.6 mm).

First, for comparison, **Fig. 4** shows the fracture prediction result by the equivalent plastic strain with MAT24 conventionally used. Tensile strength was applied until the gauge length strain (gauge length: 50 mm) of the model with an element size of 2 mm reached the same value as the gauge length strain (= 0.147), which caused fracture in the test, and the maximum equivalent plastic strain value (= 0.50) at this time was read and it was determined to be the criterion. After prediction of the fracture with the model of element sizes of 3 and 5 mm using the criterion, it was found that the test result cannot be predicted with delayed fracture timing because concentration of strain on the constriction cannot be reproduced with increase of the element size.

In contrast, **Fig. 5** shows the result after the element size dependency prediction formula was installed in NSafe™-MAT and prediction of the fracture was performed. With NSafe™-MAT Pre, the Swift coefficient was obtained from the S-S (stress-strain) curve and the average element size was read. Using these values, the strain FLD was created with NSafe™-MAT and it was converted to the stress FLD to predict fracture. From Fig. 5, fracture timing of the test could be accurately predicted and fracture could be predicted at the almost same timing for any element size. From the above, we believe that use of this development method can solve the issue of element size dependency when material fracture is predicted.

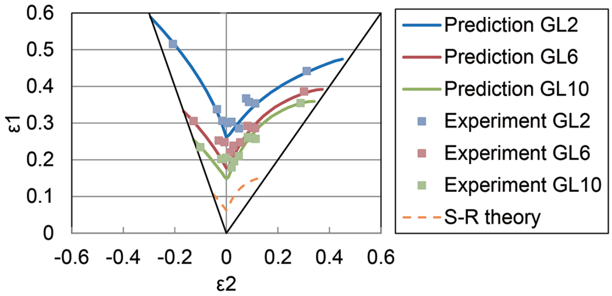

Fig. 3 Comparison of predicted values and experimental values in JSC1180Y FLD

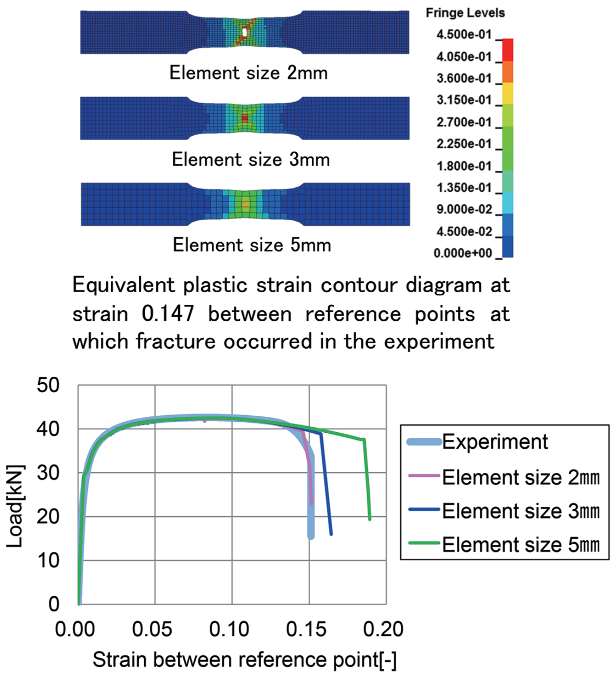

Fig. 4 JIS No.5 tensile test model fracture prediction result by conventional method (MAT24)

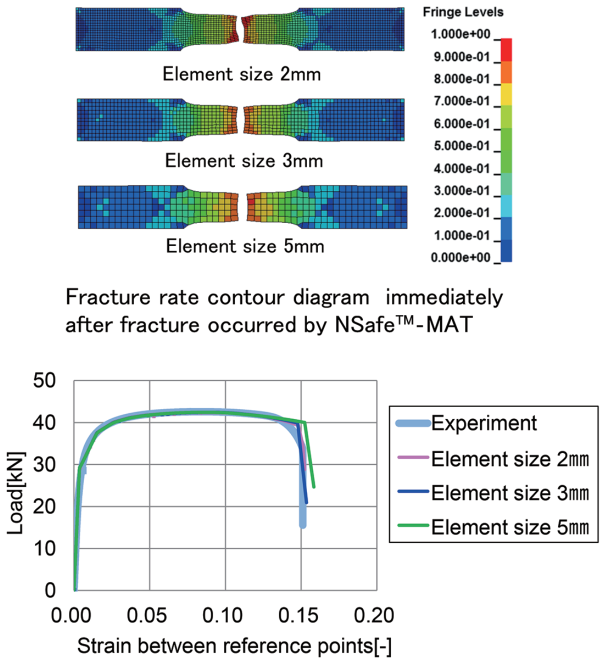

Fig. 5 JIS No.5 tensile test model fracture prediction result by NSafe™-MAT

5. Fracture Prediction Result of the HAZ-softened Area Using the Element Size Dependency Prediction Formula

Using NSafe™-MAT Pre described above, the HAZ-softened area was modeled, and using NSafe™-MAT with the element size dependency prediction formula implemented, the fracture prediction accuracy of the HAZ-softened area was verified. The three-point bending FEM model of the 1500-MPa-grade hot-stamped steel sheet and the hat material with a thickness of 1.6 mm (the back panel is a 440-MPa-grade steel sheet with a thickness of 1.2 mm) shown in **Fig. 6** was created. The test was performed, the load-stroke diagram was obtained, and the fracture position and timing were compared. For verification of accuracy, the results under the condition (element size: base metal of 1.33 mm and HAZ area of 1.16 mm) of the spider mesh recommended as the method to determine the mesh around the spot weld, and the condition (element size: base metal of 1.0 mm and HAZ area of 1.0 mm) of the lattice mesh with a low-mesh-creation load were compared. With the model using the HAZ-softened area as the spider mesh, the condition

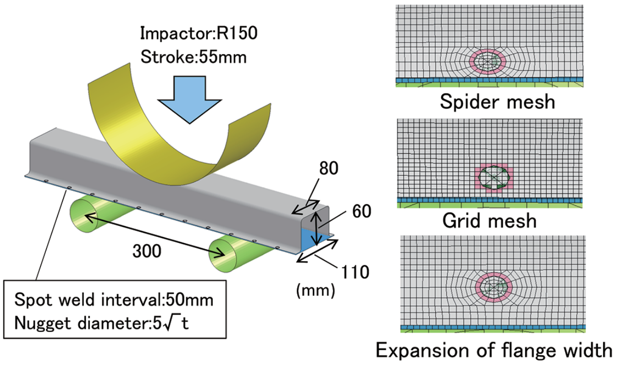

Fig. 6 Three-point bending FEM model of hat type member and HAZ part modeling

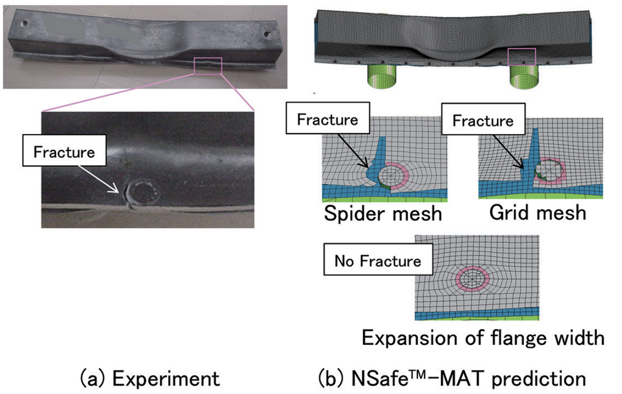

Fig. 7 Three-point bending test result of hat member and fracture prediction result by NSafe™-MAT

(flange width from 9.2 mm to 14.2 mm) with the flange width enlarged without fracture from the HAZ-softened area in the test was also analyzed.

Figure 7 shows the three-point test result of the hat part and the fracture generation status in the fracture prediction result obtained with NSafe™-MAT, and **Fig. 8** shows the load-stroke diagram. In the test, fracture occurred starting in the HAZ-softened area. In the prediction with NSafe™-MAT, when the mesh of the HAZ-softened area was turned into a spider type and a lattice type, fracture was predicted at the almost same timing and good accuracy was confirmed in comparison between these and the test. Under the enlarged flange width conditions, which did not cause fracture in the test, fracture did not occur in the final stroke and the test result could be reproduced.

Figure 9 shows the flange width enlargement condition, which did not cause fracture, and the main stress history of the element, which is the fracture start point under the spider mesh condition being the base condition. This shows that compression stress is applied at initial deformation under all conditions and that stress in the plane strain zone is then applied. It is considered that enlargement of the flange width reduces final stress in the plane strain zone, resulting in no fracture.

Then, to conduct evaluation under conditions close to those for an actual part, fracture from the HAZ-softened area was predicted using the three-point bending model (element size: base metal of 1.47 mm and HAZ area of 1.10 mm) of the B pillar (outer and reinforcement: 1 500-MPa-grade hot-stamped steel sheet with a thickness of 1.6 mm; inner: 590-MPa-grade steel sheet with a thickness of 1.2 mm) shown in **Fig. 10**.

Figure 11 shows the three-point bending test of the B pillar and fracture generation status of the fracture prediction result with NSafe™-MAT and **Fig. 12** shows the load-stroke diagram. In the test, when the stroke was 42 mm, fracture occurred at View A and when the stroke was 52 mm, fracture occurred starting from the HAZ-softened area at View B. Also in the FEM analysis, fracture from the HAZ-softened area was predicted at the same spot weld position and at almost the same timing. This confirmed that fracture from the HAZ-softened area can be predicted in an actual part by using NSafe™-MAT.

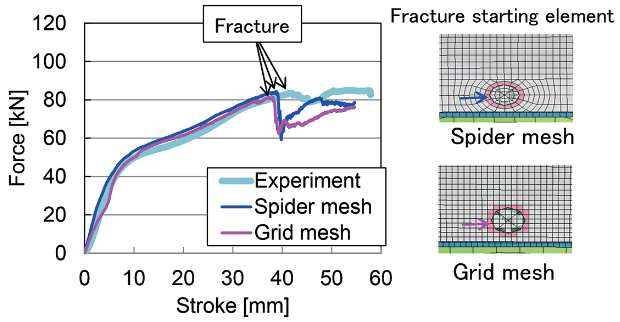

Fig. 8 Force-stroke diagram in three-point bending of hat member

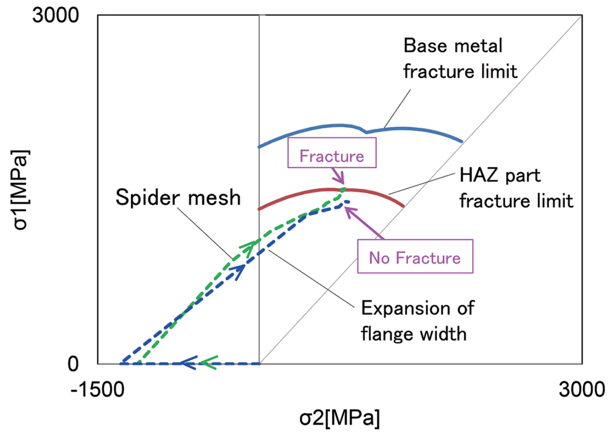

Fig. 9 Principal stress history of fracture starting element in NSafe™-MAT

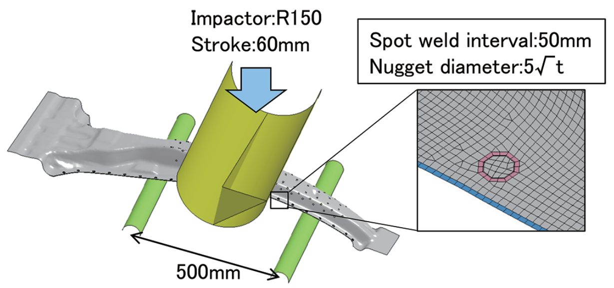

Fig. 10 Three-point bending FEM model of B-pillar and HAZ part modeling

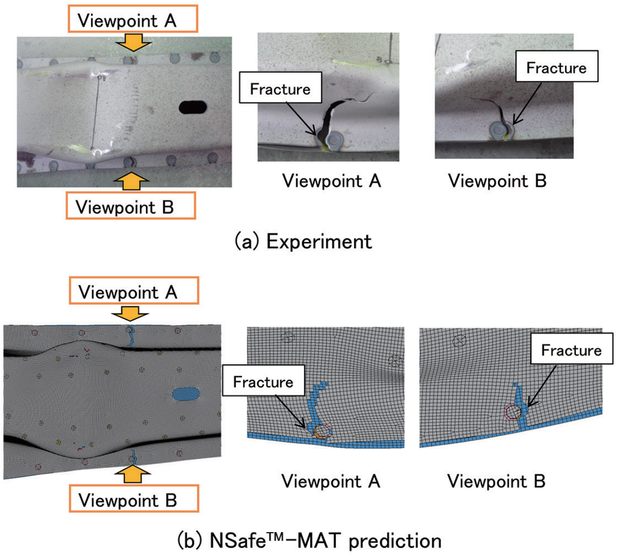

Fig. 11 Fracture prediction result by NSafe™-MAT in B-pillar three-point bending

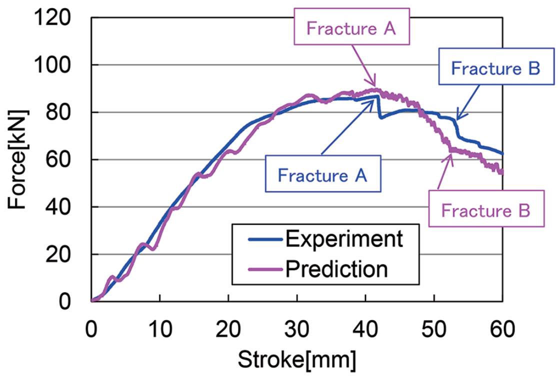

Fig. 12 Force-stroke diagram in three-point bending of B-pillar

6. Conclusion

In the crash analysis of the automobile full-vehicle model, software (NSafe™-MAT) that can predict material fracture at high accuracy was developed. If the element size is different in prediction of material fracture, the element size dependency prediction formula of fracture limit strain, which can be used for ultra-high-tensile-strength steel for the issue of variable fracture prediction timing, was devised. The devised formula was implemented in NSafe™-MAT. After the FEM analysis of the JIS No. 5 tensile test models prepared using various element sizes, the fracture timing of the test could be accurately predicted and fracture could be predicted at the almost same timing for any element size.

Also, by installing the modeling function of the HAZ-softened area on NSafe™-MAT Pre and using NSafe™-MAT implementing the element size dependency prediction formula, it was confirmed that fracture starting in the HAZ-softened area could be predicted in the three-point bending test of the hat part. In comparing the spider mesh with the lattice mesh, it was found that the effect of mesh cutting was small. It was also found that increase in flange width could suppress occurrence of fracture in the HAZ-softened area. In addition, fracture starting in the HAZ-softened area in the B pillar three-point bending test was accurately predicted, and usefulness for actual parts was confirmed.

References

1) Yonemura, S. et al.: Tetsu-to-Hagané. 93 (4), 317 (2007)
2) Uenishi, A. et al.: Shinnittetsu Giho. (393), 32 (2012)
3) Stören, S. et al.: J. Mech. Phys. Solids. 23, 421 (1975)
4) Nitta, J. et al.: The proceedings of Japanese Joint Conference for the Technology of Plasticity. 56, 39 (2005)
5) Fujimoto, H. et al.: Quarterly Journal of the JWS. 33 (2), 144 (2015)
6) Fujimoto, H. et al.: Proceedings of JSAE Annual Spring Congress. (105-02), 5 (2002)
7) Okita, Y. et al.: Preprints of the National Meeting of JWS. (89), 36 (2011)
8) Taniguchi, K. et al.: Preprints of the National Meeting of JWS. (89), 4 (2011)
9) Watanabe, F. et al.: Preprints of the National Meeting of JWS. (91), 238 (2012)
10) Fujimoto, H. et al.: Quarterly Journal of the JWS. 34 (4), 285 (2016)
11) Nakamura, T. et al.: Mazda Technical Review. (31), 14 (2013)

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