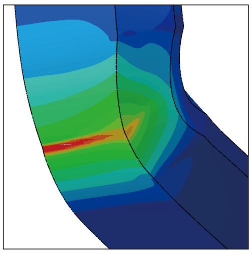

Prediction Technique for Bending Cracks in Terminal Forming of Copper Alloy Sheets

Toshiro SAKAI*, Ryoma TAKAGI, Kingo FURUKAWA, Makoto FUJIMOTO, Toru TANJI, and Soichiro OKUMURA

As terminals for automotive connectors become smaller, the copper alloys used for the terminals are becoming thinner and stronger. Terminals are formed mainly by bending, but the higher strength of copper alloys makes bending cracks more likely to occur. In the past, this problem was handled by trial and error based on experience, but in order to cope with the recent short development period, a technique for predicting bending cracks using CAE is required. Although special elasto-plastic analysis reflecting the crystallinity of metals has been reported as a conventional prediction technique for bending cracks, it has been difficult to apply this technique to actual copper alloys for terminals. Therefore, based on the occurrence mechanism of bending cracks, we considered that shear deformation resistance in the thickness direction has a significant influence on the occurrence of bending cracks, and developed a shear test method for thin sheets in the thickness direction. Based on the measurement results, it becomes possible to predict the occurrence of bending cracks by simulating bending cracks using the general elasto-plastic analysis.

Keywords: automotive connector terminal, copper alloy sheet,bending,bending crack, simulation

1. Introduction

With the recent advance in sophistication and autonomy of automobiles, the number of sensors and other electronic components used in automobiles has increased. These electronic components have also been miniaturized, and the connectors for automotive wiring harnesses that connect electronic components have become progressively smaller and more multipolar. In association with this, automotive terminals have also been miniaturized, and the thickness of the copper alloy used for the terminals has been reduced, while its strength has been increased.[1]

Since there is usually a trade-off between strength and workability, an increase in strength will result in a high likelihood of bending cracks occurring during the bending process. Since most automotive terminals are box-shaped and are usually formed by bending, bending cracks lead to dimensional defects and performance degradation of the terminals. Various time-consuming and costly countermeasures have been taken through trial and error based on the experience of the persons in charge. Such countermeasures include the use of high-strength copper alloys whose bend formability has been improved through structure control or other techniques,[2],[3] changes in molds and processes, and changes in product shape.

Meanwhile, the product life cycle has decreased in recent years, and the need has arisen to shorten the development period. If bending cracks can be predicted by simulation, their initiation points and propagation processes can be visualized, making it easier to identify the causes and formulate countermeasures. Furthermore, the number of times of trial manufacture can be reduced by verifying the countermeasures through simulation, making it possible to shorten the product development period and reduce costs.

To establish a technique for predicting bending cracks by simulation, we inquired into the mechanism of their occurrence and focused on shear deformation in the thickness direction. As a result, we have developed a simple new method for testing the shear of thin copper alloy sheets for terminals in the thickness direction. The new test method has made it possible to predict bending cracks by elasto-plastic analysis*1 using the finite element method*2 (hereafter referred to as "CAE"), by applying the test results to the material model. This paper discusses the new bending crack prediction technique.

2. Challenges for Prediction of Bending by CAE

Figure 1 shows the appearance and the cross-section of a bent section of 7-3 brass (hereafter referred to as "the brass") and Cu-Ni-Sn-P alloy (hereafter referred to as "alloy A") when they are bent to 180°. The brass is used for many automotive terminals, while alloy A is a high-strength copper alloy that is widely used for small terminals for automotive applications. For comparison, a 180° bend of pure copper is also shown. In the following discussions, the rolling direction is abbreviated as RD, the direction orthogonal to the rolling direction as TD, and the thickness direction as ND. RD and TD in Fig. 1 denote the bending direction of each material. Compared with pure copper, large streak patterns or "wrinkles" are observed on the surface of the bend of both the brass and alloy A. As can be seen from the cross-sections, wrinkles are caused by localized depressions in the surfaces. Furthermore, the cross-section of the TD-bend of alloy A verifies that cracks occurred from the bottom of the wrinkles and broke the alloy. Thus, cracks occur when the wrinkles become larger.

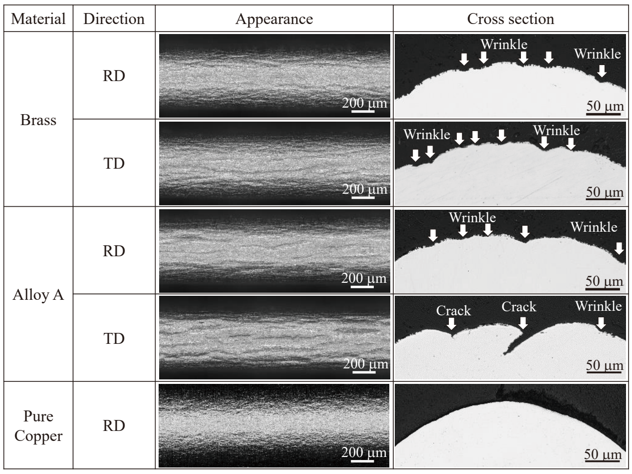

Fig. 1. Appearance and cross-sections of 180° bent section of the brass, alloy A, and pure copper

Next, the CAE analysis results for bending alloy A to 180° are shown in Fig. 2. This analysis was a two-dimensional analysis by assuming the cross-section in the center of the width of the bend. The material model was an isotropic material*[3] that reflected the stress-strain curve obtained from an RD-tensile test of alloy A. The principal strain*[4] distribution is shown in the figure. The strain increased in the vicinity of the bend apex. However, the above analysis could not reproduce localized depressions such as wrinkles that were observed in the actual bending. Thus, conventional CAE could not reproduce wrinkles that appeared in the preliminary stage of cracking, making prediction of bending cracks difficult. In the past, a bending wrinkle and crack prediction technique called "crystal plasticity analysis" was reported.[(4),(5)] This technique uses a special analysis method, which reflects the crystalline nature of metals. However, this method raises problems when it is used for copper alloy materials for actual terminals. There was thus a need to establish a technique for predicting bending wrinkles and cracks using conventional CAE.

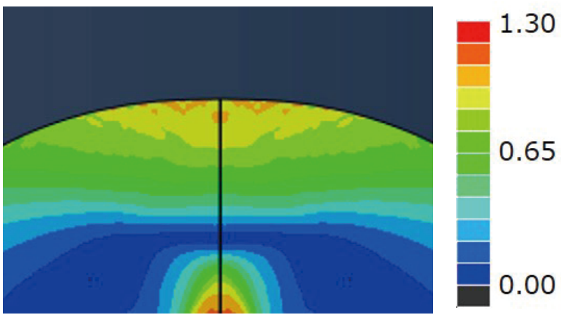

Fig. 2. Bending analysis result obtained by conventional CAE (principal strain distribution)

3. Occurrence Mechanisms of Wrinkle and Crack in Bending

The probable reason that conventional CAE could not reproduce bending wrinkles was that the physical property values involved in the occurrence of wrinkles were not reflected in the material model. Therefore, we first reviewed the bending wrinkle occurrence mechanism. Figure 3 shows the EBSD*[5] analysis results for the crystal orientation distribution in the TD direction near the bending wrinkles that occurred during 180° bending (TD) of alloy A. This figure shows that the crystal grains in the area separated by white dotted lines are finer than those in the surrounding areas, and that they are elongated in a specific direction. This area, where deformation is concentrated locally, is called the "shear zone." It has already been found that bending wrinkles are formed by shear zones and bending cracks occur along the shear zones.[(6),(7)] Since shear zones are composed of grain groups elongated in a specific direction, we concluded that shear zones are produced by the following mechanism.

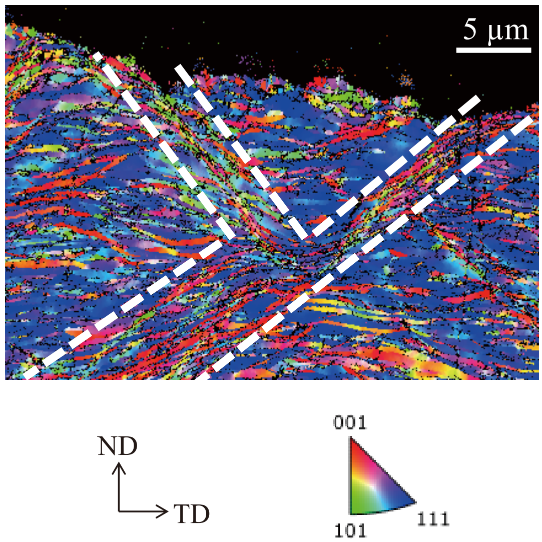

Fig. 3. Crystal orientation distribution of TD 180° bending wrinkles on alloy A

Bending is usually associated with the deformation shown in Fig. 4 (a). Tension is mainly induced in the bending direction on the outside of the neutral plane, while compressive plastic deformation is mainly induced on the inside. Since plastic deformation such as shear in the thickness direction is minute, no large irregularities occur on the sheet surface. However, some materials have small deformation resistance to shear. Materials with small deformation resistance to shear in the thickness direction are likely to cause local plastic deformation due to shear stress in the thickness direction. In such materials, the direction of shear deformation is inclined from the thickness direction as shown in Fig. 4 (b), since they undergo shear stress in the thickness direction and tensile stress in the bending direction on the outside of the neutral plane, while undergoing shear stress in the thickness direction and compressive stress in the bending direction on the inside of the neutral plane. This local deformation is considered to create shear zones. Furthermore, we considered that if multiple shear zones are created by the same mechanism, localized depressions and wrinkles would be formed as shown in Fig. 4 (c).

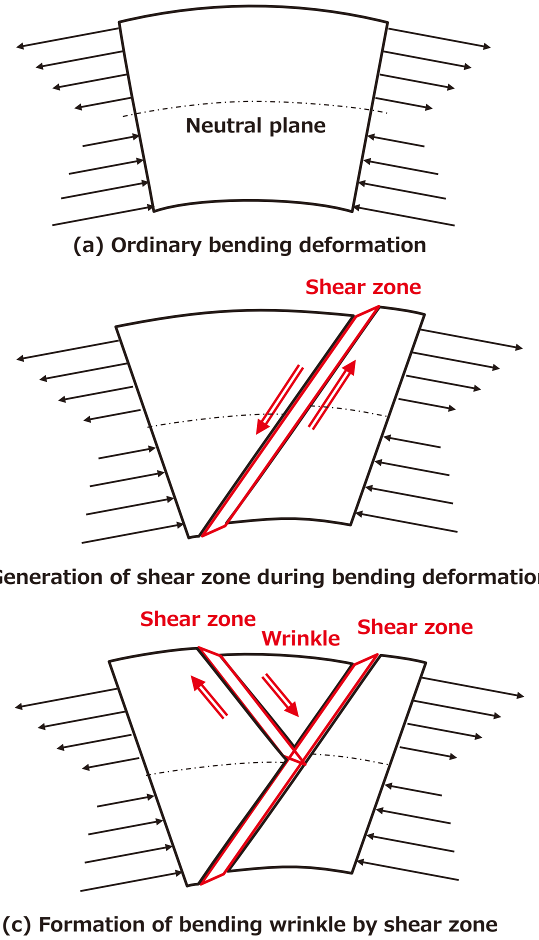

Fig. 4. Mechanism of shear zone generation due to shear stress in the sheet thickness direction during bending deformation and the wrinkle formation mechanism

As described above, the shear zone, which is the cause of bending wrinkles and cracks, is considered to be generated by shear deformation in the sheet thickness direction. Therefore, we considered that measuring the deformation resistance to shear in the sheet thickness direction and reflecting the measured value in the CAE material model was indispensable for predicting bending wrinkles and cracks.

4. Measurement Method of Deformation Resistance

To measure the deformation resistance to shear in the thickness direction, it is necessary to conduct a shear test in the thickness direction. Despite in-plane shear tests for metallic materials being specified in ASTM B831 and other standards, there is no standard that specifies shear tests for metallic materials in the thickness direction. Furthermore, it was difficult to apply the shear tests for composite materials and resins to copper alloys since they are as thin as approximately 0.25 mm. Recently, we have developed a simple method for testing the shear in the thickness direction of copper alloys for terminals. An outline of the new method is given below.

4-1 Simple shear test method

The appearance and schematic illustration of the test jigs we designed are shown in Fig. 5. Rectangular specimens measuring 5 mm in width and 10 mm in length were used. The test jigs were attached to a tensile testing machine, and the shear stress was calculated by measuring the test load with a load cell. However, in the method for calculating strain from the change in the stroke of the testing machine, it was difficult to accurately measure the strain due to the large influence of the elastic deformation of the testing machine and jigs.

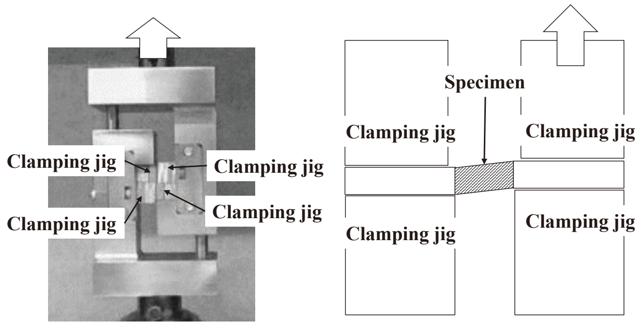

Fig. 5. Appearance and schematic illustration of jigs for simple shear test

To overcome this difficulty, we photographed and recorded the end face of the test part with a digital microscope during the test, and measured the strain by analyzing the images using the digital image correlation method.*[6] Figure 6 shows an example of the strains on the ND-TD cross-sections of the brass, which were obtained by this test method. In the figure, shear represents the shear strain, while ND and TD represent the tensile or compressive

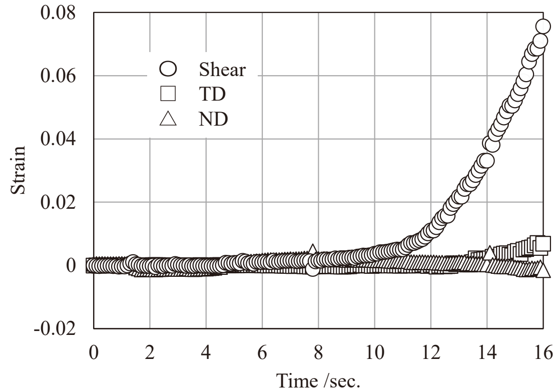

Fig. 6. Strains obtained by using the digital image correlation method for the simple shear test (the brass, ND-TD cross-section)

strain in each direction. As the test progressed, only the shear strain increased, verifying that the simple shear test had been conducted as intended.

4-2 Simple shear test result

As described above, shear deformation in the thickness direction is involved in the generation of shear zones that cause bending cracks, and a material being deformed by bending is subjected to shear stress in the thickness direction along with tensile and compressive stresses in the bending direction. In other words, RD bending causes RD tensile and compressive deformations as well as shear deformation in the RD-ND cross-section. This means that a simple shear test in the thickness direction and a tensile test in the in-plane direction are necessary to predict bending wrinkles and cracks. Figure 7 shows the stress-strain curves obtained from the RD tensile tests of the brass and alloy A, together with those obtained from a simple shear test for the RD-ND cross-section of these materials.

For both materials, the stress and strain had a linear relationship in the elastic region where the strain was small. The slope of the stress is called “Young’s modulus” (longitudinal modulus) in a tensile test and “shear modulus” (transverse modulus) in a simple shear test. The Young’s modulus and shear modulus of the brass were measured to be 102 GPa and 43 GPa, respectively, while those of alloy A were measured to be 120 GPa and 40 GPa, respectively. These values were reasonable for both materials, being copper alloys. From these stress-strain curves, 0.2% proof stress was obtained as an indicator of deformation resistance.

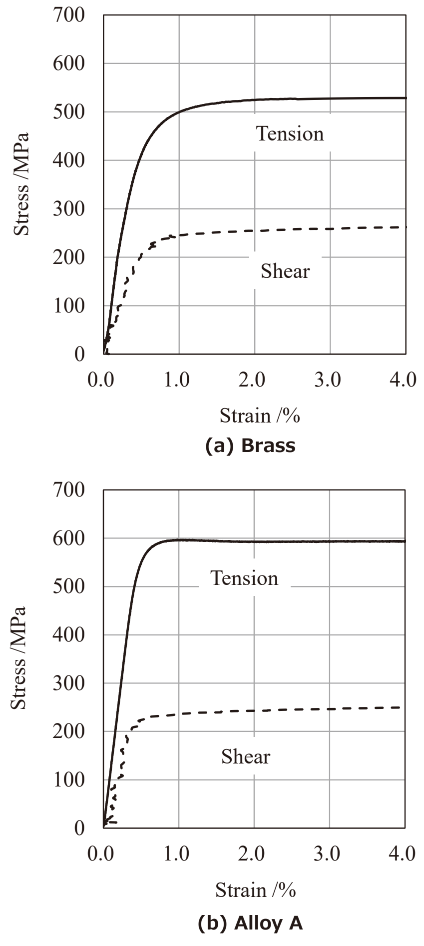

Fig. 7. Stress-Strain curves obtained from uniaxial tensile and simple shear test

Table 1 shows the 0.2% proof stresses obtained from the tensile and simple shear tests. In the table, the values for the test direction of RD are the test results for RD tension, which is involved in RD bending, and the simple shear of the RD-ND cross-section. The values for the test direction TD are the same as those for the test direction RD. Based on the consideration that shear deformation resistance relative to tensile and compressive deformation resistances is an indicator of the generation of shear zones, the proof stress ratios (shear/tension) and bendability are also shown in the table. The proof stress ratio of isotropic materials is 0.57 (= 1/√3). All of the copper alloy sheets for terminals measured in this study exhibited a proof stress ratio of less than 0.50, indicating that these sheets are more likely to cause shear deformation in the thickness direction than isotropic materials. In particular, in the TD bending of alloy A that caused bending cracks, the proof stress ratio was 0.40, which was 30% smaller than that of isotropic materials. This suggests that TD bending of alloy A tends to cause shear deformation in the thickness direction, and that shear zones generate and develop in the early stage of the bending process, resulting in the occurrence of bending cracks. The above results support the idea that shear deformation in the thickness direction is involved in the development of shear zones that cause bending wrinkles and cracks, and that a simple shear test in the thickness direction is important for predicting the occurrence of bending wrinkles and cracks.

Table 1. 0.2% proof stresses obtained from shear and tensile tests of the brass and alloy A, along with their proof stress ratio (shear/tension) and bendability

Material		Brass		Alloy A	
Direction		RD	TD	RD	TD
0.2% proof stress MPa	Shear	233	217	251	230
	Tension	473	457	560	583
	Ratio	0.49	0.48	0.45	0.40
Bendability		▲	▲	▲	×

▲: wrinkle ×: crack

5. Prediction of Bending Wrinkles and Cracks by CAE

The above results show that it was impossible to predict the occurrence of bending wrinkles and cracks by conventional CAE, because it was assumed that the material models were isotropic. We worked on the possibility of predicting bending wrinkles and cracks by reflecting the actual tensile and shear test results for copper alloys for terminals in the CAE material model.

In this study, we applied Hill’s quadratic yield function to the material model in order to reflect the behavior of shear deformation resistance that becomes smaller than tensile and compressive deformation resistance, which is observed in copper alloys for terminals. The above anisotropic yield function can be used for many software and is relatively easy to handle. Figure 8 shows the results of the analysis conducted by reflecting the 0.2% proof stress obtained from tensile and shear tests of alloy A in the material model. Figures 8 (a) and (b) show the principal strain distribution in RD and TD bending, respectively. As in actual bending of alloy A, the occurrence of shear zones where the strain was localized on a straight line could be reproduced. In addition, depressions were formed on the surface by multiple shear zones, which verified that bending wrinkles could be reproduced. Furthermore, the difference between RD bending and TD bending could also be expressed. It can also be seen that in TD bending where bending cracks had actually occurred, shear zones developed more rapidly than in RD bending.

As discussed above, using thickness direction simple shear test results and the anisotropic yield function has made it possible to predict bending wrinkles and cracks by commonly used CAE.

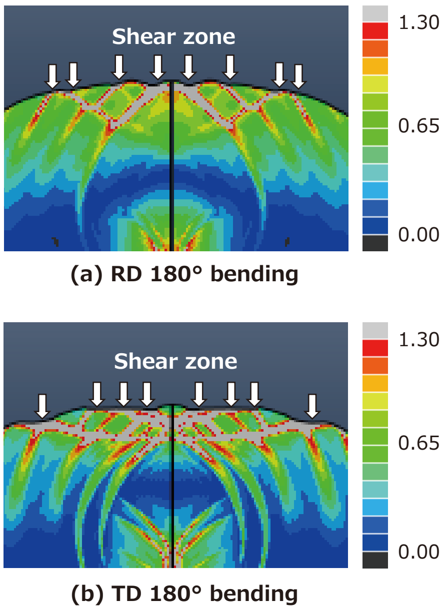

Fig. 8. Analysis results of 180° bending by CAE for which shear test results were reflected in the material model (principal strain distribution)

6. Conclusion

To predict the occurrence of bending wrinkles and cracks in copper alloys used for automotive connector terminals by CAE, we have established a simple new method for testing shear in the thickness direction. It has become possible to predict bending wrinkles and cracks by CAE, by applying the results obtained from the new shear test to the material model.

Currently, the new technique is used for terminals under development to shorten the development time, improve their reliability, and increase the productivity by reducing defects.

In the future, we will use this technique for other metallic materials and products in order to develop new processing methods and materials.

7. Acknowledgment

We would like to express our gratitude to Kobe Steel, Ltd. for providing samples and examining them in the pursuit of this study.

Technical Terms

*1 Elasto-plastic analysis: A method for analyzing the stress and strain of elasto-plastic materials, which exhibits both elastic and plastic properties, using a mathematical model of nonlinearity.

*2 Finite element method: A method for numerically analyzing structures by dividing them into multiple elements (meshes).

*3 Isotropic material: A material whose mechanical properties do not change with direction.

*4 Principal Strain: Tensile or compressive strain (vertical strain) at any point in an object varies in magnitude depending on the direction. However, there are always mutually orthogonal directions in which the vertical strain reaches an extreme value. The vertical strain in such directions is called the “principal strain.”

*5 EBSD: An abbreviation for the “electron back scattered diffraction” pattern, a method for analyzing the orientation of crystal grains of samples by irradiating samples with electrons beam and analyzing the backscattered diffraction generated from the electrons diffracted on the surfaces of the samples.

*6 Digital image correlation method: A method for measuring strain by determining the displacement of the measurement target from images captured by CCD camera or other means.

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