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O. Koray Demir

#### Abstract

A new method is proposed to determine the electromagnetic forming limits of sheet metal. The method deforms the specimen apex on a constant strain path, as strain measurements and simulations confirm. The strain path can be varied between uniaxial tension and biaxial tension by changing the specimen and tool shapes. Furthermore, the method breaks the specimen at the apex. In order to ensure an apex failure and avoid bending, a new specimen concept that promotes uniform pressure application is developed.

The proposed method is used to find the electromagnetic forming limit curves for AA1050A, AA5083, and Mg AZ31 sheets. These materials exhibit higher necking limits in the electromagnetic forming, when compared to quasi-static forming. In addition, in the electromagnetic forming, the limits increase with the strain rate. The proposed method is also used to find the fracture limits of these materials under uniaxial tension. The materials exhibit higher fracture limits in the electromagnetic forming. In order to explain the higher forming limits in the electromagnetic forming, fracture surfaces of quasi-static and electromagnetic samples are examined.

Fracture surfaces reveal that the failure in the quasi-static forming is driven by inplane shear stress, while the failure in the electromagnetic forming is driven by tensile and out-of-plane shear stress. This suggests the existence of out-of-plane shear stress in the electromagnetic forming. Out-of-plane shear stress is shown by Allwood and Shouler (2009) to increase elongation to failure in quasi-static tensile tests. This dissertation proposes out-of-plane shear stress as a reason for the higher limits in the electromagnetic forming. In the electromagnetic forming, out-of-plane shear stresses can arise from the out-of-plane electromagnetic forces. Simulations of the electromagnetic forming limit test shows that they reach considerable magnitudes (about 30% of the initial shear yield stress). Simulations at different velocities show that they increase with the forming rate.

For the reasons of higher forming limits in the electromagnetic forming, previous research has identified inertial stabilization, strain rate hardening, impact with a die, and an increased deformation by twinning. This dissertation demonstrates the positive effect of inertial stabilization, and documents the increase of twinning in the electromagnetic deformation of AZ31. Besides, out-of-plane shear is proposed as a new addition to the list of reasons for higher limits in the electromagnetic forming.

### Zusammenfassung

Eine neue Methode wird vorgeschlagen, um elektromagnetische Grenzformänderungskurven für Blech zu bestimmen. Diese Methode verformt Blechproben auf einem konstanten Dehnpfad, wie Dehnungsmessungen und Simulationen bestätigen. Der Dehnpfad kann zwischen einachsigem und zweiachsigem Zug variiert werden, indem die Proben- und Werkzeuggeometrien geändert werden. Außerdem führt die Methode zu einem Riss in der Probenmitte. Um den mittigen Riss zu gewährleisten wird eine neue Probengeometrie entwickelt, die eine gleichmäßige Druckverteilung begünstigt.

Die vorgeschlagene Methode wird verwendet, um Grenzformänderungskurven für Bleche aus AA1050A, AA5083, und Mg AZ31 zu bestimmen. Diese Werkstoffe zeigen in der elektromagnetischen Umformung höhere Einschnürungsgrenzen als in der quasi-statischen Umformung. Außerdem erhöhen sich mit steigender Formänderungsgeschwindigkeit die Einschnürungsgrenzen. Durch die vorgeschlagene Methode werden auch die Bruchgrenzen dieser Werkstoffe unter einachsigem Zug bestimmt. In der elektromagnetischen Umformung liegen die Bruchgrenzen höher als in der quasistatischen Umformung. Um die höheren Einschnürungs- und Bruchgrenzen zu erklären werden die Versagensmechanismen der Proben anhand von Bruchbildern untersucht.

Die Bruchbilder zeigen, dass das Versagen in der quasi-statischen Umformung durch Schubspannungen *in der* Blechebene, in der elektromagnetischen Umformung dagegen durch Schubspannungen *außerhalb* der Blechebene verursacht wird. Schubspannungen außerhalb der Blechebene erhöhen nach Allwood und Shouler (2009) die Formänderungsgrenzen beim quasi-statischen Zugversuch. Diese Dissertation setzt dieses auch für die elektromagnetische Umformung voraus. Schubspannungen außerhalb der Blechebene können aus elektromagnetischen Prozesskräften entstehen, die außerhalb der Blechebene wirken. Simulationen zeigen, dass sie ungefähr 30% der initialen Fließspannung erreichen und sich geschwindigkeitsabhängig erhöhen.

Bisher wurden als wichtigste Gründe der höheren Formänderungsgrenzen in der elektromagnetischen Umformung die Massenträgheit, die dehnratenabhängige Verfestigung, der Aufprall der Matrize und die erhöhte Zwillingsbildung angenommen. Diese Dissertation zeigt die positive Wirkung der Massenträgheit und beweist die Erhöhung der Zwillingsbildung bei Mg AZ31. Schubspannung außerhalb der Blechebene wird als neuer Grund vorgeschlagen.

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