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The Recovery of Elastic Properties at 35 °C in TRIP 700 Steel Following Deformation

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The influence of plastic deformation on the elastic properties that determine the magnitude of springback following forming was investigated using dynamic modulus analysis. For this study, the elastic modulus of TRIP 700 steel was measured continuously at 35 °C and a loading frequency of 1.0 Hz for 1000 min following deformation by cold rolling to varying levels up to 27%. The elastic modulus increased at an exponentially decaying rate during these experiments and with a magnitude that increased with pre-strain. These observations are consistent with the hypothesis that deformation creates microstructural defects that contribute compliance when the stress state changes and that these defects are removed by annealing at this low temperature.

Keywords anelastic, dynamic modulus analysis, elastic modulus, forming, modulus recovery, springback, TRIP steel

1. Introduction

The ability of metals and alloys to be readily formed into a variety of shapes is a major reason why they are selected over other materials for applications such as stamping of automobile bodies. One factor inhibiting the development of stamped products is the cost of recutting and reshaping the stamping dies to account for springback. Springback is defined as the spontaneous (elastic) shape change that occurs in the stamped part when the forming load is removed. Computer-generated springback-compensated die designs would eliminate or reduce the cost of the recutting and reshaping of dies during tryouts.

The accurate prediction of springback requires knowledge of two things: (i) the changes that occur in the stress distribution when the forming load is removed and (ii) the elastic modulus. Initially, the latter was not thought to be an issue, as the elastic modulus is easily measured and values for most alloys can be found in handbooks. However, as finite element springback prediction codes started evolving, they were found to consistently underpredict for springback. These underprediction errors could be due to consistent errors in the finite element prediction codes, but the alloy and strain magnitude-dependent nature of these errors lead many investigators to postulate that material properties were being altered by plastic strain enough that the handbook values for the elastic modulus could not be used for accurate predictions (Ref 1-5).

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There are a number of different techniques to measure the elastic modulus; and unfortunately, the measured values depend on the measurement technique (Ref 6-9). Relatively large uncertainties are common and usually result from the uncertainties in size, shape, and density of the sample. Unless stated otherwise, one should assume an uncertainty of 10% in any handbook value for the elastic modulus. However, if these uncertainties were responsible for springback prediction errors, they would be randomly distributed. Instead, consistent alloy and strain-dependent underprediction errors are observed. Therefore, a series of studies was conducted to evaluate elastic modulus measurement techniques and the influence of plastic strain on elastic modulus.

The underprediction of springback could be due to the measurement method for elastic modulus not accurately representing conditions during springback, and/or a lowering of the elastic modulus by plastic deformation. As mentioned above, there are many different techniques for determination of the elastic modulus, and each tends to yield a slightly different value for the same material. These differences can be attributed to many sources; the most likely is the loading rate. Following forming, the load is removed very quickly, but it may be several days before the workpiece is needed for the next processing step. Therefore, the most representative elastic modulus measurement technique should remove the applied load quickly, but not measure the spontaneously recovered strain until a representative period of time has expired. This is illustrated in Fig. 1. The elastic modulus can be defined as:

$$E = \frac{\sigma}{\varepsilon} = \frac{1}{J}, \qquad \text{(Eq 1)}$$

where σ represents the change in stress, the ε represents the change in strain, and J is the elastic compliance. Then, any time-dependent change in the displacement after the load is removed will lower the elastic modulus value compared to that measured immediately following load removal.

Handbook values for elastic modulus of metals and alloys are typically determined from tensile tests. In these tests, the stress and strain are continuously varied at a fixed strain rate

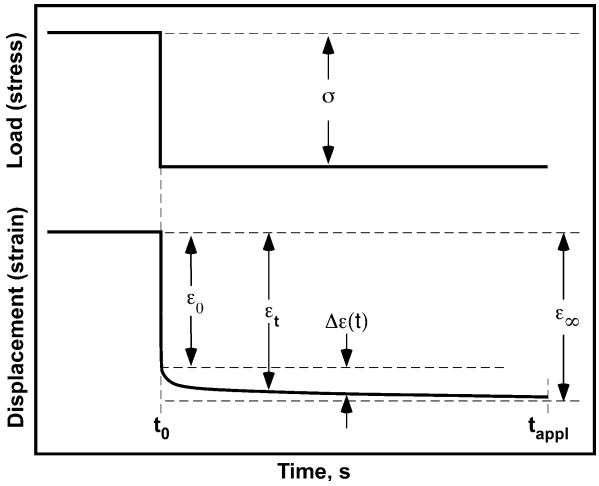

Fig. 1 Schematic diagram of a strain recovery or springback experiment showing an instantaneous change in load or stress with the corresponding change in strain including a spontaneous time-dependent (anelastic) strain

and the modulus is determined by the slope of the stress-strain curve. The strain rates of these tests, while much slower than the rate of load removal in forming operations, are fast compared to the time the workpiece has to relax before the next processing step. Therefore, underprediction errors will occur if modulus values from tensile tests are used and if a spontaneous time-dependent (anelastic) relaxation occurs at a rate that is slow compared to the strain rate. While this would explain the underprediction errors, it cannot explain the strain dependence unless the magnitude of this anelastic relaxation varies with plastic strain. Therefore, the hypothesis of this investigation is that plastic strain increases the dislocation density and the magnitude of a dislocation-dependent anelastic relaxation mechanism (Ref 5). This effect lowers the observed modulus during springback without altering the instantaneous elastic modulus.

This hypothesis assumes that the true, instantaneous, elastic modulus (E_0) is determined by interatomic forces and remains unaltered by deformation. In a real material, an increment of strain is created by the motion of microstructural defects that occur with a change in applied load. Since the motion of these defects requires thermal activation or is triggered by an event that is thermally activated, there will be a time dependence associated with the observed strain ($\varepsilon(t)$). In this case Eq (1) can be written in terms of a time-dependent compliance as:

$$J(t) = \frac{\varepsilon_0 + \Delta\varepsilon(t)}{\sigma} = J_0 + \Delta J(t), \qquad \text{(Eq 2)}$$

where the terms are illustrated in Fig. 1. If each microstructural feature has distinct relaxation kinetics, then $\Delta J(t)$ can be expressed as a sum of exponentials with each term being a product of a density term (ρ_i), a strain increment per defect term ($\Delta\varepsilon_i$), and a decay term with a time constant (τ_i), of the form:

$$\Delta J(t) = \sum_i \Delta J_i = \left(\frac{1}{\Delta\sigma}\right) \sum_i \rho_i \Delta\varepsilon_i \exp(-t/\tau_i) \qquad \text{(Eq 3)}$$

These relaxations produce a time, frequency, or strain rate dependence in elastic modulus measurements. Since the density of microstructural features may be altered by plastic deformation, the magnitude of these relaxations should also vary with plastic strain. The magnitudes of these relaxations and the uncertainties they produce in the elastic modulus measurements are not large compared to the uncertainties derived from sample geometry measurements, they can be ignored for elastic models of most materials where accuracies greater than about ±10% are not required.

In the past, when the uncertainties in elastic modeling were large and safety factors of 200% and 300% were not uncommon, elastic modulus data with uncertainties as large as ±10% were perfectly acceptable. At this level of resolution, the elastic modulus of most metals does not change significantly with microstructure; and therefore, can be considered to be a function of only temperature and composition. However, current computational tools and finite element analysis have enabled elastic modeling to go beyond this level of uncertainty. To take full advantage of these advances, these models require input data with substantially reduced uncertainties. Reducing the uncertainties in data representing the elastic response of materials will require inclusion of the effects of microstructure, anelastic relaxations, and low temperature creep.

2. Experimental Procedure

The objectives of this study were to determine if there is a recovery of the elastic modulus of TRIP 700 steel following deformation, and to measure the rate of this recovery at a temperature near room temperature. If dislocation-related relaxation is lowering the elastic modulus, then the elastic modulus should recover during annealing. According to this hypothesis, the rate of recovery should be proportional to the concentration of the microstructural defects that produce the increment of strain, and therefore, should decay exponentially with time. In addition, full recovery should not occur until all of the defects responsible for increasing the compliance of the microstructure have been removed by annealing. Morestin and Boivin (Ref 1) observed a time-dependent modulus recovery in steels following deformation and reported complete recovery at room temperature. A rapid room temperature recovery requires an elastic modulus measurement to be measured in situ immediately following straining. Thus, a series of experiments was conducted to determine the rate of recovery at 35 °C and to investigate the hypothesis that plastic strain affects the elastic modulus during forming.

Samples were prepared from a 1.0 mm thick sheet of galvanized TRIP 700 steel as used for stamping of automotive bodies. The Zn coating, shown in Fig. 2(a), was left on these samples to be more representative of the actual forming conditions. The samples were deformed by cold rolling to (3, 5, 7, 9, 12, 14, 17, 20, 25, and 27) % reduction in thickness. After straining to the desired level, the samples were sheared to ≈58 × ≈12 mm, deburred using 400-grit paper and the dimensions measured using a digital micrometer with ±0.001 mm resolution. Data acquisition was started at 35 °C exactly 10 min after deformation. This experiment was duplicated with samples where the Zn was removed by immersion in a 50% hydrochloric acid solution.

A commercially manufactured dynamic mechanical analyzer was used to evaluate the elastic modulus. This equipment consists of a furnace with a cryogenic (liquid nitrogen) cooling

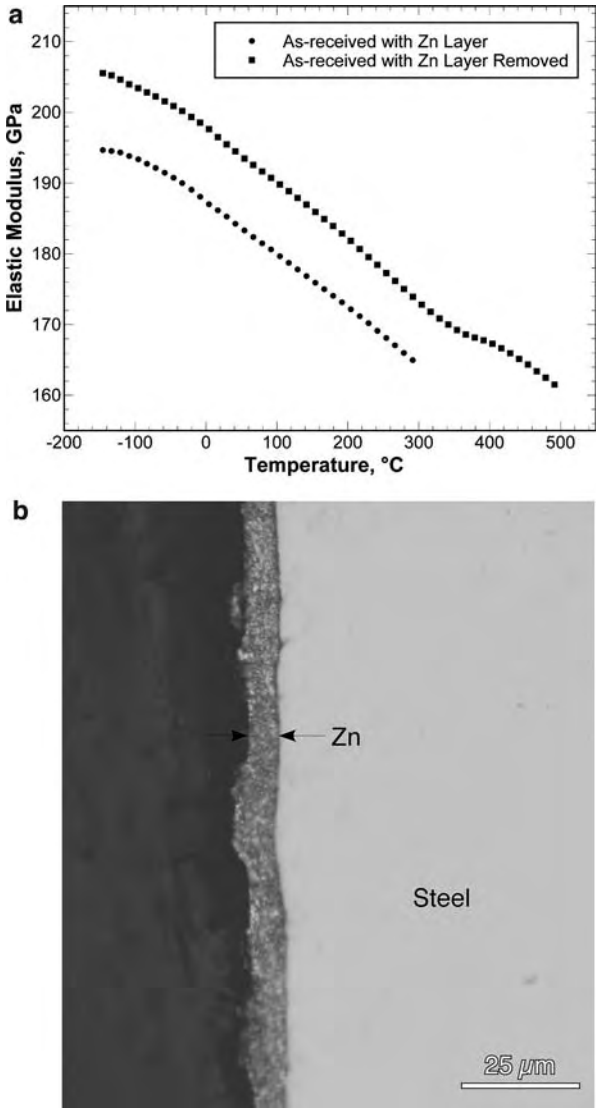

Fig. 2 (a) Micrograph of the galvanized Zn layer on TRIP 700 sheet in the as-received condition. (b) The influence of the Zn layer on the elastic modulus measured in three-point bending as a function of temperature by comparing before and after removal of the Zn layer

system capable of testing at temperatures from −150 °C to 600 °C and an electromagnetic driver capable of testing at frequencies from 0 Hz to 200 Hz and at applied loads up to 18 N. The test chamber is cylindrical with resistance heaters positioned on the inner wall and ports for the cooling gas to enter and exit the chamber at the bottom and top of the chamber, respectively. The closed loop temperature control system uses a feedback thermocouple placed about 3 mm from the test sample and is capable of controlling the temperature to within ±1.0 °C at 35 °C. The force from the linear drive motor is applied to the sample through a frictionless air bearing and a three-point bending grip with a 50 mm span. The three-point bend grip has pivoting roller supports to reduce friction at the contact points and to allow for testing of imperfect or slightly twisted samples. An optical encoder with a resolution of 1.0 nm is used to measure displacement. The system is calibrated with the three-point bend grip in place to minimize errors from grip geometry and compliance. The sample dimensions are limited by the physical size of the testing chamber, by the maximum force that can be applied, and by sample stiffness or compliance.

Two different types of testing programs were used for these experiments: (i) temperature scans and (ii) isothermal aging experiments. The temperature scans were performed by sinusoidal oscillation of the samples at an amplitude of 15 μm and a frequency of 1.0 Hz as the temperature was increased from −150 °C. For samples with a Zn layer, the maximum temperature was 300 °C; and for samples with the Zn layer removed, the maximum temperature was 500 °C. For these experiments, the samples were initially cooled to the lowest temperature and held for 5 min before beginning data acquisition. The temperature was then ramped at 5 °C per min, while continuously acquiring data, until the final temperature was reached. The isothermal aging experiments were performed with the same loading frequency and amplitude, but with the temperature held constant at 35 °C for 1000 min. For these experiments, each sample was prestrained and prepared as above and then placed into the test chamber and heated to 35 °C and held at this temperature for 5 min before acquisition of force and displacement data started. The sample preparation procedures were designed to enable the reproducible initiation of measurement at 10 min after deformation.

As with most techniques for the measurement of elastic modulus, the influence of the sample geometry measurements on the uncertainty of the elastic modulus is large. For three-point bending, the measurement uncertainty is strongly dependent on the thickness of the sample perpendicular to the bending axis. In three-point bending, the elastic modulus is determined from the applied force (P) and displacement (δ) as (Ref 10)

$$E = \left(\frac{P}{\delta}\right)\left(\frac{L^3}{4bh^3}\right), \quad \text{(Eq 4)}$$

where L is the total span length, b is the sample width, and h is the sample thickness. The method of partial differentiation was used for estimating the propagation of errors in a measurement (Ref 11, 12). Assuming that the covariant terms are negligible, the standard deviation of the measured modulus (σ_E) is

$$(\sigma_E)^2 = \sum_{i=1}^{n}\left[\left(\frac{\partial E}{\partial x_i}\right)^2 (\sigma_{x_i})^2\right], \quad \text{(Eq 5)}$$

where x_i represents the input parameters (P, δ, L, b, and h). This relationship states that the influence of the uncertainty of any measured parameter in a calculation is proportional to the rate that the calculated value changes with that parameter. Applying Eq (5) to Eq (4) yields the following relationship for the uncertainty of value determined for the elastic modulus from these measurements

$$\sigma_E = E\sqrt{\left(\frac{\sigma_P}{P}\right)^2 + \left(\frac{\sigma_\delta}{\delta}\right)^2 + \left(\frac{3\sigma_L}{L}\right)^2 + \left(\frac{\sigma_b}{b}\right)^2 + \left(\frac{3\sigma_h}{h}\right)^2} \quad \text{(Eq 6)}$$

Substituting the experimental values for these parameters given above, yields

$$\sigma_E = E\sqrt{\left(\frac{.001}{18}\right)^2+\left(\frac{.001}{15}\right)^2+\left(\frac{3(0.01)}{50}\right)^2+\left(\frac{.01}{12}\right)^2+\left(\frac{3(0.01)}{1}\right)^2} \cong E(0.03) \quad \text{(Eq 7)}$$

So, the error in the value determined for the elastic modulus of any one sample by this technique is about 3%. However, if one compares the modulus of a sample from one point in time to another such that the sample dimensions and mounting conditions are unaltered, then the only error sources are those derived from the force and displacement measurements and the uncertainty becomes

$$\sigma_E = E\sqrt{\left(\frac{.001}{18}\right)^2+\left(\frac{.001}{15}\right)^2} \ll E(0.001) \quad \text{(Eq 8)}$$

Therefore, when one examines the effects of time or temperature on the modulus of a sample, any change greater than ≈0.1% can be considered significant while a difference of more than 3% is required for significance when comparing different samples with uncertainties in sample width and thickness.

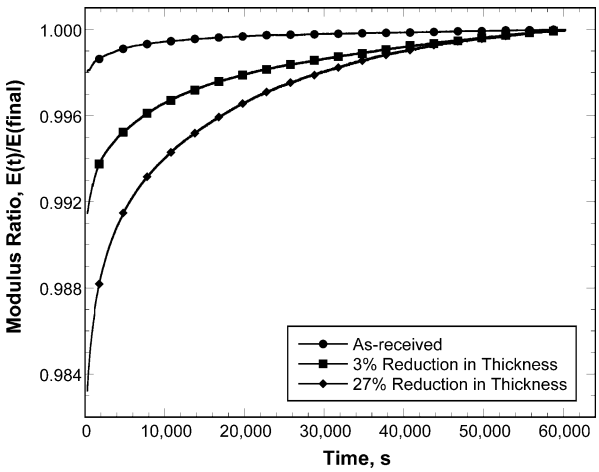

Fig. 3 The variation of the measured elastic modulus as a function of time at 35 °C for three different prestrain conditions: 0, 3, and 27% reduction in thickness by cold rolling

3. Results and Discussion

The results of the temperature scans are shown in Fig. 2(b). This figure shows how the elastic modulus changes as a function of temperature for TRIP 700 steel with the Zn coating in place and after it has been removed. The elastic modulus decreases monotonically as temperature increases for both surface conditions. The sample with the Zn coating exhibited a significantly lower elastic modulus value at all temperatures due to the lower elastic modulus of Zn and the influence of this surface layer in bending. The influence of Zn surface layer on the measured elastic modulus of the sample is exaggerated because of the three-point bend test method, where the outer most fiber of the test material has a strong influence on the measured elastic modulus. The magnitude of this modulus reduction was verified for this Zn layer shown in Fig. 2(a) using a finite element model with 0.01 μm thick elements calculated as a function of distance from the neutral axis.

The results of the isothermal aging experiments on the prestrained samples are shown in Fig. 3 and 4. The modulus data in these figures are normalized to the final modulus value. The elastic modulus increased with time at 35 °C for all samples in these experiments, but the magnitude of this increase varied with the level of plastic prestrain. Figure 3 shows the elastic modulus changes that occurred for three strain conditions: (i) as-received, (ii) 3% reduction in thickness, and (iii) 27% reduction in thickness. The elastic modulus of TRIP 700 steel in the as-received condition changed less than 0.2%, while the modulus of the 27% prestrained sample increased by about 1.7%. The as-received condition establishes a baseline curve for the complex TRIP 700 steel microstructure. Figure 4 summarizes the results of the isothermal modulus measurements. This figure shows that the magnitude of the modulus change in these experiments increased with plastic prestrain, but in a nonlinear fashion with the slope decreasing with increasing strain.

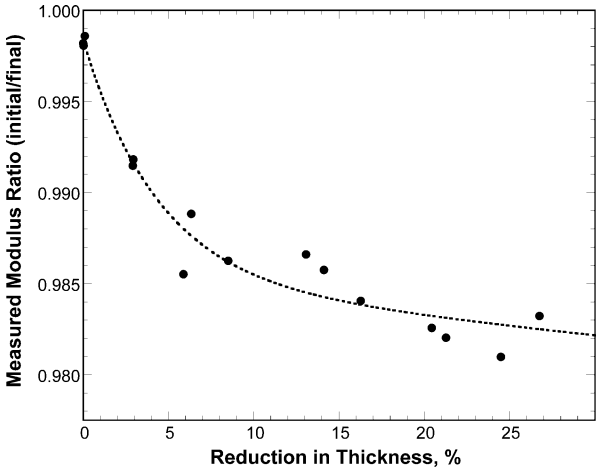

Fig. 4 The ratio of the minimum to maximum modulus measured during 1000 min at 35 °C as a function of prestrain by cold rolling

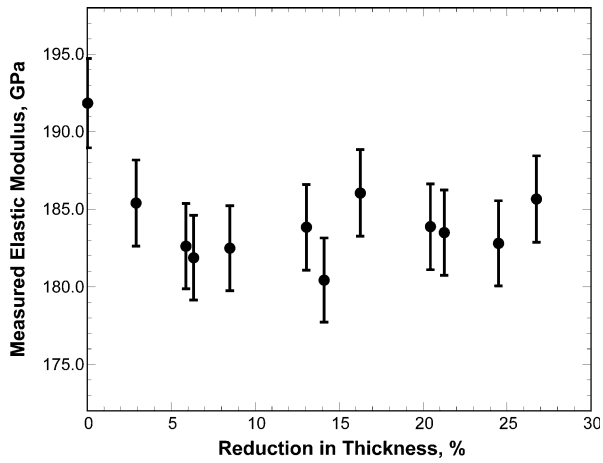

Fig. 5 The initial modulus value at 35 °C, 10 min after cold rolling as a function of prestrain

Figure 5 shows the initial value of the modulus determined in the isothermal experiments as a function of the magnitude of the prestrain. Since this figure compares direct modulus measurements, the values include sample geometry uncertainties that are eliminated when ratios for the same sample are compared as in the figures above. However, there does appear to be a reduction in the modulus with plastic prestrain that is slightly greater then the measurement uncertainty. Figure 4 shows modulus increases that vary from about 0 to about 1.7% for annealing at 35 °C. If these increases were due to a microstructural feature that is not created by deformation, they would occur at the same magnitude in the as-received condition as in the deformed condition. Therefore, it is concluded that each modulus increase observed during the isothermal modulus measurements is due to the recovery of a modulus decrease that was produced by plastic strain. Since this modulus recovery occurs at 35 °C and follows exponential recovery behavior, it must be due to a metastable microstructural feature that is being removed by a thermally activated process at this temperature.

At this time, the magnitude of the decreases indicated in Fig. 5 should be considered preliminary as cold rolling may produce a disproportionately greater change in the thickness of the softer Zn layer than in the underlying steel. A greater thinning rate for the Zn layer would create an increasing modulus with strain trend that would counter any trend to decreasing modulus with strain from the underlying steel. These results indicate that the modulus must be reduced by more than that recovered at 35 °C. Research on experimental methods for better quantification of these effects is in progress.

4. Conclusions

The elastic modulus of a TRIP 700 steel was recovered at 35 °C following plastic deformation. The magnitude of the modulus recovery was strain dependent and exhibited exponential behavior indicating the removal of a metastable microstructural feature by a thermally activated process. The uncertainty in the modulus measurements due to sample geometry prohibited analysis of the magnitude of the modulus decrease due to plastic deformation. However, the greater resolution of the isothermal recovery experiments allowed for the unambiguous conclusion that the modulus of this steel was being lowered by plastic deformation.

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