Construction of the Hill48 and Yld89 for Auto-body Steel Sheets considering the Strain Rate

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Abstract

This paper deals with the anisotropic material properties and the initial yield locus considering the strain rate. Uni-axial tensile tests are performed with variation of the strain rate in order to obtain flow stress curves and the tensile properties. The R-values have been measured with a high speed camera by analyzing the deformation history during the tensile test. Anisotropy of auto-body steel sheets have been described by using Hill48 and Yld89 (Barlat89) yield functions according to the strain rate ranged from 0.001/sec to 100/sec. Hill48 and Yld89 yield loci of auto-body steel sheets at various strain rates have been constructed in order to visualize the initial yield state. The performance of two yield criteria is evaluated by comparing yield loci constructed in the principal stress plane. The initial yield locus becomes different from the static one when the strain rate is considered to describe the anisotropy of the steel sheets.

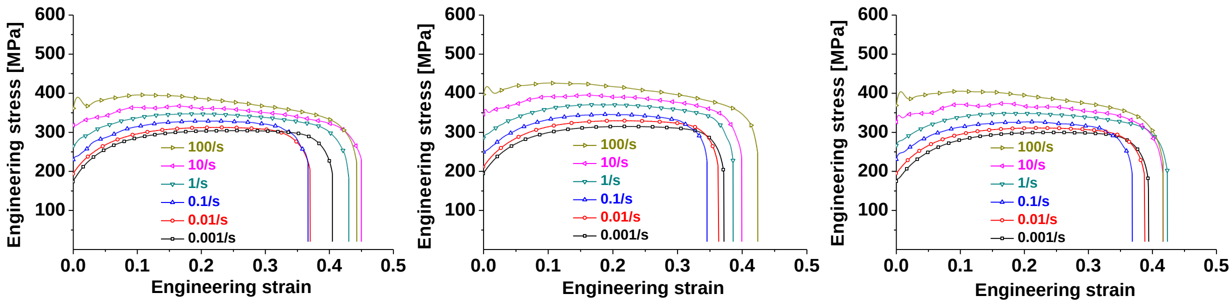
Keywords

Anisotropy, Strain Rate, Sheet Metal Forming, Yield Function, Auto-body Steel Sheets

1 Introduction

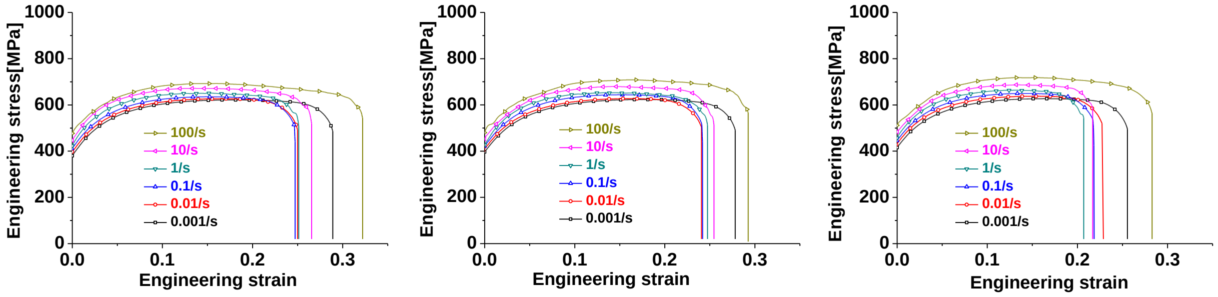
The sheet metal forming is an effective process widely used in many industries. The main concern of industries is to secure good formability at the higher forming speed in order to increase productivity of sheet metal parts. In sheet metal forming processes, the quality of deformed parts is influenced by many process parameters, such as the shape of the die, the shape and thickness of the initial blank, the material properties, the blank holding force, the friction, and so on. The sheet metal forming simulation has proven to be beneficial to reduce the time and cost at the initial stage of the tool design and for optimizing process parameters [1]. The deformation of steel sheets generally involves strain rate effects during the practical forming process. When the deformation of steel sheets is accelerated, the strain rate effect becomes important. Therefore, it is essential to calculate the final shape and deformation history of a product considering the strain rate effect in the forming process. However, the change of the material properties has been seldom considered in the real forming analysis since it is difficult to measure the change of the material properties with experimental methods. Recently, it was demonstrated that the material properties can be changed according to the strain rate [2]. Among material parameters, the R-value and the yield stress have a significant effect on the initial anisotropic state of auto-body steel sheets. The initial anisotropic state has an effect on the amount of spring-back since it calculates the different residual stress and strain distribution after the forming process. Spring-back is a challenging issue in the sheet metal forming industry because of the assembly problem among formed parts. Therefore, the modeling of the anisotropic behavior of metal sheets can be one of the most important aspects in the simulation of sheet metal forming process. In order to precisely describe the initial anisotropic yield state of metal sheets, many anisotropic yield functions have been proposed such as Hill48 [3], Hill79 [4], Hill90 [5], Hill93 [6], Yld89 [7], Yld2000-2d [8], BBC2000 [9] and Yld2000-18p [10]. The order of anisotropic yield functions becomes higher to describe complicated plastic behavior of metal sheets such as aluminum alloy. This means that newly developed yield functions are formulated by using more variables from many kinds of experiments in order to obtain higher accuracy in the forming simulation [1]. However, the changes of the material properties according to the strain rate have not been considered in these yield functions.

This paper is concerned with the anisotropic material properties and the initial yield state considering the strain rate. Unit-axial tensile tests are performed with the variation of the strain rate ranged from 0.001/s to 100/s and tensile angle at intervals of 15° from 0° to 90° with respect to the rolling direction in order to obtain flow stress curves and the tensile properties. Hill48 is used to describe the anisotropy of two auto-body steel sheets, CQ and DP590. Yld89 is additionally selected to compare the initial yield state with Hill48. The anisotropy of steel sheets is evaluated based on experimental data according to the strain rate. Finally, the strain rate effect on the initial yield state is analyzed by comparing yield loci.



(a) 0° (RD) (b) 45° (DD) (c) 90° (TD)

***Figure 1**: Engineering stress-strain curves of CQ at various strain rates.*



(a) 0° (RD) (b) 45° (DD) (c) 90° (TD)

***Figure 2**: Engineering stress-strain curves of DP590 at various strain rates.*

2 UNIAXIAL Tensile tests considering the strain rate

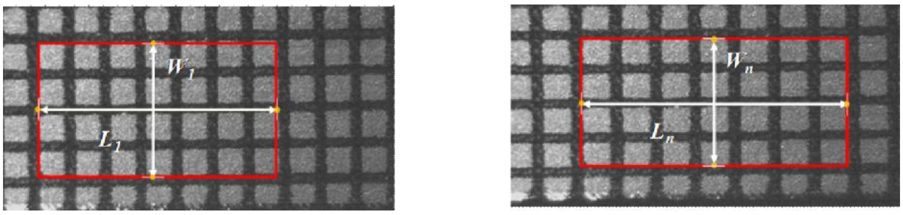
The most common mechanical test is the uni-axial tensile test to measure the material properties of sheet metals. Since the rate sensitivity is important for steel sheets, tests were performed with variation of the strain rate ranged from 0.001/sec to 100/sec, which is the common range in most practical forming process [1, 11]. INSTRON 5583 and HSMTM (High Speed Material Testing Machine) [12] were used to obtain tensile properties at various strain rates. Two typical auto-body steel sheets, CQ (Commercial Quality) and DP590 (Dual Phase), were selected in this research. The specimens were extracted at intervals of 15° from 0° (RD; rolling direction) to 90° (TD; transverse direction). The dimensions of a specimen for uni-axial tensile tests are adopted from the previous research [11]. Engineering stress-strain curves of the two steel sheets from uni-axial tensile tests for RD (rolling direction); DD (diagonal direction); and TD (transverse direction) are shown in FIGURE 1 and 2. (a) ~ (c).

3 Measurement of the R-value considering the Strain Rate

The plastic strain ratio, *r*, is defined as the incremental plastic strain in width, $d\varepsilon_w$, divided by the incremental plastic strain, $d\varepsilon_t$ in thickness, of a tested specimen during the tensile test. It is expressed as Eq. (1) on the assumption of the volume constancy:

$$r = \frac{d\varepsilon_w}{d\varepsilon_t} = \frac{-d\varepsilon_w}{d\varepsilon_l + d\varepsilon_w} \tag{1}$$

where $d\varepsilon_l$ is the increment of the plastic longitudinal strain [13].

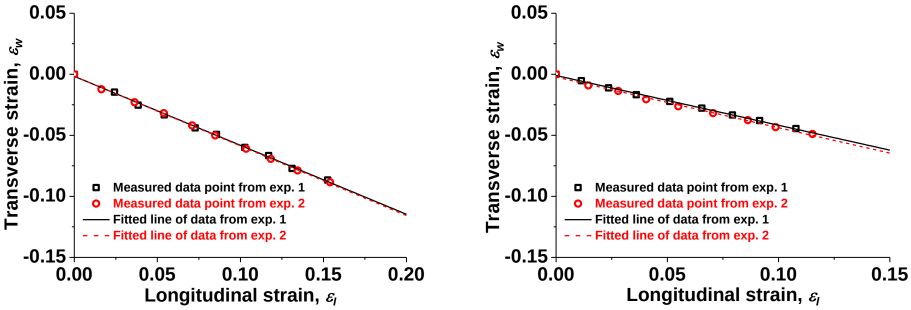


(a) Initial grids (b) Deformed grids (15% to the longitudinal direction)

***Figure 3**: Deformation of grids and measurement region in the gauge section at the strain rate of 100/sec.*

(a) INSTRON5583 (b) High Speed Material Testing Machine

***Figure 4**: Experimental setup of tensile testing apparatus with a high speed camera.*



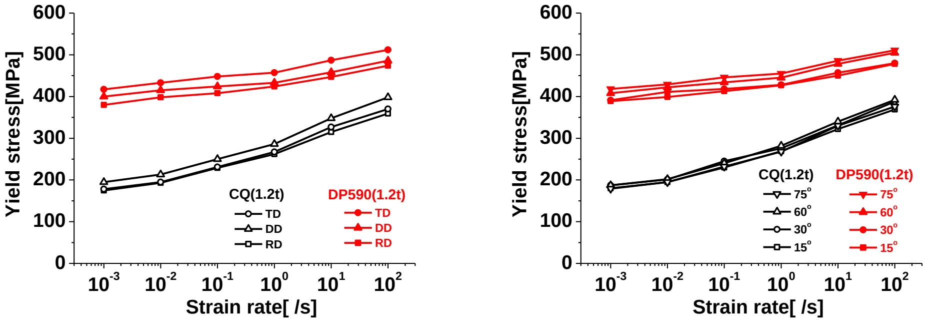
(a) CQ (b) DP590

***Figure 5**: Transverse strain vs. longitudinal strain and the fitted line along the RD at 100/s.*

In order to measure the deformation of steel sheets, square grids of 1*mm* by 1*mm* were marked in the gage section by the silk-screen. The longitudinal and transverse deformations were measured in the maximum broad region for minimizing a measurement error as shown in FIGURE 3. The R-values were measured with a high speed camera of Phantom V. 9.0 by analyzing the deformation history during the tensile test [14, 15]. FIGURE 4 shows an experimental setup of a tensile testing apparatus with a high speed camera. To obtain reliable R-values, the measurement range is limited to the necking instability strain of steel sheets. The longitudinal and transverse strains of CQ and DP590 were measured by longitudinally straining up to 15% and 12% corresponding to the uniform elongation respectively. The Eq. (1) can be rewritten as Eq. (2) based on the fitted slope of longitudinal and transverse strains.

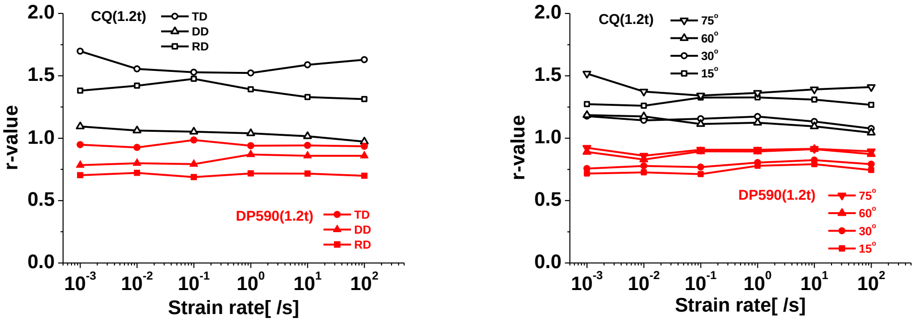
$$d\varepsilon_l = \ln\left(\frac{L_n}{L_1}\right),\ d\varepsilon_w = \ln\left(\frac{W_n}{W_1}\right),\ Slope\ \ in\ \ FIGURE\ 5 = \frac{-r}{1+r} \tag{2}$$

Using the established measuring procedure as shown in FIGURE 5, linear relationships were observed in plots for ε_l *vs.* ε_w according to all strain rates and loading angles from RD [13]. The R-values were calculated by using an average slope obtained from the tensile tests. The initial yield stresses of the two steel sheets were determined using the method of 0.2% offset.



(a) 0°(RD), 45°(DD), 90°(TD) (b) 15°, 30°, 60°, 75° from RD

Figure 6: *Rate sensitivity of yield stresses of CQ(1.2t) and DP590(1.2t).*



(a) 0° (RD), 45° (DD), 90° (TD) (b) 15°, 30°, 60°, 75° from RD

Figure 7: *Rate sensitivity of r-values of CQ (1.2t) and DP590 (1.2t).*

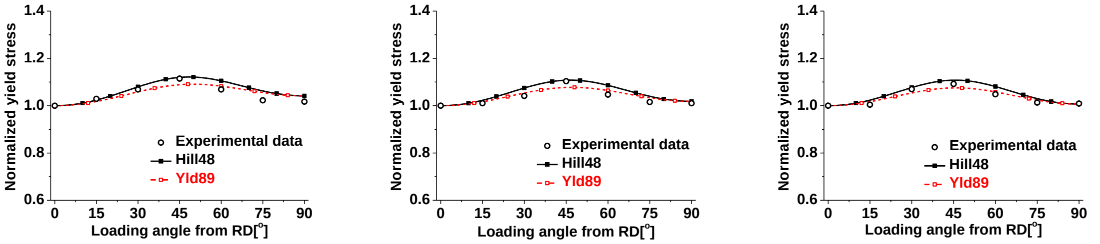
4 Change of the Yield Stress and the R-value with respect to the Strain Rate

The yield stress increases as the strain rate increases for both auto-body steel sheets, and it is also observed that the R-value is globally more insensitive than yield stress according to the strain rate. However, the yield stress and the R-value of CQ are more sensitive to the strain rate effect than DP590 as shown in FIGURE 7 and 8. In previous research, it has been observed that the flow stress increases along with strain rate in several auto-body steels due to an abrupt increase of dislocation density obtained from TEM (Transmission Electron Microscopy), while the texture of a material observed by EBSD (Electron Backscattered Diffraction) [16] has little connection with strain rate effect.

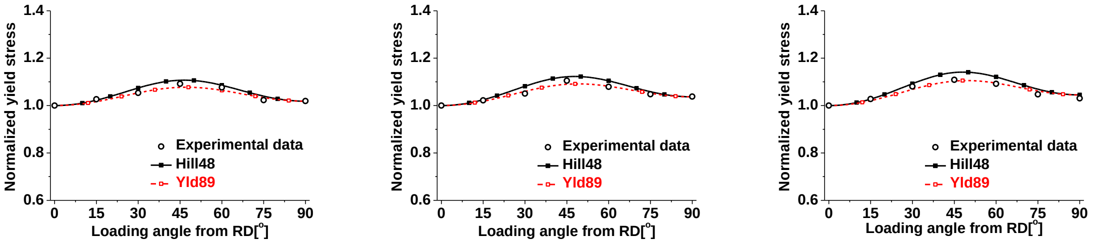
5 Evaluation of Anisotropy according to the strain rate

A Hill48 quadratic yield criterion is basically used to describe anisotropy of two auto-body steel sheets. It has been widely used for simulations of forming processes of auto-body steel sheets due to the simplicity of its numerical formula and the low computing cost. It has been also known that Hill48 shows good performance to approximate anisotropy of auto-body steel sheets. Yld89 is additionally selected in order to evaluate the performance of Hill48 with the same experimental data (σ_0, r_0, r_{45}, r_{90}). The exponent value of Yld89 is six since the crystal structure of CQ and DP590 is BCC.

The uni-axial yield stress and the R-value were predicted from the Hill48 and Yld89 and were compared with the measured values of CQ and DP590 in FIGURE 8~11. The uni-axial yield stresses were normalized by yield stress at RD. The normalized yield stress at 0° is always unity as a reference and calculated R-values at 0°, 45°, 90° coincide with experimental data since they were used to calculate the anisotropic coefficients in Hill48 and Yld89. Figures show that Hill48 and Yld89 well represent anisotropy of the yield stress and the R-value at the given range of the strain rate for CQ and DP590. Moreover, it is observed that anisotropy of the R-value of CQ is relatively greater than that of DP590 as shown in FIGURE 12.

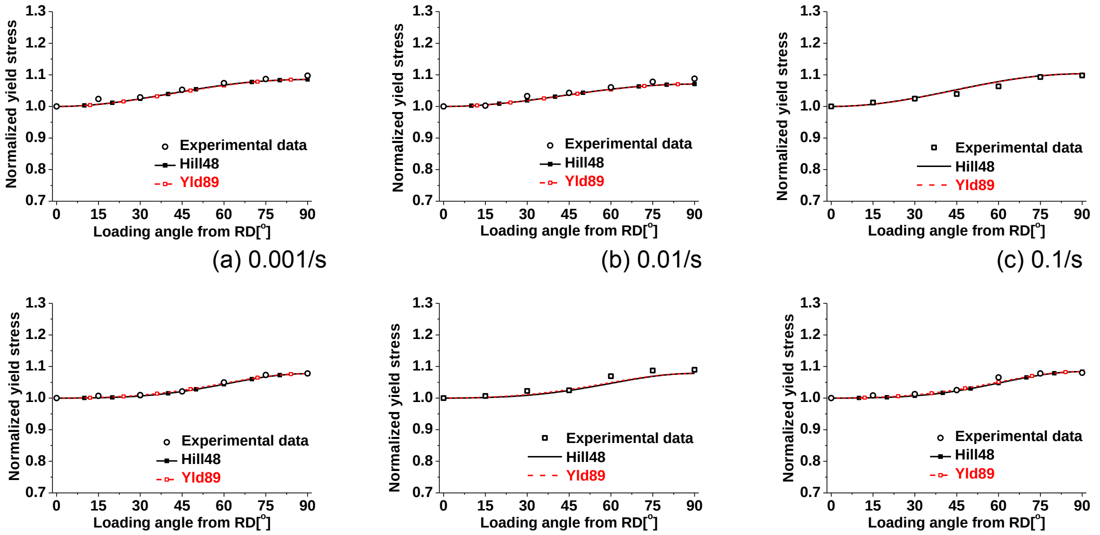


(a) 0.001/s (b) 0.01/s (c) 0.1/s



(d) 1/s (e) 10/s (f) 100/s

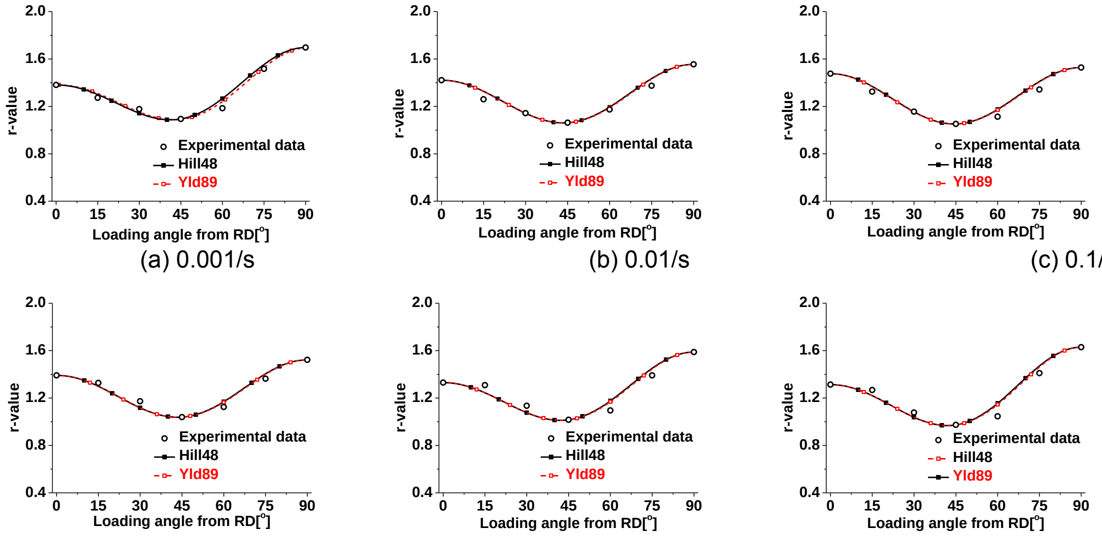
***Figure 8**: Normalized yield stress of CQ (1.2t) with variation of the loading angle from RD.*



(a) 0.001/s (b) 0.01/s (c) 0.1/s

(d) 1/s (e) 10/s (f) 100/s

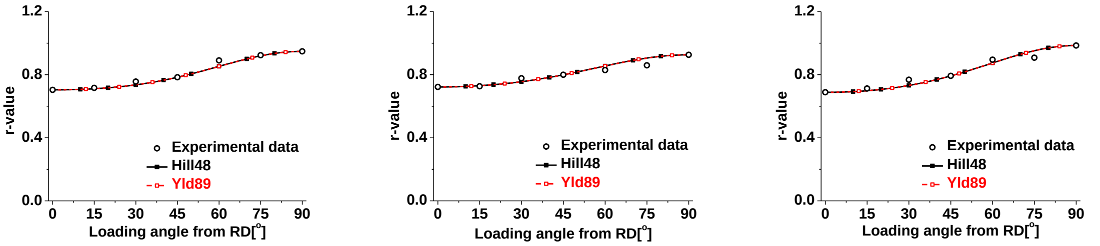
***Figure 9**: Normalized yield stress of DP590 (1.2t) with variation of the loading angle from RD.*



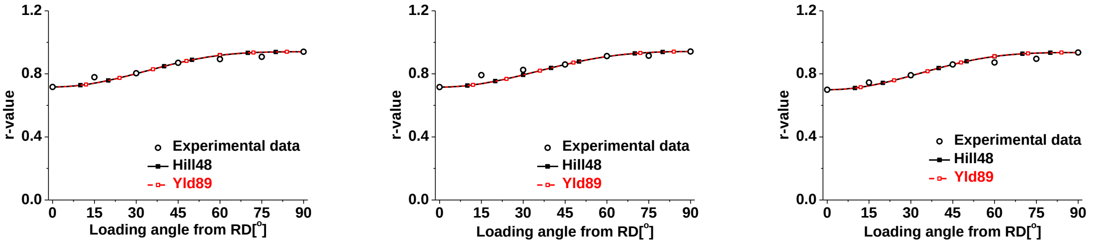
(a) 0.001/s (b) 0.01/s (c) 0.1/s

(d) 1/s (e) 10/s (f) 100/s

***Figure 10**: R-value of CQ (1.2t) with the variation of the loading angle from RD.*

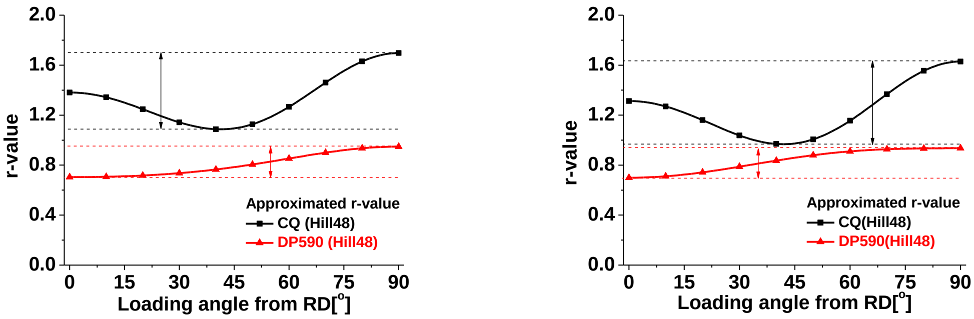


(a) 0.001/s (b) 0.01/s (c) 0.1/s



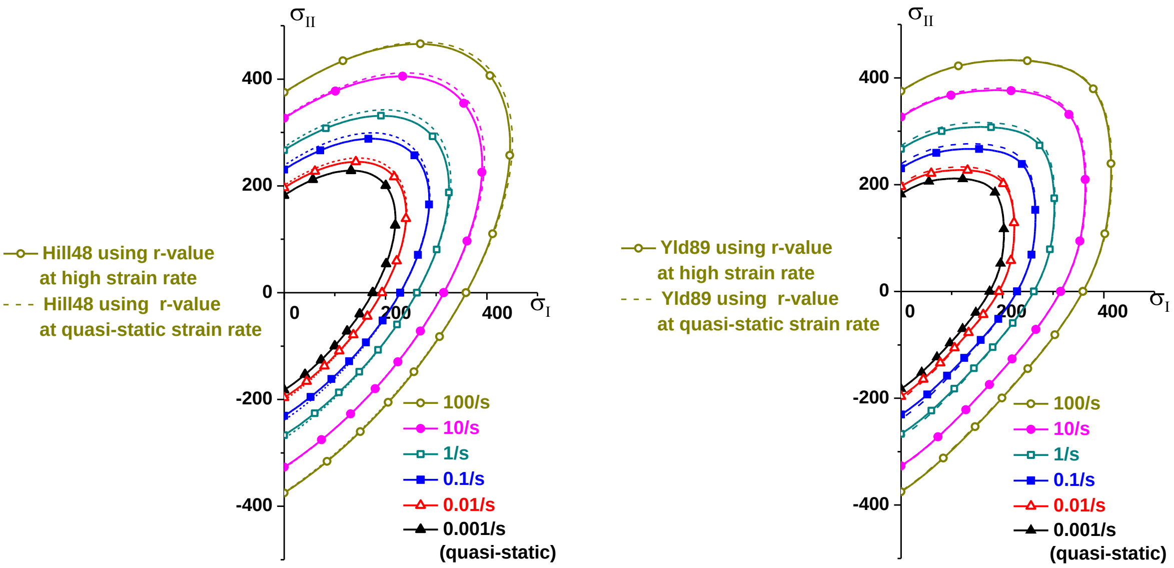
(d) 1/s (e) 10/s (f) 100/s

***Figure 11**: R-value of DP590 (1.2t) with the variation of the loading angle from RD.*



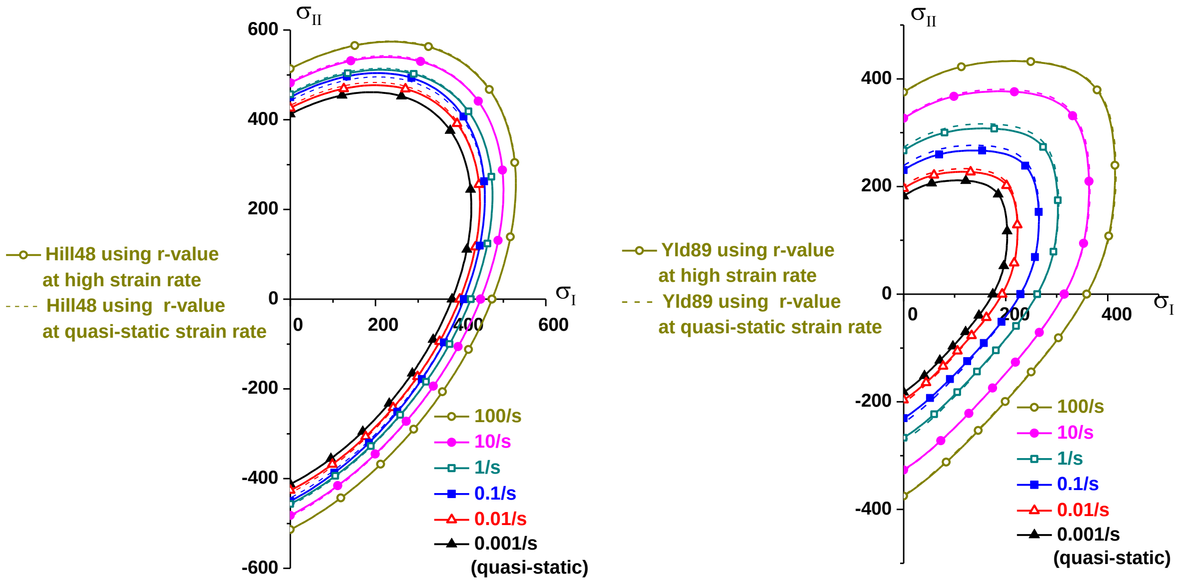
(a) 0.001/s (b) 100/s

***Figure 12**: Comparison between approximated R-values of CQ and DP590 with the variation of the loading angle from RD.*



(a) Hill48 (b) Yld89

***Figure 13**: Yield loci of CQ at various strain rates.*



(a) Hill48 (b) Yld89

***Figure 14**: Yield loci of DP590 at various strain rates.*

6 Construction of Yield loci according to the strain rate

Assuming that principal axes of stress and anisotropy coincide with each other, Hill48 and Yld89 yield loci are able to be presented in the principal stress plane. This is an effective way to visualize the initial yield state of a material in the sheet metal forming process. Both yield loci can be constructed by using the yield stress and the R-value obtained from uni-axial tensile tests. The yield stress and the R-value influence the size and shape of a yield locus, respectively. Therefore, the initial yield state is determined by the combination of those parameters. The yield loci of CQ and DP590 according to the strain rate are shown in FIGURE 13 and 14. As previously stated, the predicted yield stress can be evaluated in the uni-axial state. The predicted σ_{90} using Hill48 and Yld89 are deemed to be reasonable based on σ_0, r_0 and r_{90} in the principal stress plane. The performance of both yield functions is almost same at the uni-axial state, while two yield functions show slightly different behavior in the biaxial state. The different biaxial state is basically caused by the difference of the exponent values of yield functions which are two for Hill48 and 6 for Yld89 [17]. The Hill48 yield locus has a more rounded shape than the Yld89 yield locus. To evaluate accuracy of the two yield functions in the biaxial state, additional mechanical tests should be conducted in the equi-biaxial, plane strain, pure shear condition according to the strain rate.

In the figures, the solid line and the dotted line stand for yield loci using R-values at the corresponding strain rate and a constant R-value at quasi-static state. It shows that the initial yield states are different from the static one when the strain rate is considered to describe anisotropy of steel sheets. Since the R-value of DP590 is less sensitive to the strain rate effect than CQ, there was little deviation of the initial yield state in case of DP590.

7 Conclusions

This paper represents experimental results for the anisotropic material properties and the initial yield state considering the strain rate. Two auto-body steel sheets, CQ and DP590 are considered to demonstrate the change of the R-value and the yield stress. It is observed that the R-value is globally more insensitive than yield stress according to the strain rate. However, the yield stress and the R-value of CQ are more sensitive to the strain rate effect than DP590. Based on the experimental results, Hill48 and Yld89 are constructed to investigate the anisotropy of the yield stress and R-value at the given range of strain rate. The comparison between the measured data and the constructed ones shows that the R-value and the yield stress have some deviation from each other according to the loading angle and Hill48 and Yld89 have to be modified to accurately describe the initial yield state. The initial yield states are different from the static one when the strain rate is considered to describe anisotropy of steel sheets. Since the R-value of DP590 is less sensitive to the strain rate effect than CQ, there was little change of the initial yield state in case of DP590. In case of a sensitive metal sheet according to the strain rate, there is a need to describe initial yield state accurately considering the strain rate in the forming simulation.

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