



Characterization of anisotropy in sheet metals using digital image correlation

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Abstract: This study develops and applies an in-house two-dimensional digital image correlation (2D-DIC) system to investigate the anisotropic behavior of sheet metals under uniaxial tensile loading. Two materials, SUS304 stainless steel and DP1200 dual-phase steel, were examined. Tensile specimens were prepared along three orientations with respect to the rolling direction: rolling direction (RD), diagonal direction (DD), and transverse direction (TD), and the tests were performed in accordance with ISO 6892-1. The DIC method provided full-field displacement and strain measurements on the specimen surface, enabling the determination of stress-strain curves, Lankford coefficients, normalized yield stresses, and yield surface characteristics. The results show that SUS304 exhibits high ductility, strong strain hardening capacity, and more pronounced planar anisotropy than DP1200. In contrast, DP1200 shows higher tensile strength but lower elongation, and its Lankford coefficients and normalized yield stresses are closer to isotropic behavior. Comparison of the yield criteria indicates that Hill48 represents the anisotropic response more accurately than the von Mises criterion. Hill48-R agrees better with the experimental Lankford coefficients, whereas Hill48-S more accurately describes the normalized yield stresses.

Keywords: 2D digital image correlation, sheet metal, anisotropy, Lankford coefficient, Hill48, SUS304, DP1200.

1. Introduction

Sheet metals are widely used in automotive manufacturing, aerospace structures, household appliances, mechanical components, and modern production systems because of their good formability, favorable strength-to-weight ratio, and efficient material utilization [1]. In forming processes such as bending, drawing, deep drawing, and stretch forming, the mechanical response of sheet metals directly affects product quality, thickness distribution, dimensional accuracy, and the formation of defects such as

cracking, wrinkling, and earing [1, 2]. Therefore, accurate determination of mechanical properties and anisotropic characteristics is essential for material selection, die design, process optimization, and finite element simulation of sheet-metal forming operations.

One of the most important characteristics of rolled sheet metals is mechanical anisotropy, in which yielding behavior, plastic flow, and deformation resistance vary with the in-plane material direction. This directional behavior is primarily associated with the crystallographic

texture developed during sheet rolling [3]. Therefore, sheet metal anisotropy is commonly characterized using tensile specimens extracted along three representative directions: the rolling direction, RD, 0°; the diagonal direction, DD, 45°; and the transverse direction, TD, 90°. Variations in yield stress, tensile strength, elongation, and Lankford coefficient among these directions are closely related to sheet formability and to the accuracy of constitutive models used in numerical simulations [4]. In particular, the Lankford coefficient, also known as the plastic strain ratio, is an important parameter for evaluating resistance to thickness thinning and deep-drawing performance of sheet metals [4].

Several studies have emphasized that reliable characterization of anisotropic behavior is necessary for accurate prediction of sheet-metal forming. Banabic [3] showed that the accuracy of forming simulations strongly depends on the selected constitutive model and the quality of experimental data used for calibration. Hill [5] proposed one of the earliest anisotropic yield criteria for rolled sheets, and the Hill48 model is still widely used because of its simple mathematical formulation and convenient calibration from directional tensile data. However, later studies have shown that quadratic yield functions may not simultaneously capture the directional variation of yield stress and plastic strain ratio in materials with strong anisotropy or complex crystallographic texture. To overcome this limitation, advanced non-quadratic yield functions, such as Yld2000-2d and polynomial-type yield criteria, have been developed to improve the description of anisotropic yielding in sheet metals [6, 7]. For austenitic stainless steels, Şener et al. [7, 8] investigated the anisotropic behavior of AISI 304 stainless steel sheets using directional tensile data and a fourth-order polynomial yield function. Their results showed that the angular variation of yield stress and plastic strain ratio should be considered to improve the accuracy of finite element simulations

of sheet forming. This finding is relevant to SUS304 stainless steel, which has a chemical composition and mechanical response comparable to AISI 304. For advanced high-strength dual-phase steels, Cadoni et al. [9] studied the mechanical behavior of DP1200 and DP1400 under uniaxial tensile loading over a wide range of strain rates. Their study confirmed that DP1200 exhibits very high strength and strain-rate-sensitive behavior, which is important for automotive forming and crashworthiness applications. In addition, Tasan et al. [10] reviewed the microstructure–property relationship of dual-phase steels and showed that the ferrite–martensite microstructure strongly affects strength, ductility, strain hardening, and damage evolution. Although previous studies have separately investigated the anisotropic modeling of AISI 304/SUS304-type stainless steels and the mechanical behavior of DP1200 dual-phase steels, direct comparison of these two sheet materials using the same experimental and data-processing framework remains limited. Such a comparison is useful because SUS304 and DP1200 exhibit clearly different mechanical responses. SUS304 generally shows high ductility and strong strain-hardening capability, whereas DP1200 provides high strength but limited elongation [8, 10]. Therefore, evaluating the von Mises [11] and Hill48 [5] yield criteria for both materials under identical testing conditions can provide practical insight into the capability of simple yield models to describe different levels of sheet-metal anisotropy. To perform such a comparison reliably, accurate strain measurement is required because the determination of stress–strain curves, Lankford coefficients, normalized yield stresses, and yield surfaces strongly depend on the quality of experimental strain data. Conventional strain measurement techniques, such as extensometers and strain gauges, generally provide only local strain data at a limited number of positions on the specimen. This limitation restricts their ability to evaluate nonuniform strain distributions,

particularly during necking and localized deformation. By contrast, digital image correlation (DIC) is a non-contact optical measurement technique that determines full-field displacement and strain distributions on the specimen surface by tracking the movement of random speckle patterns in a sequence of digital images [12, 14]. Owing to this capability, DIC has become an effective tool in experimental mechanics, especially for analyzing sheet-metal deformation during tensile testing and forming operations. Wattrisse et al. [13] demonstrated that 2D-DIC is suitable for in-plane displacement and strain measurement, making it particularly useful for tensile testing of sheet metals. Sutton et al. [14] presented the fundamental theory and practical implementation of image correlation methods, while Hild and Roux [15] reviewed the capability of DIC for displacement measurement and mechanical property identification. Previous studies have applied DIC to tensile testing and forming analysis to obtain full-field strain data, observe localized deformation, and improve the identification of mechanical properties [12-15]. However, many studies have focused mainly on either DIC-based strain measurement or anisotropic yield-function calibration. Fewer studies have presented a combined experimental framework in which 2D-DIC is used to determine stress-strain curves, Lankford coefficients, normalized yield stresses, and yield surfaces for different sheet metals, followed by a direct comparison between isotropic and anisotropic yield criteria.

The contribution of this article is a directional characterization of the plastic anisotropy of DP1200 dual-phase steel sheet using an in-house 2D-DIC system. While the plastic anisotropy of lower and intermediate dual-phase grades (DP590, DP780, DP800) has been studied extensively, comparable data for DP1200 remains limited. This study measures the Lankford coefficients and normalized yield-stress ratios of DP1200 in the RD, DD, and TD orientations and uses these data to

calibrate and compare the Hill48-R and Hill48-S models. The study further compares DP1200 with the more anisotropic SUS304 stainless steel under an identical experimental and data-processing framework, providing a direct assessment of how well simple quadratic yield functions describe two contrasting levels of sheet-metal anisotropy.

2. Theoretical Background

2.1. Lankford Anisotropy Coefficient

The Lankford anisotropy coefficient is an important parameter used to characterize the resistance of sheet metals to through-thickness deformation during uniaxial tension. It is defined as the ratio of the true strain in the width direction to the true strain in the thickness direction [4]:

$$r = \frac{\varepsilon_w}{\varepsilon_t} \quad (1)$$

where ε_w is the true width strain and ε_t is the true thickness strain. Because the thickness strain ε_t is difficult to measure directly on a thin sheet, it is obtained from the in-plane strains using the plastic incompressibility condition. For metals, plastic deformation occurs at negligible volume change, so the three true strain components ε_l , ε_w , ε_t sum to zero. Where ε_l is the true longitudinal plastic strain.

Assuming plastic incompressibility, the thickness strain can be indirectly determined from the longitudinal and width strains as follows:

$$r = \frac{\varepsilon_w}{-(\varepsilon_l + \varepsilon_w)} \quad (2)$$

A higher r value indicates greater resistance to thinning and is therefore generally associated with better deep-drawing performance. For rolled sheet metals, the r value is usually determined in the RD, DD, and TD orientations, corresponding to r_0 , r_{45} , and r_{90} . The average normal anisotropy is commonly calculated as:

$$\bar{r} = \frac{r_0 + 2r_{45} + r_{90}}{4} \quad (3)$$

The average $\bar{r}$ value reflects the overall formability of the sheet in the plane, whereas the directional variation of Δr values indicates the

degree of planar anisotropy.

$$\Delta r = \frac{r_0 - 2r_{45} + r_{90}}{2} \quad (4)$$

A value of $\Delta r = 0$ indicates no planar anisotropy, whereas larger $|\Delta r|$ indicates a stronger directional variation in resistance to thinning, which is associated with a higher tendency for earing during deep drawing.

2.2. Von Mises and Hill48 Yield Functions

The von Mises [11] and Hill48 [5] yield functions are widely used in solid mechanics and finite element analysis to determine the onset of plastic deformation. For isotropic materials, the von Mises yield criterion is commonly used. In its general stress-state form, the equivalent von Mises stress can be expressed as:

$$\bar{\sigma} = \sqrt{\frac{1}{2} \left[(\sigma_{11} - \sigma_{22})^2 + (\sigma_{22} - \sigma_{33})^2 + (\sigma_{33} - \sigma_{11})^2 + 6(\sigma_{23}^2 + \sigma_{31}^2 + \sigma_{12}^2) \right]} \quad (5)$$

However, the von Mises criterion assumes identical mechanical properties in all material directions. It therefore cannot describe directional variations in yield stress and plastic strain ratio. For anisotropic sheet metals, the Hill48 yield function is often used to account for material directionality. In a general stress state, the Hill48 function can be written as:

$$\bar{\sigma} = \sqrt{H(\sigma_{11} - \sigma_{22})^2 + F(\sigma_{22} - \sigma_{33})^2 + G(\sigma_{33} - \sigma_{11})^2 + 2L\sigma_{23}^2 + 2M\sigma_{31}^2 + 2N\sigma_{12}^2} \quad (6)$$

The parameters F , G , H , L , M , and N are material coefficients determined through experimental calibration. The coefficients are normalized such that $(G+H=1)$; consequently, under uniaxial loading along the rolling direction, the Hill48 equivalent stress reduces to the reference uniaxial yield stress. Under plane-stress conditions, $(\sigma_{33}=0; \sigma_{31}=0; \sigma_{23}=0)$. Therefore, the terms associated with L and M vanish, whereas N remains relevant because it governs the in-plane shear contribution. For the isotropic case, $(F = G = H = 0.5)$ and $(L = M = N = 1.5)$, and the Hill48 function reduces to the von Mises yield function.

Several approaches exist for calibrating the coefficients of Hill's quadratic criterion. The first determines them from the measured Lankford coefficients, giving the Hill48-R formulation, Eqs. 7(a)–7(d), where r_0 , r_{45} , and r_{90} are the experimental Lankford ratios in the RD, DD, and TD orientations, respectively. The remaining coefficients are fixed at their isotropic values, $L = M = 1.5$. The second approach identifies the coefficients from the directional yield-stress ratios, giving the Hill48-S formulation, Eqs. 8(a)–8(d).

$$G = \frac{1}{1+r_0} \quad (7a)$$

$$F = \frac{r_0/r_{90}}{1+r_0} \quad (7b)$$

$$H = \frac{r_0}{1+r_0} \quad (7c)$$

$$N = \frac{(1+2r_{45})(r_0+r_{90})}{2r_{90}(1+r_0)} \quad (7d)$$

$$G = \frac{1}{2} \left(\frac{1}{\sigma_0^2} - \frac{1}{\sigma_{90}^2} + \frac{1}{\sigma_b^2} \right) \quad (8a)$$

$$F = \frac{1}{2} \left(-\frac{1}{\sigma_0^2} + \frac{1}{\sigma_{90}^2} + \frac{1}{\sigma_b^2} \right) \quad (8b)$$

$$H = \frac{1}{2} \left(\frac{1}{\sigma_0^2} + \frac{1}{\sigma_{90}^2} - \frac{1}{\sigma_b^2} \right) \quad (8c)$$

$$N = \left(\frac{1}{\sigma_{45}^2} - \frac{1}{\sigma_b^2} \right) \quad (8d)$$

3. Materials and Experimental Methods

3.1. Specimen Preparation

Two sheet metals were used in this study: SUS304 and DP1200 dual-phase steel. SUS304 is an austenitic stainless steel with good corrosion resistance, high ductility, and strong strain-hardening capability. It is widely used in household appliances, decorative structures, mechanical components, and products requiring corrosion resistance. DP1200 is a high-strength dual-phase steel with a microstructure consisting of ferrite and martensite. The combination of a soft ferritic matrix and hard martensitic phase enables DP1200 to achieve very high tensile strength, making it suitable for load-bearing and energy-absorbing

components in the automotive industry [9, 10]. The SUS304 and DP1200 sheets had nominal thicknesses of 0.5 mm and 1.6 mm, respectively. Tensile specimens were machined in three

orientations relative to the rolling direction: RD, DD, and TD. The specimen geometry is shown in Fig. 1 and was designed for uniaxial tensile testing in accordance with ISO 6892-1:2019 [16].

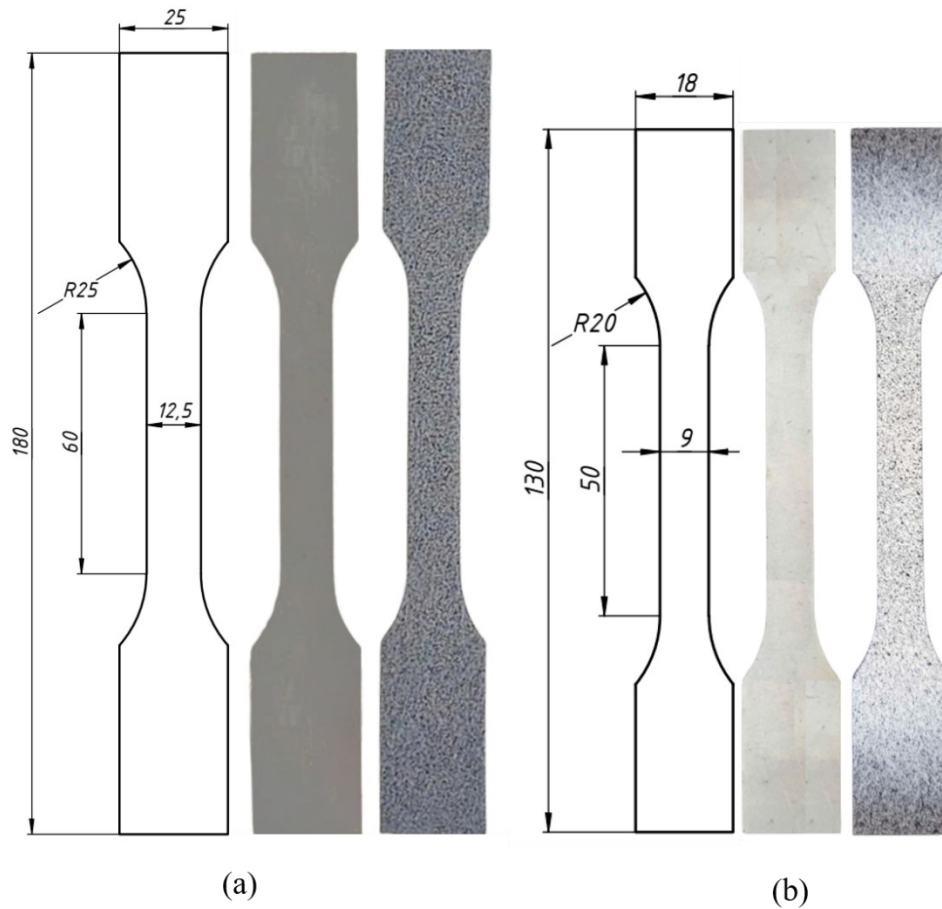


Fig. 1. Tensile specimens used in the experiments: specimen dimensions, specimens cut from the sheet, and painted specimens: (a) SUS304 and (b) DP1200

3.2. Speckle Pattern Preparation

Before tensile testing, the specimen surface was coated with a white base layer and then sprayed with random black speckles to create the speckle pattern. Speckle quality directly affects the accuracy of DIC analysis. A suitable speckle pattern should have high contrast, random distribution, particle sizes compatible with the camera resolution, and sufficient adhesion to remain stable throughout deformation. Patterns with low speckle density, nonuniform particle size, or poor contrast can reduce image-correlation quality and introduce errors in strain calculation. Fig. 2(a) shows acceptable speckle patterns for 2D-DIC analysis. All four samples provide sufficient

contrast and a random distribution for reliable image correlation. Samples 1 and 3 combine high speckle density with small, uniform particles, making them suitable for small-strain and localized-deformation measurement requiring high spatial resolution, whereas Samples 2 and 4 use larger, sparser speckles better suited to large-deformation analysis at the cost of spatial resolution. The choice of pattern should therefore balance the expected deformation level, the required spatial resolution, and computational efficiency. In contrast, the patterns in Fig. 2(b) are not suitable for DIC analysis. The first pattern has a very low speckle density, which provides insufficient image features for correlation. The

second pattern contains excessively large and nonuniform speckles, which may reduce spatial resolution and cause correlation errors. The third pattern has poor contrast and connected/blurred speckle regions, making it difficult to identify unique

subsets. Therefore, unsuitable speckle patterns can lead to noisy strain fields, loss of correlation, and inaccurate displacement and strain measurements.

3.3. Tensile test

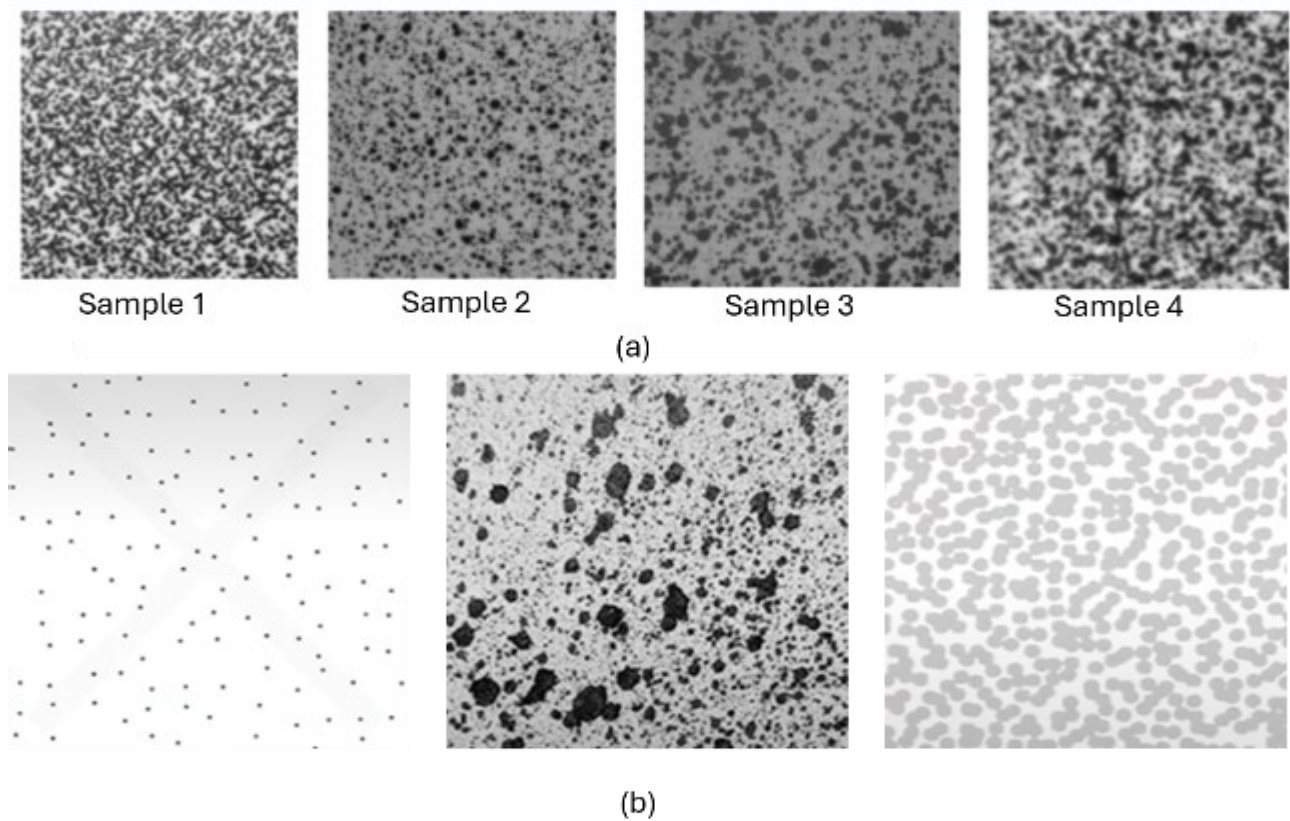


Fig. 2. Speckle patterns for DIC analysis: (a) acceptable patterns; (b) unacceptable patterns

Fig. 3 shows the experimental system, which consisted of a universal testing machine, an industrial camera, a lens, a lighting system, a camera support frame, a light-intensity controller, and GOM Correlate 2018 image-processing software. The universal testing machine was used to apply uniaxial tensile loading to the specimens at a crosshead speed of 3 mm/min. This crosshead speed was selected to maintain quasi-static loading conditions, consistent with ISO 6892-1:2019 [16], while providing a sufficiently low deformation rate for the camera to acquire a dense image sequence throughout the test. The gauge lengths of the SUS304 and DP1200 specimens were 60 and 50 mm, respectively, corresponding to nominal initial strain rates of $8.33 \times 10^{-4} (\text{s}^{-1})$ and $1 \times 10^{-3} (\text{s}^{-1})$, respectively. During testing, the

camera continuously recorded images of the specimen surface, while the tensile force was recorded from the load cell of the testing machine. To ensure the accuracy of the 2D-DIC measurement, the camera was positioned perpendicular to the specimen surface. The lighting system was adjusted to obtain images with sufficient contrast and to avoid glare, underexposure, or motion blur. After testing, the image sequence was imported into GOM Correlate to calculate the displacement field within the region of interest. The force data from the testing machine and the displacement data from DIC were synchronized using the image acquisition time, which enabled force-displacement and stress-strain relationships to be constructed for each deformation state of the specimen. The DIC

measurement parameters and image-processing procedure were selected following established recommendations for planar DIC measurements [12, 17].

Fig. 4(a) shows the strain-field distribution within the gauge-length region at a representative deformation stage, obtained directly from the 2D-DIC analysis. The recorded image sequences were processed using the user-defined computation mode, with a facet (subset) size of 19 pixels and a point distance (step size) of 16 pixels. Two virtual

extensometers were defined within the region of interest to extract local displacement values used in the subsequent strain and Lankford-coefficient calculations, together with a virtual point gauge (Point 1) for local strain monitoring. Fig. 4(b) shows the corresponding displacement–time response extracted from the same specimen, which increases monotonically with loading time and provides the basis for synchronizing the DIC displacement data with the force data recorded from the testing machine.

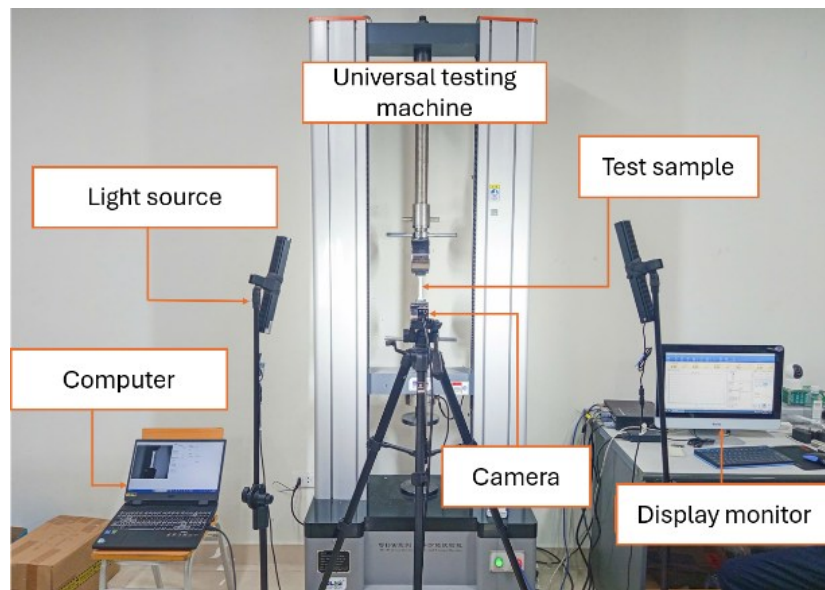


Fig. 3. Experimental DIC measurement system

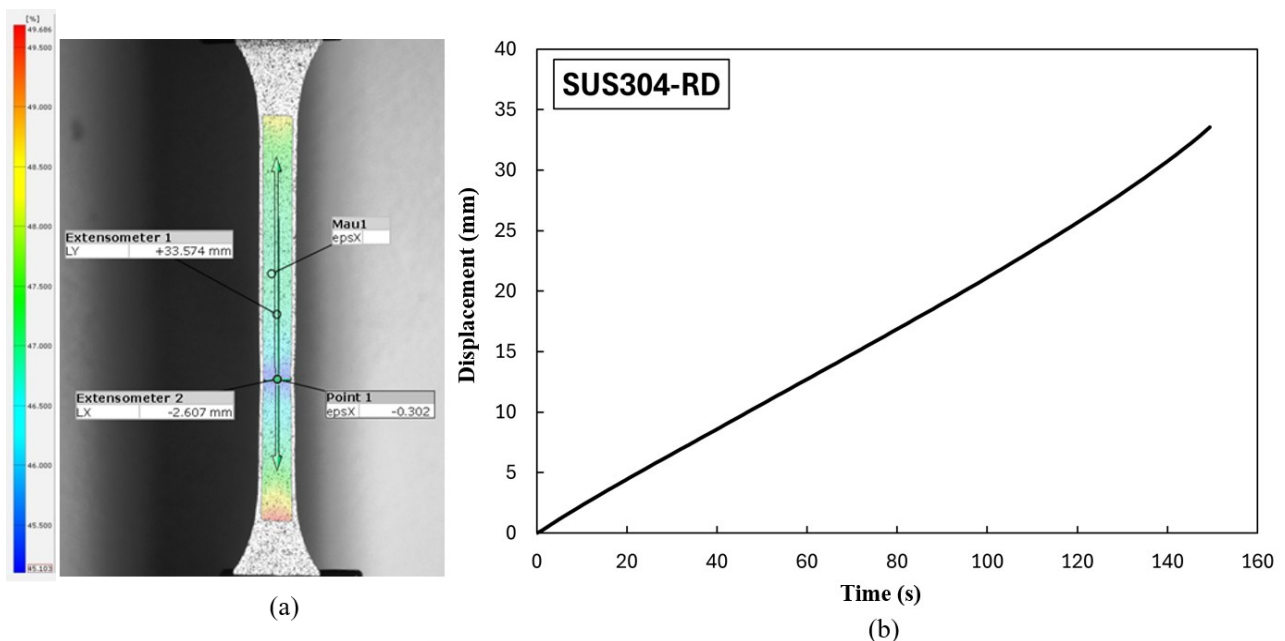


Fig. 4. (a) DIC strain-field distribution and (b) displacement–time response extracted from the tensile specimen.

4. Results and Discussion

4.1. Force-Displacement Curve

Three independent tensile specimens were tested for each material and orientation $n = 3$. As an assessment of experimental repeatability, Fig. 5 compares the force–displacement responses of three SUS304 specimens tested in the diagonal

direction. The curves show close agreement in the deformation process.

The force-displacement responses obtained from tensile testing of SUS304 and DP1200 are shown in Fig. 6. For SUS304 (Fig. 6a), the curve increases gradually in a nonlinear manner, which is typical of ductile materials.

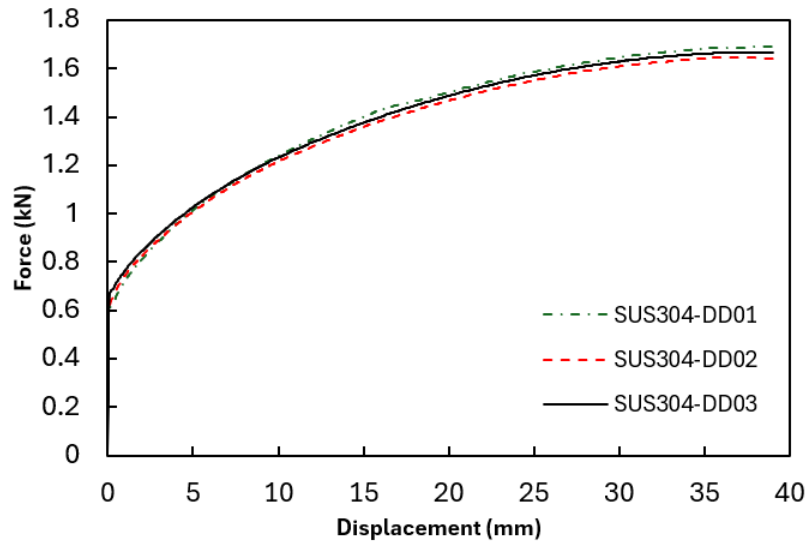


Fig. 5. Force–displacement curves of three SUS304 specimens tested in the diagonal direction

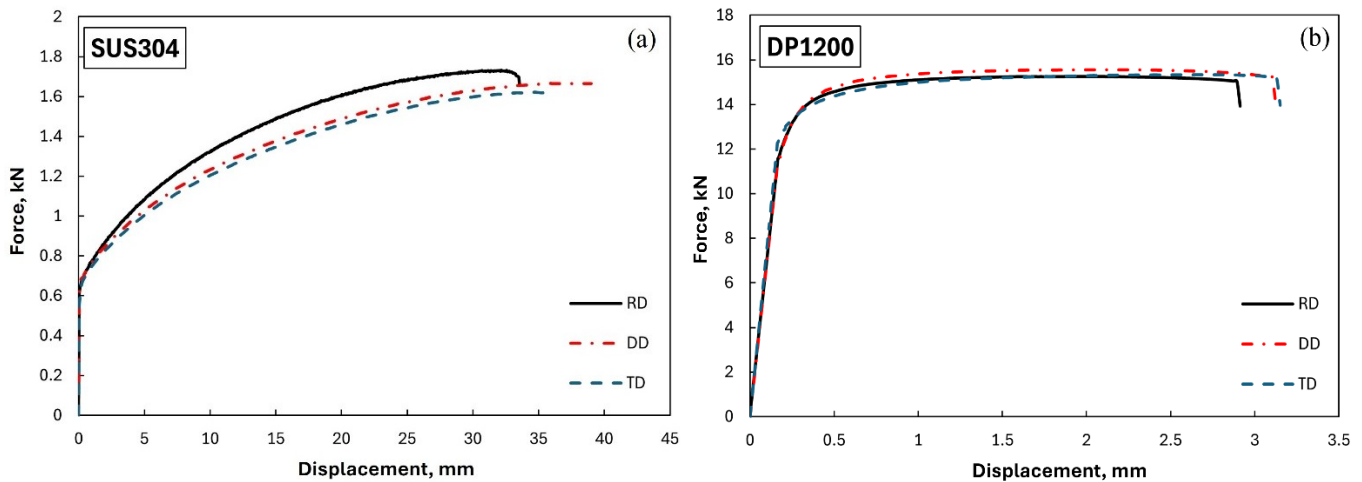


Fig. 6. Experimental force-displacement curves for (a) SUS304 and (b) DP1200 specimens

After the initial elastic stage, the force continues to increase in the plastic region because of strain hardening. The maximum tensile force of SUS304 is approximately 1.6–1.7 kN, after which the force decreases slightly as necking develops and the load-carrying capacity decreases. By contrast, in Fig. 6b, DP1200 exhibits a rapid increase in force at the early stage, reflecting its high stiffness and high load-bearing capacity. The

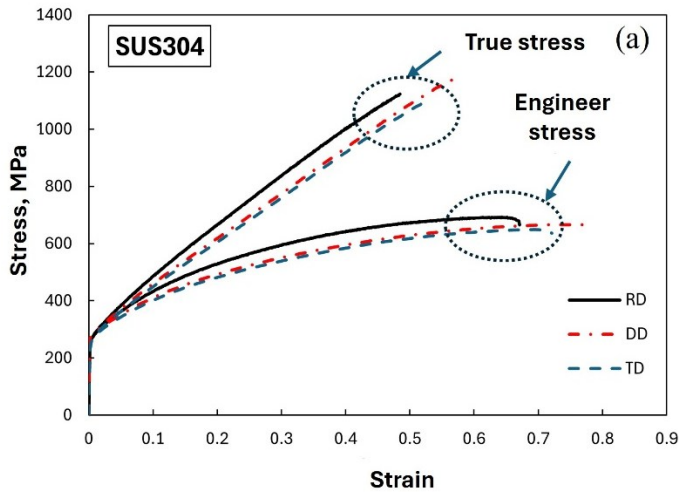
maximum tensile force reaches approximately 15–16 kN, which is much higher than that of SUS304, whereas the displacement to fracture is only a few millimeters. This behaviour indicates that DP1200 has high strength and stiffness but lower ductility.

The tensile test results reveal distinct mechanical responses for SUS304 and DP1200. SUS304 exhibits high ductility and large deformation before fracture, whereas DP1200

provides much higher load-carrying capacity but a more limited deformation range.

4.2. Stress-Strain curve

Based on the experimental force data and



DIC displacement measurements, Fig. 7 presents the engineering and true stress-strain curves, calculated using the initial cross-sectional area and the initial gauge length of the measurement region.

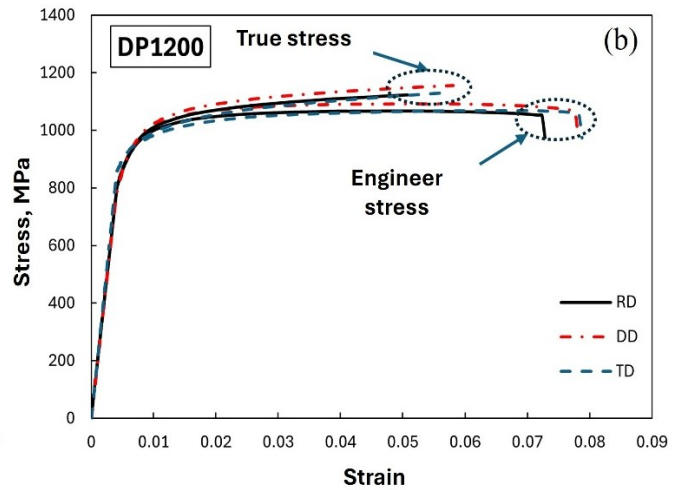


Fig. 7. Experimental stress-strain curves for (a) SUS304 and (b) DP1200 specimens.

For SUS304 (Fig. 7a), the stress-strain response is initially nearly linear, representing the elastic stage. After yielding, the curve enters the plastic region, where the slope gradually decreases, but the stress continues to increase with strain owing to the strong strain-hardening behavior of austenitic stainless steel. The true stress curve remains higher than the engineering stress curve at large strains because it accounts for the reduction in the actual cross-sectional area during tension. SUS304 reaches a true stress of approximately 1100-1200 MPa and a large fracture strain of about 0.5-0.6, indicating excellent ductility and toughness. For DP1200 (Fig. 7b), the initial slope is higher, indicating higher stiffness and yield strength. The material rapidly reaches a stress level of approximately 1100-1200 MPa within a small strain range below 0.1. After the maximum stress is reached, the curve approaches a nearly saturated state and decreases slightly as necking occurs. Similar to SUS304, the true stress is higher than the engineering stress at large strains; however, because the total strain of DP1200 is much smaller, the difference between the two curves is less pronounced. Overall, DP1200 exhibits the typical behavior of a high-strength

dual-phase steel: very high tensile strength and load-bearing capacity, but significantly lower plastic deformation and elongation than SUS304.

4.3. Anisotropic Behavior

Fig. 8 presents the Lankford coefficients (r -values) determined from the linear relationship between width strain and thickness strain for the RD, DD, and TD orientations. The Lankford coefficient in each orientation was determined as the slope of the linear regression of true width strain against true thickness strain, in accordance with ISO 10113 [4]. The regression was performed over the uniform plastic-deformation range prior to necking. For SUS304 (Fig. 8a), the relationships are nearly linear within the investigated range, with slopes of approximately 0.89 (RD), 1.10 (DD), and 0.92 (TD). These results indicate that SUS304 has greater resistance to thinning in the DD orientation ($r > 1$), whereas the lower r values in the RD and TD orientations reflect a relatively higher tendency for thickness reduction.

For DP1200 (Fig. 8b), the relationship between width strain and thickness strain is also nearly linear in the early plastic region. The obtained slopes are approximately 0.95 (RD), 1.04 (DD), and 1.01 (TD). Compared with SUS304, the

r values of DP1200 are more closely grouped and are approximately equal to 1, indicating more uniform resistance to thinning across the sheet directions. This suggests that DP1200 has a lower degree of planar anisotropy and a more stable in-

plane strain distribution under tensile loading. Overall, the Lankford coefficient results show that SUS304 exhibits a clear directional variation in r value, whereas DP1200 has r values closer to unity with smaller directional differences.

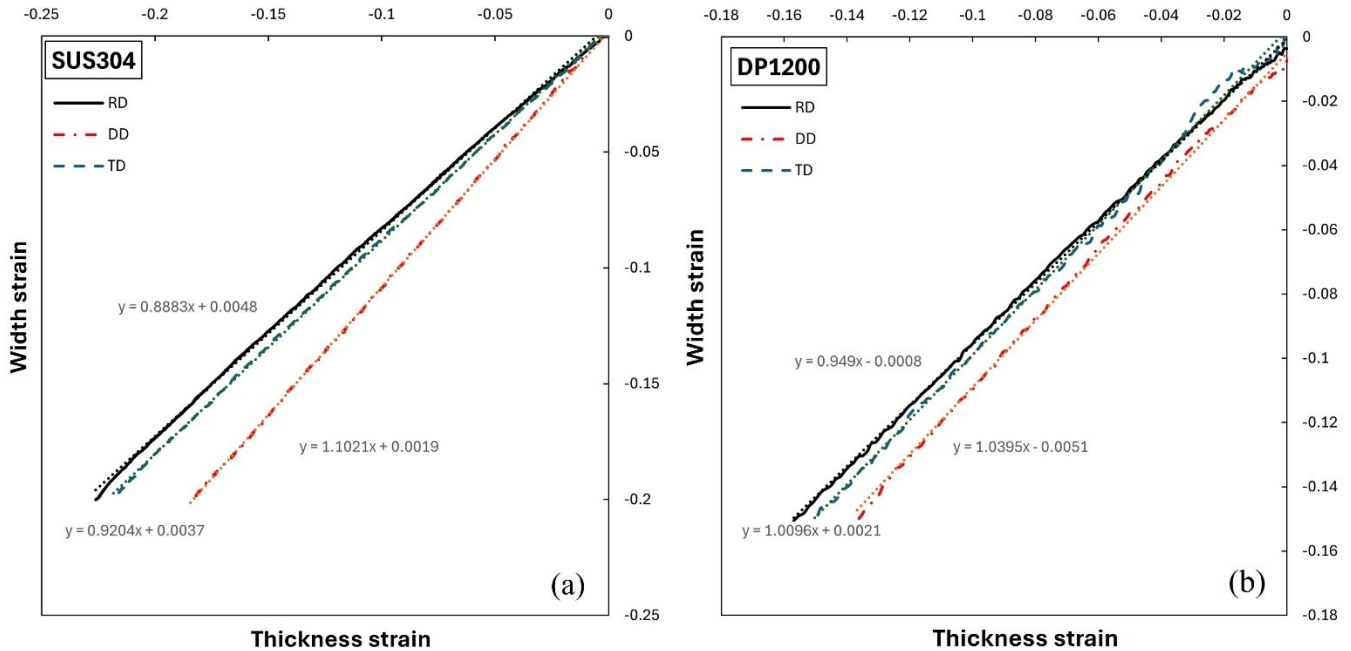


Fig. 8. Linear relationship between width strain and thickness strain used to determine the Lankford coefficients in the RD, DD, and TD orientations for (a) SUS304 and (b) DP1200.

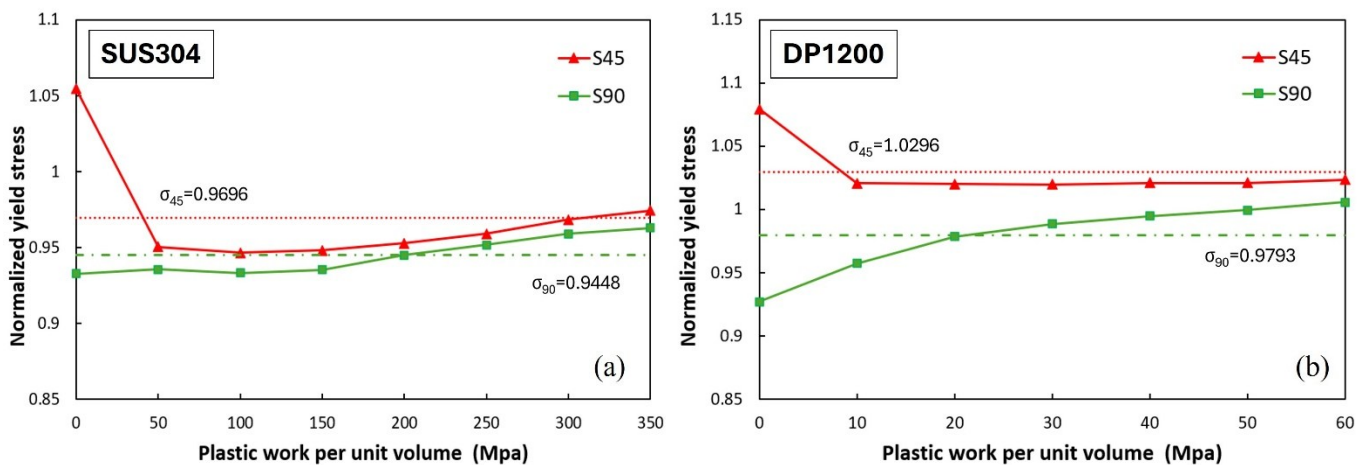


Fig. 9. Normalized yield stresses plotted as a function of plastic work per unit volume for (a) SUS304 and (b) DP1200.

In addition to the Lankford coefficient, the normalized yield stress was analyzed to evaluate the direction-dependent anisotropy of the investigated materials, as shown in Fig. 9. For SUS304 in Fig. 9a, the average normalized yield stresses in the DD and TD orientations are 0.9696 and 0.9448 relative to the RD orientation,

respectively. Values below 1 indicate that the yield stresses in the DD and TD orientations are lower than those in the rolling direction, demonstrating a clear dependence of yield stress on specimen orientation. For DP1200 in Fig. 9b, the normalized yield stresses in the DD and TD orientations are 1.0296 and 0.9793, respectively. These values are

closer to 1 than those of SUS304, indicating a lower degree of yield-stress anisotropy. This observation is consistent with the Lankford coefficient results, which show that DP1200 tends to behave more nearly isotropic in the sheet plane.

The stronger strain hardening and more pronounced planar anisotropy of SUS304 compared with DP1200 can be linked to its metallurgical behaviour. SUS304 is a metastable austenitic stainless steel that undergoes strain-induced martensitic transformation, the TRIP effect, during plastic deformation, with the transformed martensite fraction increasing with plastic strain [8]. The progressive formation of hard martensite within the softer austenitic matrix raises the flow stress and contributes to the strong strain-hardening response evident in the stress–strain curves of Fig. 7(a). Because the extent of transformation depends on strain level, the effective anisotropy parameters of SUS304 vary with plastic work rather than remaining strictly constant, as reflected in the trend of the normalized yield-stress ratios in Fig. 9(a). This variation was small over the measured range, so constant average values were used for the yield-function calibration. The transformation-driven evolution of anisotropy is consistent with the larger directional variation of SUS304 relative to the near-isotropic DP1200, whose ferrite–martensite structure is stable under deformation. To assess the reliability of the in-house 2D-DIC system, the measured anisotropy of SUS304 was compared with independent results for SUS304 obtained using commercial instrumentation. The present study gives Lankford coefficients of $r_0 = 0.89$, $r_{45} = 1.10$, and $r_{90} = 0.92$. Sener et al. [8], testing cold-rolled SUS304, reported $r_0 = 0.76$, $r_{45} = 1.25$, and $r_{90} = 1.01$. A Shimadzu measurement of SUS304 [18] using dual length and width extensometers per ISO 10113:2020 gave $r_0 = 0.86$, $r_{45} = 1.08$, and $r_{90} = 0.83$. The ultimate tensile strength also agrees closely, at 693 MPa for the present RD specimen against 696 MPa reported by Shimadzu. The

higher 0.2% proof stress reported by Shimadzu, 311 to 326 MPa against 253 to 277 MPa, reflects differences in thickness, temper, and heat rather than measurement error. This agreement indicates that the in-house 2D-DIC system provides accurate r -value and strength measurements.

Fig. 10 compares the experimental results (EXP) with the predictions of different yield models, including von Mises, Hill48-S, and Hill48-R, for the Lankford coefficients and normalized yield stresses at 0° , 45° , and 90° with respect to the rolling direction. In this comparison, the von Mises criterion gives constant values in all directions because it assumes isotropic material behavior.

The Hill48-R model, calibrated using the Lankford coefficients, better predicts the directional variation of the r -value. For SUS304, Hill48-R (Fig. 10a) follows the experimental points more closely, particularly in the DD orientation where the Lankford coefficient reaches its maximum value. By contrast, Hill48-S (Fig. 10b), calibrated from the normalized yield stresses, more accurately represents the directional variation of yield stress. For DP1200, because the degree of anisotropy is lower, the differences among the von Mises, Hill48-R, and Hill48-S predictions are relatively small (Fig. 10c, d). The predicted curves are closer to each other and agree reasonably well with the experimental data. This finding suggests that the isotropic assumption may be acceptable for some engineering analyses of DP1200, whereas an anisotropic yield model is required for SUS304 to improve prediction accuracy.

Fig. 11 compares the yield surfaces of SUS304 and DP1200 constructed using three yield models: von Mises, Hill48-S, and Hill48-R. The yield surfaces are plotted in the plane-stress space using the normalized stress components σ_{11} and σ_{22} . For SUS304 (Fig. 11a), the yield surfaces predicted by Hill48 differ noticeably from the von Mises yield surface. The distortion of the yield surface reflects the influence of planar anisotropy on the material response under different stress

states. This effect is particularly important in forming simulations, where the material is subjected to complex stress states rather than simple uniaxial tension. For DP1200 (Fig. 11b), the

von Mises, Hill48-S, and Hill48-R yield surfaces are nearly superimposed within the investigated stress range, confirming its lower anisotropic sensitivity.

4.4. Mechanical properties

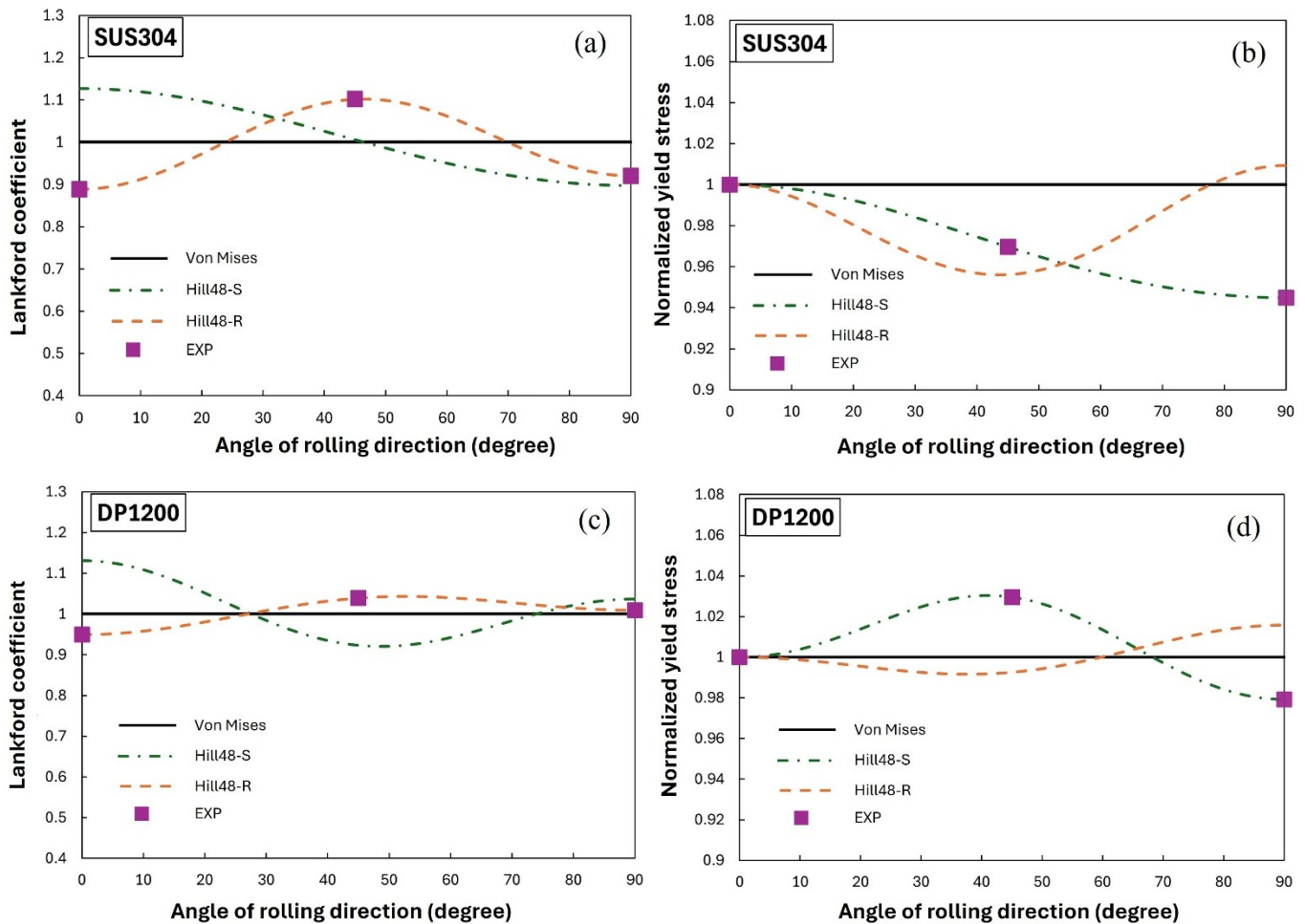


Fig. 10. Comparison between experimental values and predictions of different yield functions for the Lankford coefficient and normalized yield stress: (a, b) SUS304 and (c, d) DP1200

The mechanical properties of SUS304 and DP1200 obtained from uniaxial tensile tests in the RD, DD, and TD directions are summarized in Table 1. For SUS304, the elastic modulus varies slightly from 195 to 199 GPa, indicating a nearly direction-independent elastic response. The yield strength ranges from 253.47 to 276.79 MPa, while the ultimate tensile strength decreases from 692.84 MPa in RD to 648.83 MPa in TD.

These results show that SUS304 has relatively low yield strength but good plastic deformation capability. DP1200 exhibits much higher strength than SUS304. Its yield strength is approximately 932.54–940.83 MPa, and its

ultimate tensile strength reaches 1067.64–1091.06 MPa. The small variation in strength among RD, DD, and TD indicates that DP1200 has a more uniform in-plane mechanical response.

The anisotropic parameters also show different trends for the two materials. SUS304 presents a wider variation in normalized yield stress and Lankford coefficient, indicating more pronounced planar anisotropy. In contrast, the values for DP1200 are closer to unity, suggesting a nearly isotropic plastic response in the plane. Therefore, SUS304 shows stronger anisotropic behavior, whereas DP1200 is characterized by high strength and lower directional dependence.

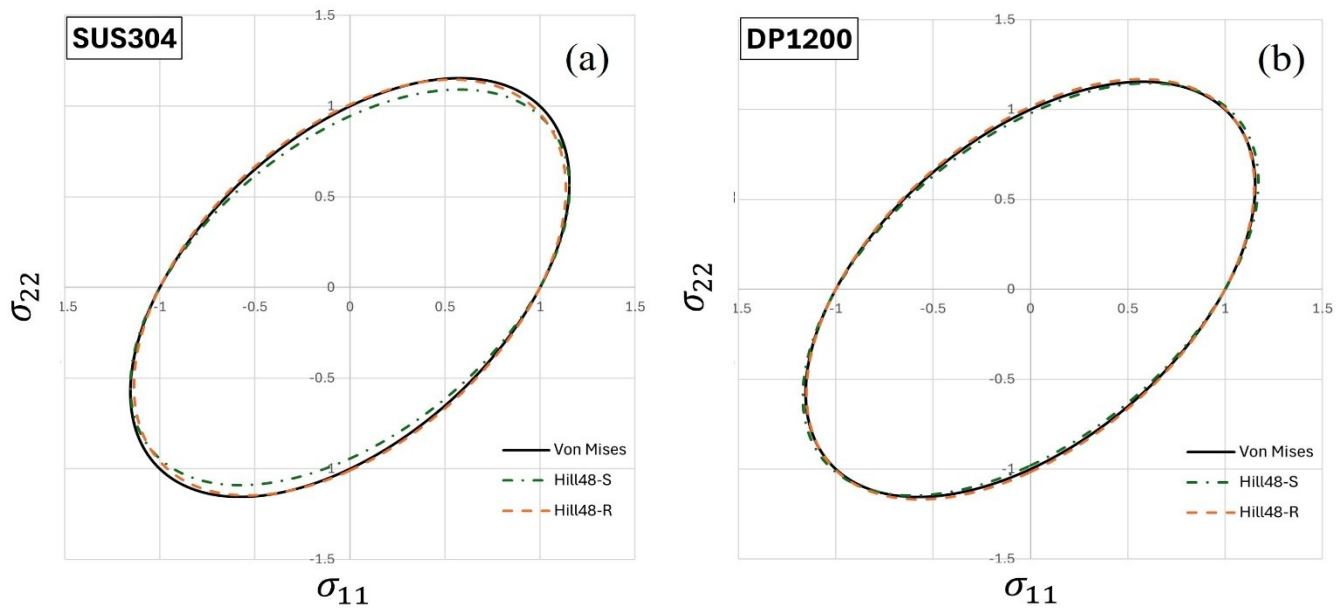


Fig. 11. Comparison of different yield surfaces for (a) SUS304 and (b) DP1200.

Table 1. Mechanical properties of SUS304 and DP1200 obtained from uniaxial tensile tests in the RD, DD, and TD directions

SUS304	RD	DD	TD
Elastic modulus (GPa)	195	198	199
Yield strength (MPa)	253.47	276.79	258.17
Tensile strength	692.84	666.66	648.83
Normalized yield stress	1	0.9696	0.9448
Lankford coefficient	0.8883	1.1021	0.9204
$\bar{r}$		1.0032	
Δr		-0.1978	
DP1200	RD	DD	TD
Elastic modulus (GPa)	195	196	212
Yield strength (MPa)	936.17	940.83	932.54
Tensile strength	1067.64	1091.06	1068.12
Normalized yield stress	1	1.0296	0.9793
Lankford coefficient	0.949	1.0395	1.0096
$\bar{r}$		1.0094	
Δr		-0.0602	

5. Conclusions

This study integrated an in-house 2D-DIC system with uniaxial tensile testing to characterize the anisotropic behavior of SUS304 and DP1200 sheet metals. The system enabled full-field strain measurement and provided reliable data for determining stress-strain curves, Lankford coefficients, normalized yield stresses, and yield

surfaces. The results revealed distinct mechanical responses for each material. SUS304 exhibited high ductility, strong strain hardening, and clear planar anisotropy, with Lankford coefficients ranging from 0.8883 to 1.1021 across the RD, DD, and TD directions. Conversely, DP1200 showed much higher strength but lower directional dependence, with r -values close to unity indicating

nearly isotropic in-plane behavior. Regarding constitutive modeling, the von Mises criterion could not capture the directional variations, whereas the Hill48 model yielded better agreement, especially for SUS304, where Hill48-R better described the r -values and Hill48-S better represented the normalized yield stresses. Future work will extend this framework to 3D-DIC and multiaxial testing to further refine anisotropic yield model calibration.

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Declaration of Generative AI

During the preparation of this work, the author(s) used Claude.ai to improve the readability and language of the manuscript. After using this tool, the author(s) reviewed and edited the content as needed and take full responsibility for the content of the published article.

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