Influence of zinc coating on anisotropic mechanical properties of hot dip galvanized steel sheet DP600

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Abstract. The influence of zinc coating on the anisotropic mechanical properties of hot dip galvanized steel sheet DP600 is studied by tensile test. The results show that zinc coating makes the yield strength of the steel plate decrease, but has no obvious influence on the hardening index. Compared with the bare steel sheet, in the direction of R00 direction parallel to the rolling direction, the tensile strength and yield strength of galvanized steel sheet decrease, while the elongation and thickness anisotropy coefficient increase. After comprehensive analysis, it is found that the plastic deformation ability has decreased in the direction of R00 direction. and the plastic deformation ability decreases after comprehensive analysis. In the R90 direction, the mechanical property parameters of galvanized sheet all increased, and zinc coating improves the plastic deformation ability of the steel sheet. However, in the R45 direction, the variation extent of the mechanical property parameters of galvanized steel sheet is between R00 and R90. Therefore, the influence of zinc coating on the mechanical properties of steel plate is closely related with the rolling direction, which also illustrates that the adhesion strength between the galvanized layer and steel plate substrate is affected by the surface microstructure of rolled steel sheet.

1. Introduction

Advanced high strength galvanized steel sheet has excellent comprehensive properties, such as high strength, light weight and corrosion resistance. It has outstanding performance in anti-collision, energy saving and emission reduction, and extends the service life of the workpiece. It has become one of the major materials for the manufacture of modern automotive panels [1]. However, compared to the ordinary low carbon steel sheet, the formability of the advanced high strength galvanized steel sheet is also restricted to a certain extent. Due to the larger forming force during stamping, the higher contact pressure and temperature between the die and workpiece, the more serious the cracking, powdering and falling off of the galvanized layer, which results in the increase of the friction coefficient of the contact interface [2]. Furthermore, the wear of the die surface is worse and the surface quality of the stamping workpiece is seriously reduced. Therefore, some scholars have considered the cause of the failure of the galvanized layer and its influence on the stamping performance of the steel sheet. The effect of the oxide and alloying elements on the bonding strength of the interface between coating and substrate was
investigated by Song [3,4,5]. Ploypech [6,7] studied the effect of phase thickness on the crack resistance of the zinc coating, and simulated the crack growth mechanism by finite element simulation. Hassani [8] and Cocco [9] have also carried out similar studies by using a mathematical calculation and bending experiments respectively. The effect of the elastic-plastic of the galvanized layer on the friction characteristics and the forming properties of the galvanized steel sheet was studied by Lee [10]. Petit [11] has carried out tensile tests and fatigue tests on advanced high strength galvanized steel Trip800. It was found that zinc plating improves the yield strength, tensile strength and elongation of the steel sheet, but had no bearing on its hardening exponent. From the above results, it is known that the zinc coating layer is an important factor which cannot be ignored in the stamping forming of galvanized steel sheet, which has a significant influence on the formability of the steel sheet.

Due to the rolling process, forming property of the steel sheet is obviously anisotropic. However, the current research focuses on the failure mechanism of galvanized layer and its influence on the mechanical properties of the steel sheet. There is no study on the effect of zinc coating on the anisotropic mechanical properties of the steel sheet. Therefore, the mechanical parameters and microstructure of advanced high strength galvanized steel sheet are measured based on the static non-contact measurement system platform. Based on the above test results, the reasons for the change of mechanical properties of hot-dip galvanized steel DP600 before and after removal of zinc coating layer in the direction of R00 degrees, R45 degrees and R90 degrees with rolling direction are analyzed from macro and micro perspectives.

2. Experimental Materials and Methods

2.1. Experimental materials

The experimental steel sheet is hot-dip galvanized steel DP600, which is produced by Thyssen Krupp Steel Corp. The thickness of the steel sheet is 1.2 mm, and the thickness of the galvanized layer on the upper and lower surfaces of which is about 12 μm. The specification for uniaxial tensile specimen is 255*20*1.2 mm, as shown in figure 1. The cross-section morphology and measurement results of energy spectrum of the galvanized sheet is obtained by the field emission scanning electron microscope, as shown in figure 2. Figure 3 shows the surface morphology of the galvanized steel sheet before and after the removal of the zinc coating layer.

![Figure 1. Uniaxial tensile specimen.](image1)

![Figure 2. Cross-section morphology and measurement results of energy spectrum.](image2)

2.2. Experimental methods

In order to ensure the same parameters of the experimental samples, the samples are taken from the same batch. By the method of the electro sparks wire-electrode cutting, the samples of R00 degrees, R45 degrees and R90 degrees with the rolling direction are obtained and marked respectively. Two samples in each direction are the original steel sheet with zinc coating layer and substrate steel sheets that have been removed from the zinc coating layer. It is considered that the physical method can easily damage the surface morphology and influence the mechanical properties of the substrate. Therefore,
chemical pickling method is utilized to remove zinc coating layers on the surfaces of galvanized steel sheet in this experiment.

Samples which need chemical pickling are placed into a certain concentration of hydrochloric acid solution until the surfaces of the samples appear obvious delamination and no more bubbles are produced. Then take out the samples and rinse with clean water, then wipe them with filter paper, and then dry them with a cold air. Make the corresponding mark again, and apply the antirust oil to the surface immediately. In order to prevent the reoxidation of the substrate surfaces of the steel sheet, which affects the results of the uniaxial tensile test. Therefore, the prepared samples have to be stored in a dry sealed box.

![Image](a) (b) (c) (d) (e) (f)

**Figure 3.** Measurement results of surface morphology: (a)500 Max, (b)1000 Max and (c)2000 Max are the surfaces morphology of the original steel sheet with zinc coating layer; (d)500 Max, (e)1000 Max and (f)2000 Max are that of the substrate steel after the removal of the zinc coating layer.

The surface antirust oil is removed with alcohol before the experiment, and the experiment requires to be completed in the shortest possible time. In order to minimize the effect of lubrication and surface oxidation on the experimental results, tensile tests of the bare substrate steel sheet specimens need to be completed first. The tensile tests are tested by a static non-contact measuring system platform. The experimental data are collected by the computer and processed with the VIC-2D software. The actual displacement of the sample and the Lagrange strain tensor at each point of the surface are obtained, and the engineering stress-strain data of each sample are obtained. Finally, the stress strain data of engineering are further processed and analyzed with MATLAB software, and the stress-strain curves of each sample are obtained.

### 3. Experimental results and discussions

After the experiments, it is observed that the fracture direction of the galvanized steel and the bare substrate steel specimens are all 45 degrees. It can be observed that the shear strength of the hot galvanized steel sheet DP600 is lower than that of its tensile strength. The performance index data of each experiment and its stress-strain curve are obtained by computer and its related software. The change of yield strength $\sigma_y$, tensile strength $\sigma_b$, elongation $\delta$, normal anisotropy $r$ and hardening index $n$ of
galvanized steel sheet DP600 in three directions before and after removal of zinc coating layer before are compared and analyzed, so as to determine the influence degree of zinc coating on the anisotropic mechanical properties. The detailed mechanical parameters obtained by the experiment are shown in table 1. The results of the processing of the experimental data are shown in figure 4.

| Angle with rolling direction | With zinc coating layer | Yield strength $\sigma_s$ / MPa | Tensile strength $\sigma_b$ / MPa | Elongation ratio $\delta$/% | Normal anisotropy $r$ | Hardening index $n$ |
|-----------------------------|------------------------|-------------------------------|-------------------------------|-------------------------|----------------------|-------------------|
| R00°                        | Yes                    | 394                           | 609                           | 27.1                    | 1.171                | 0.168             |
|                             | No                     | 396                           | 621                           | 24.4                    | 1.124                | 0.173             |
| R45°                        | Yes                    | 388                           | 609                           | 24.8                    | 0.94                 | 0.176             |
|                             | No                     | 396                           | 608                           | 25.1                    | 1.023                | 0.17              |
| R90°                        | Yes                    | 377                           | 608                           | 25.5                    | 0.853                | 0.181             |
|                             | No                     | 387                           | 601                           | 25.3                    | 0.902                | 0.175             |

![Figure 4](image)

**Figure 4.** The change of anisotropic mechanical properties: (a)R00°, (b)R45°, (c)R90°, and (d) the fluctuation value in three directions.

According to the results of table 1 and figure 4 show that the mechanical properties parameters such as yield strength, tensile strength, elongation and normal anisotropy of the uniaxial tensile specimens have changed obviously in the direction of R00 degrees, R45 degrees and R90 degrees before and after the removal of the zinc coating layer. Compared with the substrate steel without zinc coating layer, the yield strength of galvanized steel in the direction of R00 degrees, R45 degrees and R90 degrees decrease by 2MPa, 8MPa and 10MPa respectively, while the hardening index is less affected. The tensile strength in the direction of R45 degrees and R90 degrees increases 1MPa and 7MPa, and the elongation increases...
by 2.7% and 0.2%, respectively. Moreover, the yield ratios of the galvanized plates in the three directions before and after removing the zinc coating layer are (1.5457, 1.5682), (1.5696, 1.5354) and (1.6127, 1.5530) respectively, with a difference of -0.0225, 0.0342 and 0.0598. It is not difficult to find that the yield ratio of galvanized steel in R90 degree direction is the largest increase compared with the substrate steel, and the tensile strength and elongation also increase, and the yield strength decreases the largest, which indicates that the coating can improves the mechanical properties of the steel in this direction. However, in the direction of R00 degrees, the change of tensile strength and elongation is the largest before and after removing the zinc coating layer, which fully indicates that the zinc coating layer has the most influence on the mechanical properties of steel plate in this direction.

![Figure 5](image.png)

**Figure 5.** Stress-strain curves of galvanized sheet with zinc coating layer and substrate steel without zinc coating layer: (a)R0°, (b)R45°, (c)R90°.

Figure 5 is the comparison of stress and strain curves in three different directions. In the direction of R00 degrees and R90 degrees, the coincidence degree of stress-strain curves is relatively low before and after removing the zinc coating layer, which indicates that zinc coating layer has great influence on the mechanical properties of steel sheet in these two directions. In the direction of R45 degree, the stress-strain curves have a high coincidence degree, which indicates that the zinc coating layer has little influence on the mechanical properties in this direction. From R00 degrees to R90 degrees, the influence of zinc coating layer gradually weakened on the anisotropic mechanical properties of the galvanized steel sheet.

Zinc coating layers are attached to the surfaces of the substrate steel sheet by adhesion force, and the phenomenon of alloying in the process of hot galvanizing will strengthen the adhesion. Therefore, the galvanized layer can be considered as a plastic body. When the plastic deformation occurs, the adhesive force is applied to the substrate, which makes the anisotropic mechanical properties changed before and after removing the zinc coating layer. Moreover, because the rolling direction of the steel plate has a certain effect on the surface morphology of the substrate, the interface bonding strength between the zinc coating layer and the steel substrate in the direction of R0 degrees, R45 degrees and R90 degrees...
is also quite different, which makes the galvanized layer have different effects on anisotropic mechanical properties parameters of advanced and high strength hot-dip galvanized steel sheet DP600.

4. Conclusions

- Before and after removing zinc coating layers, the yield strength, tensile strength, elongation, normal anisotropy and hardening index of hot dip galvanized steel DP600 change greatly in the direction of R00 degrees and R90 degrees, while the change is less in R45 degrees direction. Therefore, the effect of zinc coating layer on the anisotropic mechanical properties of galvanized steel sheet should be considered in the future study.
- The influence degree of the zinc coating layer on the anisotropic mechanical properties of galvanized steel sheet is different because the rolling direction of the steel plate has a certain effect on the surface morphology of the substrate. Furthermore, the interfacial bonding strength between the coating and the substrate is not uniform in different angles with rolling direction.

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