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Experimental Investigations of Bend Force in Air Bending of Electrogalvanized Steel Sheets

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This article deals with bend force behavior of electro-galvanized (EG) steel sheets in air bending process. A detailed experimental study was carried out on EG steel sheets of various coating thicknesses to investigate the influence of parameters such as coating thickness, orientation of the sheet, punch radius, die opening, die radius, and punch velocity on bend force behavior. From the results, it is found that zinc coating reduces the bend force and the increase in coating thickness reduces the bend force significantly. It is observed that the bend force is larger for larger punch radius, smaller die opening, and smaller die radius. It is also observed that the bend force is larger for 0° orientation than for 90° orientation. The bend force decreases with increase in punch velocity, and this influence is more prevailing in EG sheets than in plain sheets.

Keywords air bending, bend force, electro-galvanized steel sheet, process parameters

1. Introduction

Sheet metal forming is one of the major near-net-shape processes for the manufacturing of different automobile components. Sheet metal bending, being an important sheet metal-forming process, employs a press brake with proper tooling to produce different bend components. The flexibility of the bending process is improved by the air bending technique (Ref 1). Flexibility is achieved in such a way that the different bend angles can be produced simply by controlling the punch travel into the die without the need for changing tool sets. Owing to this, air bending is commonly used in automotive manufacturing and other fabrication industries to meet the precision demands and shorter lead time.

In the automotive industry, hot-dipped galvanized and electro-galvanized (EG) steel sheets are widely used. Besides providing better corrosion resistance, the coated sheet steels must also satisfy the other requirements such as formability and surface quality. The formability of zinc-coated steels depends on both the characteristics of the substrate and the nature of the coating (Ref 2). The surface damage of the layer during forming affects the formability of the sheet. In hot-dipped coatings, as the steel is immersed in molten zinc at high temperature, the Fe-Zn intermetallic phases are formed at the coating-substrate interface. These intermetallic phases are hard and brittle (Ref 3). Hence, cracks are formed in the earlier stage of forming and as a result, the formability will be reduced. As the EG coating has a constant chemical composition over their whole thickness, small grain size, and lower hardness, the coating follows deformation of the substrate easily without cracking (Ref 4). Hence, the EG steel sheets have better formability (Ref 2) and surface finish; these sheets are naturally much preferred as a substitute for uncoated cold-rolled steel sheets in automotive applications, such as panels, fenders, hoods, and gas tanks.

During bending, bend force is the force needed to deform the sheet metal to the required shape. The information on bend force provides a base to the designer for the design of tooling and selection of press (Ref 5). Very few studies on bend force are available in various bending processes. Huang and Leu (Ref 5) investigated the effect of process variables on punch load in closed die V-bending process of steel sheet by performing experiments and finite element simulation. It was found that punch load increases as strain hardening exponent decreases, whereas punch radius and punch speed increase. Hamouda et al. (Ref 6) studied the springback and load-displacement characteristics for different types of stainless steel in V-bending process using finite element approach. They established that the bend force increases with increasing initial effective stress and coefficient of friction. Fei and Hodgson (Ref 7) carried out an experimental study to understand the springback and punch load behavior of TRIP steels in air V-bending process. In this study, it was identified that the die gap and blank thickness have strong influence on the process. Narayanasamy and Padmanabhan (Ref 8) developed a model for bend force using response surface methodology for air bending operation of interstitial-free steel sheet. This study shows that the punch travel is the dominant factor determining the bend force followed by punch radius and punch velocity. Bahloul et al. (Ref 9) employed three optimization procedures based on the response surface method to reduce the maximum bend force in wiping die bending process. The die radius and clearance between the punch and the sheet are considered for optimizing the bend force. These investigations on bending show that the process parameters, such as orientation, punch travel, punch

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radius, die opening, die radius, and punch velocity have considerable influence on the bend force.

In air bending, the bend force-punch travel relations can be compared with bending model results and necessary corrections can be made to achieve better in-process control (Ref 10, 11). Hence, the understanding of the bend force behavior is essential in air bending. From the review, it is found that most of the investigations concentrate on studying the springback (Ref 10, 12-16) and not much attention has been paid on bend force studies. To make up the lack of the literature available on bend force behavior in air bending, the present investigation has been carried out. In the present study, the air bending tests are performed on the EG steel sheet blanks to analyze the effect of various process parameters including coating thickness, orientation of the sheet, punch radius, die opening, die radius, and punch velocity on bend force behavior.

2. Experimental Work

The substrate used in this investigation is aluminium-killed draw quality (AKDQ) steel sheet with 1-mm thickness. The chemical composition of the uncoated steel sheet was found out using spectroscopy, and the major elements are given in Table 1. The tensile tests were conducted as per ASTM E8 standard to determine the mechanical properties of the uncoated steel sheet. The measurements were taken for the two orientations: 0° (along the rolling direction) and 90° (perpendicular to the rolling direction). The measured mechanical properties are given in Table 2.

The steel sheets were EG for various coating thicknesses, such as 4 and 7 μm. The coating was obtained by zinc chloride electrolyte, and pure zinc was used as anode. The pH value was adjusted to 4.8 at 30°C. Pretreatments were necessary to get rid of the impurities before electrogalvanizing.

The blanks from the coated and uncoated steel sheets were cut to the required dimensions of 120 mm × 40 mm, and the edges were cleaned to remove the burrs. A 40 T Universal Testing Machine (UTM) was used for conducting the air bending experiments. The tool set consisted of a die and a punch, made of hardened steel. The experimental set up is shown in Fig. 1. In the UTM, the punch was mounted in the cross head and the die was located on the platform. The blanks were placed on the die in proper position with necessary care. The steel blanks were bent by moving the punch gradually to various depths such as 5, 10, 15, 20, and 25 mm. The corresponding punch travel and the bend force were measured from the digital display of UTM and the load cell (Universal S type load cell of capacity 100 kgf) setup respectively. Three tests were conducted for each punch travel, and the average values were taken.

3. Experimental Results and Discussions

Experiments were conducted with combination of process variables and tooling geometries and the process parameters used in this study are given in Table 3. The bend force values were measured accurately and were converted to per unit meter width. The effects of various parameters on bend force were illustrated by plotting graphs with punch travel in *X*-axis and bend force in *Y*-axis. The second-order polynomial function was adopted for fitting curves in graphs.

3.1 Bend Force and Punch Travel Curve

The bend force-punch travel curve is shown in Fig. 2. The curve can be divided into two major regions (Ref 17). In the first region, the bend force increases nonlinearly with the punch travel and reaches a maximum value. This increase in bend force is caused by the development and spreading of plastic zone (Ref 18).

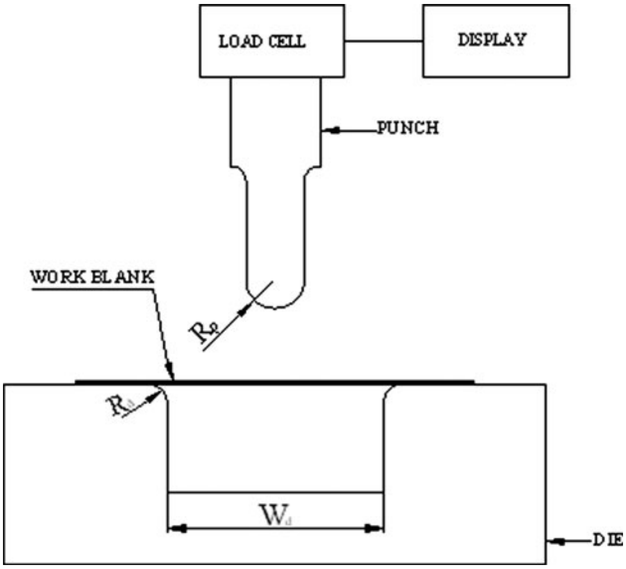

Fig. 1 Schematic diagram of experimental setup

Table 1 Chemical composition of uncoated sheet (A) and coating (B)

Elements	C	Si	Mn	P	S	Al	Fe	Zn
Composition of A (wt.%)	0.079	0.025	0.332	0.016	0.015	0.031	Rest	···
Composition of B (wt.%)	···	···	···	···	···	···	···	100

Table 2 Mechanical properties of uncoated sheet

Orientation related to rolling direction	Yield strength (σ_y), MPa	Ultimate strength (σ_u), MPa	Young's Modulus (*E*), GPa	Strain hardening exponent (*n*)	Strength coefficient (*K*), MPa
0°	208.6	345.3	206	0.211	413.4
90°	214.3	335.2	206	0.227	436.1

Table 3 Tool and process parameters

Parameters	Dimensions
Work blank ($L_s \times W_s \times t_s$) in mm	120 × 40 × 1
Coating thickness (t_c) in µm	0, 4, 7
Punch radius (R_p) in mm	8, 12, 16
Die radius (R_d) in mm	3, 5, 8
Die opening (W_d) in mm	40, 60, 80
Punch travel (d_p) in mm	5, 10, 15, 20, 25
Punch velocity (V_p) in mm/s	0.4, 0.6, 0.8

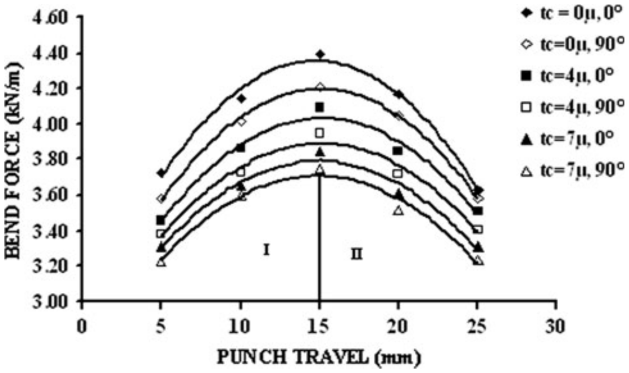

Fig. 2 Variation of bend force with respect to punch travel for different coating thicknesses and orientations (R_p = 8 mm, R_d = 5 mm, W_d = 60 mm, V_p = 0.4 mm/s, W_s = 40 mm)

Further, in the second region, the bend force gradually falls. This reduction in bend force is due to the lower deformation resistance and large rigid body displacement (Ref 6).

The bend force-punch travel curves for different parameters are shown in Fig. 2-6. It is found that in all the cases, the bend force curves exhibit similar pattern of behavior.

3.2 Influence of Coating Thickness on Bend Force

The relationship between the bend force and coating thickness is shown in Fig. 2.

It is noted that for the same punch travel, there is a decrease in bend force with increasing coating thickness. It is considered that this behavior is due to the frictional properties of the coating. When the sheet comes in contact with tooling, the presence of zinc changes the friction experienced by the sheet. Since the shear strength of zinc is comparatively lower than the steel, this softer zinc coating acts as a lubricant (Ref 4) and reduces the friction. Hence, there is a decreased membrane force (Ref 6), which is expected to decrease the bend force. The increase in coating thickness reduces friction further (Ref 3, 19), resulting in decreasing bend force.

3.3 Influence of Orientation on Bend Force

The effect of orientation on bend force is shown in Fig. 2. It is found that for both uncoated and coated sheets, the orientation has an influence on bend force. The blanks along 0° orientation exhibit greater bend force than the blanks of 90° orientation. This is because the bend force depends on ultimate tensile strength (Ref 20) and strain hardening exponent (Ref 8). Increase in ultimate tensile strength increases the bending moment, and hence the bend force. Strain hardening exponent (n) represents the ability of the metal to undergo plastic deformation before necking and strongly influences the formability of the metal (Ref 3). The higher the n value is, the higher the resistance is to neck formation, and hence, the more enhanced the formability of the metal will be. The inner bending radius is the significant parameter indicating the bendability in the bending process. The strain level in the bending region and the risk of fracture are decided by this radius. This radius is also related to the bending moment and the required bend force (Ref 12). Smaller n values will induce a larger bending radius which implies difficulty in bending. Besides, the bending moment increases with the decreasing n values causing the bend force to increase (Ref 21). Hence, higher n value indicates better bendability and lower n value marks difficulty in bending. The basis for higher bend force in 0° orientation than in 90° orientation is its higher ultimate tensile strength and lower strain hardening exponent.

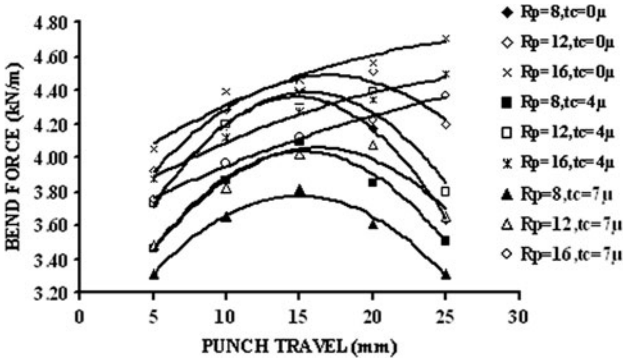

Fig. 3 Variation of bend force with respect to punch travel for different punch radii (R_d = 5 mm, W_d = 60 mm, θ = 0°, V_p = 0.4 mm/s, W_s = 40 mm)

3.4 Influence of Punch Radius on Bend Force

Figure 3 illustrates the bend force for uncoated and coated steel sheets for different punch radii. It is observed that bend force increases when the punch radius increases. In air bending, the bend force depends on the total bending moment which is contributed to a larger extent by fully plastic bending (Ref 22). The fully plastic bending occurs in the punch-sheet contact region, known as wrap-around region (Ref 1). This region increases with increasing punch radius and causes greater bend force for large bend radius.

It is also noted that maximum bend force is reached at different punch travel for various punch radii. The inner radius at air bending determines the strain level in the bending region, thus the required bend force (Ref 12). During the bending process, the sheet bends with larger radius initially, and for further punch travel, the sheet radius gradually decreases until complete wrap around (inner sheet curvature and punch curvature are same) or till the end of punch travel. This behavior is determined by effective die width. The effective die width is larger for smaller punch radius with larger die opening, and in this case, the complete wrap around may occur at a shorter punch travel (Ref 23). The increase in punch radius decreases the effective die width, which causes the change in the course of bend force.

3.5 Influence of Die Parameters on Bend Force

From the Fig. 4 and 5 it is noted that the bend force increases as the die opening and die radius decreases for both

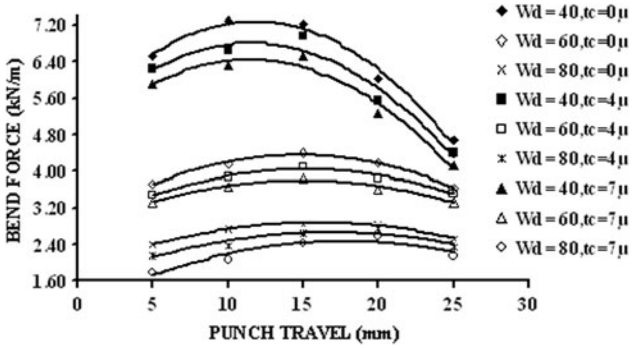

Fig. 4 Variation of bend force with respect to punch travel for different die openings (R_p = 8 mm, R_d = 5 mm, θ = 0°, V_p = 0.4 mm/s, W_s = 40 mm)

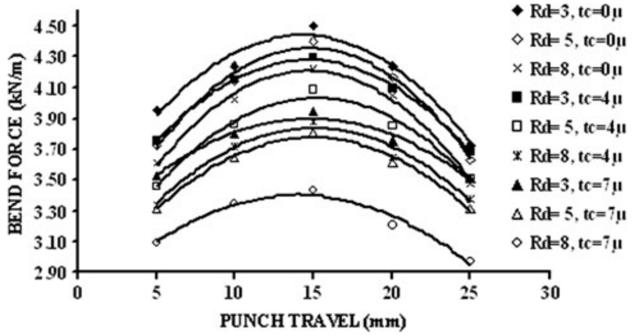

Fig. 5 Variation of bend force with respect to punch travel for different die radii (R_p = 8 mm, W_d = 60 mm, θ = 0°, V_p = 0.4 mm/s, W_s = 40 mm)

plain and coated steel sheets. The die opening determines the lever arm that is utilized to transfer the bend force into bending moment (Ref 11). It is evident that, as the lever arm becomes smaller for a smaller die opening, a higher bend force is needed to provide the necessary bending moment.

It can be explained that an increase in die radius is similar to an increase in die opening in a restricted sense (Ref 13). Since the point of contact of the tool and support to the sheet are spaced further apart for larger radius, the lever arm increases, and a smaller bend force is needed to produce the required bending moment. Moreover, the die radius has an effect on the contact pressure, and the larger die radius reduces the contact pressure (Ref 24), thereby the bend force. However, the influence of die radius is not as significant as die opening.

3.6 Influence of Punch Velocity on Bend Force

The effect of punch velocity on bend force is shown in Fig. 6. Bend force is decreased with an increase in punch velocity for both plain and coated steel sheets. The reason is, punch velocity has an effect on friction (Ref 24, 25). Since the increase in punch velocity decreases the friction (Ref 26), the bend force decreases accordingly. However, the difference in bend force is more for EG sheet compared to that of the plain sheet. It can be concluded that the effect of velocity on bend force is dominant in EG steel sheet than in uncoated steel sheet.

3.7 Microstructure Study

Cracking of coated layer is one of the major problems observed in forming of coated steel sheets. The cross section of a bent specimen has been studied using SEM for cracking of zinc coating with a magnification of ×4000. The SEM images of bent and unbent specimens are shown in Fig. 7(a) and (b). It is clear that, the cracking has not occurred even when the studied specimen is bent with a longer punch travel of 25 mm and a narrow die opening of 40 mm. Since the coating is relatively softer than the substrate, the coating deforms much easily with substrate, and hence the cracks have not occurred.

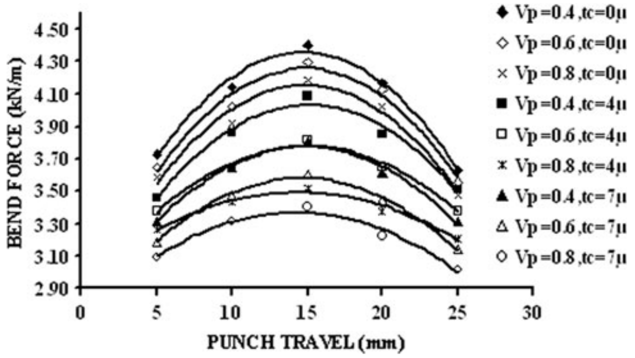

Fig. 6 Variation of bend force with respect to punch travel for different punch velocities (R_p = 8 mm, R_d = 5 mm, W_d = 60 mm, θ = 0°, W_s = 40 mm)

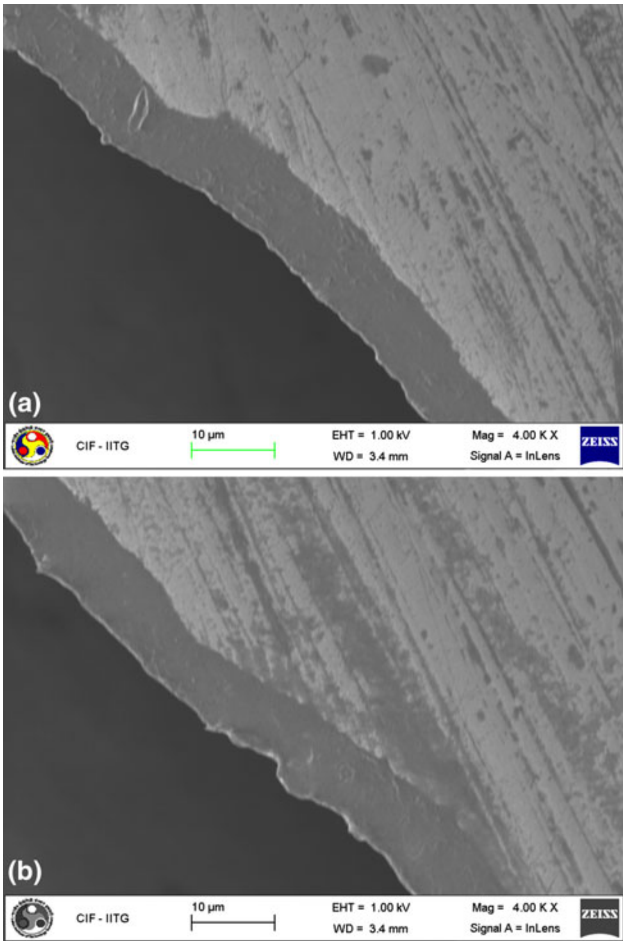

Fig. 7 SEM micrographs of (a) unbent specimen and (b) bent specimen (t_c = 7 μ, R_p = 8 mm, R_d = 5 mm, W_d = 40 mm, t_p = 25 mm, θ = 0°, V_p = 0.4 mm/s, W_s = 40 mm)

4. Conclusions

The study is carried out to understand the influence of various parameters on bend force during air bending of EG steel sheets. The major conclusions derived from the study are listed below:

1. The bend force decreases when the coating thickness increases. This is due to the lubricating action of zinc coating which lowers the friction and hence reduces the bend force.
2. The bend force is greater for 0° orientation than for 90° orientation, as the ultimate tensile strength and strain hardening exponent influence the bend force.
3. The bend force increases with increasing punch radius because of the enlargement of plastic region.
4. The increase in die parameters such as die opening and die radius reduces the bend force. Since the increases in die opening and die radius cause an increase in the lever arm, a smaller bend force is required to produce the bending moment.
5. The increase in punch velocity decreases the bend force, and this influence is more in the case of EG steel sheet than in the uncoated steel sheets.
6. Cracking of coating has not occurred as the coating deforms easily with the substrate.

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