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Spinnability Investigation of High Strength Steel in Draw-spinning and Flow-spinning

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Abstract. High strength steels are difficult to process in spinning due to their high yield and tensile strength, poor ductility and large springback. In this paper, formability of dual phase steel has been investigated on the basis of spinnability evaluation in draw-spinning and flow-spinning processes. The influences of key process parameters such as feed ratio and wheel fillet radius on forming limit coefficient in draw-spinning and maximum thinning ratio in flow-spinning are studied in detail.

Key words: Spinning, High strength steel, Process parameters

1. Introduction
In order to face the challenges of vehicle safety, fuel economy and emission standard, lightweight has already become an inevitable development trend for automotive and steel industries [1]. Some studies indicate that fuel efficiency can be enhanced by 6 % to 8 % when vehicle weight reduces by 10 % [2, 3]. Lightweight structures, materials and processes are three most important technical routes to carry out weight reduction of vehicles. The application of high strength steels in body-in-white structure and safety components is an environmental friendly and cost effective solution of material lightweight.

Spinning has its unique advantages in fabricating rotational parts with high strength and geometric accuracy, good anti-fatigue performance and variable wall thickness [4-6]. Spinning is a typical ‘near-net-forming’ technology which integrates the process characteristics of forging, extrusion, deep drawing, bending, roll forming etc. Spinning can be classified into conventional spinning and power spinning. Furthermore, conventional spinning has three basic modes which are drawing, necking and flaring spinning; also, power spinning has shear and flow spinning. Wong et al. presented the principles of spinning and describes the development of the spinning process and its equipment in great detail [7]. Music et al. gave a good summary of academic work on the analysis and application of the mechanics of spinning [8]. Xia et al. developed many novel spinning processes in recent years, such as non-asymmetrical spinning [9]. Xia et al. found that the radial force, axial force and thickness strain increased when higher feed ratios were applied by one-pass deep drawing spinning experiment [10]. Long et al. investigated the effects of roller profile and roll path on spinning [11].

It is very difficult to process high strength steels in spinning due to their poor ductility. In this paper, dual phase (DP) steels are utilized to perform experimental investigations in draw- and flow-
spinning. Additionally, the influences of key process parameters on forming limit coefficient in draw-spinning and maximum thinning ratio in flow-spinning are studied in detail.

2. Experimental investigation of material spinnability

2.1. Material spinnability evaluation in draw-spinning

Draw-spinning is one kind of conventional spinning process, which is defined as a process where the diameter of the blank is deliberately reduced either over the whole length or in defined areas without a change in the wall thickness. In single pass draw-spinning, the ratio between diameter of spinning component \(d\) and diameter of blank sheet \(D_0\) is considered as draw-spinning coefficient which can be used to evaluate material deformation capability [12]. The draw-spinning coefficient is formulated as follows:

\[
m = \frac{d}{D_0}
\]

(1)

\(m\) is the draw-spinning coefficient. A smaller \(m\) value means larger material deformation and better spinnability. The minimum \(m\) value is named limit draw-spinning coefficient.

In this study, material spinnability tests were conducted in a horizontal spinning machine. The experimental device for material spinnability evaluation in draw-spinning is shown in figure 1. During equipment development, micrometer was used to adjust the position precision of mandrel, spinning wheel and end ejector pin. The positioning errors of mandrel and wheel were controlled within 0.1 mm and 0.05 mm, respectively.

![Figure 1. Experimental device for draw-spinning process.](image)

2.2. Material spinnability evaluation in flow-spinning

Flow-spinning or flow forming, also known as tube spinning, is one kind of power spinning process. In this process, as shown in figure 2, the metal is displaced axially along a mandrel, while the internal diameter remains constant. It is usually employed to produce cylindrical components. The difference between draw-spinning and flow-spinning is whether the wall thickness is changed after the forming. In conventional draw-spinning, the wall-thickness of the blank remains nearly constant throughout the process, thus the final wall-thickness of the spun part is equal to the thickness of the blank. In contrast, the wall-thickness of the blank is reduced in flow-spinning.

The maximum thinning ratio \(\Psi_{\text{max}}\) is used to evaluate material formability in flow-spinning process. In physical tests as shown in figure 2, spinning wheel moves at a set feed ratio and its movement direction has a very small angle \(\theta\) with mandrel generatrix. The wall thickness changes from initial thickness \(t_0\) to \(t_f\) which stands for the thickness at fracture location. The maximum thinning ratio \(\Psi_{\text{max}}\) can be expressed by the following equation:

\[
\Psi_{\text{max}} = \frac{t_0 - t_f}{t_0}
\]

(2)

Larger values of \(\Psi_{\text{max}}\) mean a better material formability in flow-spinning.

The experimental device for material spinnability evaluation in flow-spinning is shown in figure 3. The positioning errors of mandrel and end ejector pin should be limited within 0.1 mm and 0.2 mm, respectively. Moreover, the radial and axial errors of wheel alignment should be smaller than 0.05 mm and 0.1 mm due to the application of two wheels in the process.
3. Influence of process parameters on spinning quality

3.1. Influence of process parameters on draw-spinning

In this study, the influence of key process parameters, such as feed ratio, wheel radius and wheel profile face, on draw-spinning coefficient is investigated in detail by using high strength steel DP600 with thickness of 1.5 mm.

Wheel fillet radius $r_\rho$ and relative gap between mandrel and wheel $\delta$ are set as 10 mm and 0, respectively when the relation of feed ratio $f$ and draw-spinning coefficient $m$ is studied. Figure 4 shows the influence of feed ratio $f$ on draw-spinning coefficient $m$. Three different zones named ‘success zone’, ‘fracture zone’ and ‘wrinkle zone’ can be observed from the figure. When feed ratio $f$ is less than 0.1 mm/r ‘fracture zone’ is observed. This means low feed ratio will easily lead to fracture since material experiences more loading circles during unit time and gets into excessive thinning due to sufficient flow. In ‘success zone’, the distribution of sound cases follows a ‘V’ shape. This phenomenon indicates that an appropriate feed ratio $f$ is beneficial to reduce draw-spinning coefficient and improve material formability. For DP600 with sheet thickness of 1.5 mm, the minimum draw-spinning coefficient achieves 0.69 when feed ratio $f$ ranges from 0.25 to 0.3 mm/r. As compared to ‘fracture zone’ and ‘success zone’, ‘wrinkle zone’ takes much larger area in the forming window map. When draw-spinning coefficients are even smaller than the corresponding minimum values at different levels of feed ratio $f$, wrinkle defect will occur because large unformed flange area is easy to make tangential compression stress exceed its critical value of wrinkling. In addition, it should be noticed that ‘wrinkle zone’ becomes larger with an increase of feed ratio $f$. This is because more material involved into deformation will lead to higher stress level which makes the tangential compression stress at the edge of blank is also higher. It can be summarized from figure 4 that an optimal value of feed ratio $f$ to DP600 in draw-spinning can be found.

Feed ratio $f$ and relative gap between mandrel and wheel $\delta$ are set as 0.3 mm/r and 0, respectively during the tests for studying the relation of wheel fillet radius $r_\rho$ and draw-spinning coefficient $m$. Figure 5 shows the influence of wheel fillet radius $r_\rho$ on draw-spinning coefficient $m$. Similarly, the forming window also can be divided into ‘success zone’, ‘fracture zone’ and ‘wrinkle zone’. ‘Fracture zone’ is found when wheel fillet radius $r_\rho$ is smaller than 7.5 mm. This phenomenon attributes to high localized contact pressure. With the increasing of wheel fillet radius $r_\rho$, the spinnability of DP600 with thickness of 1.5 mm has been improved. ‘Success zone’ mainly locates at the area where wheel fillet radius $r_\rho$ is relatively large. ‘Wrinkle zone’ takes the largest area in the forming window map. When wheel fillet radius $r_\rho$ is relatively small, material flow becomes non-uniform and will accumulate at the outer edge of blank. It will increase the tangential compression stress during forming. Wrinkling has been found in most of cases when draw-spinning coefficient is below 0.68. In this condition, tested material achieves its forming limit in single-pass draw-spinning process. Therefore, an appropriate wheel fillet radius $r_\rho$ is very important to draw-spinning process, and it usually should be five times larger than blank thickness ($r_\rho > 5t_0$) in draw-spinning process to avoid fracture or wrinkling.
In order to study the influence of compound wheel surface on draw-spinning coefficient $m$, wheels with different fillet sizes are utilized. During the tests, feed ratio $f$ and relative gap between mandrel and wheel $\delta$ are set as 0.3 mm/r and 0, respectively, and drawing-spinning coefficient ranges from 0.67 to 0.70.

Table 1 shows the obtained results. In general, compound wheel surface and normal wheel surface have similar influence on the formed components. Large wheel fillet radius and high draw-spinning coefficient are helpful to fabricate a sound component. When draw-spinning coefficient $m$ is determined as 0.67, the wheel with fillet radius of 10-35 mm is capable to form the component without wrinkle defect; however, slight wrinkle has been detected with the utilization of the wheel with constant fillet radius of 15 mm. As compared to regular wheels, the wheels with compound surface feature have advantages in saving space and cost.

### Table 1. Influence of wheel surface on draw-spinning coefficient.

| Wheel surface dimension | Draw-spinning coefficient $m$ | 0.67 | 0.68 | 0.69 | 0.70 |
|-------------------------|-------------------------------|------|------|------|------|
| 10-15 mm                | /                             | Slight wrinkle | Sound | Sound |
| 10-25 mm                | Slight wrinkle                | Sound | Sound | Sound |
| 10-35 mm                | Sound                         | Sound | Sound | Sound |
| 10 mm (Normal)          | Wrinkle                       | Wrinkle | Sound | Sound |
| 12.5 mm (Normal)        | Wrinkle                       | Sound | Sound | Sound |
| 15 mm (Normal)          | Slight wrinkle                | Sound | Sound | Sound |

### 3.2. Influence of process parameters on flow-spinning

In this study, a multi-pass strategy will be adopted to investigate the maximum thinning ratio in flow-spinning process. A tube with inner diameter of 56 mm and length of 80 mm which was made of DP600 with sheet thickness of 2.0 mm was utilized in the tests. The spindle speed and feed ratio were set as 108 r/min and 0.3 mm/r. In different passes, the gap between mandrel and wheel $\delta$ is set as 0.2 mm. The measured length of component after each pass in flow-spinning is shown in figure 6. In 10\textsuperscript{th} and 11\textsuperscript{th} passes, the measured component length are 213.12 mm and 211.92 mm, respectively. If the component length increases less than 1 % as compared to the one obtained in former pass, the test will not continue. Figure 7 shows the original tube and the formed one after 11 passes. The surface quality
is good, and no defects such as fracture and wrinkle occur. In addition, the measured average wall thickness is 0.719 mm and the corresponding thinning ratio is 64.05 %. This means in flow-spinning the maximum thinning ratio for DP600 with thickness of 2.0 mm is 64.05 %.

Moreover, the influence of feed ratio \( f \) on forming quality is also studied. In single-pass flow-spinning process, feed ratio \( f \) is set as 0.3, 0.5, 0.7 and 0.9 mm/r. Other process parameters are same with the previous tests. Figure 8 shows the formed tubes at different feed ratios. In all the cases, the components can be formed without any defects of fracture and wrinkle. However, the surface quality becomes worse with an increase of feed ratio.

The measurements of wall thickness deviation which is the difference between maximum and minimum wall thickness at different feed ratios are listed in table 2. The wall thickness deviation of original tube ranges from 0.041 mm to 0.046 mm. With the increasing of feed ratio \( f \), the wall thickness deviation first decreases and then increases. The minimum wall thickness deviation is found at the feed ratio of 0.7 mm/r.

The measurements of ovality which is the difference between maximum and minimum outside diameter of cross-section for formed components at different feed ratio are shown in table 3. It can be found that the ovality of original tube is about 0.59 to 0.62 mm. This results from curling and welding processes. Flow-spinning process is able to significantly improve the measured ovality since the ovality of formed component ranges from 0.10 to 0.24 mm. Also, the ovality of formed component first decreases and then increases with the increasing of feed ratio \( f \).

![Figure 6. Measured length of the component formed in different passes.](image)

![Figure 7. Original tube and formed component.](image)

![Figure 8. Original tube and formed tubes at different feed ratios.](image)

| Feed ratio (mm/r) | 0.3 | 0.5 | 0.7 | 0.9 |
|-------------------|-----|-----|-----|-----|
| Wall thickness deviation of original tube (mm) | 0.046 | 0.042 | 0.044 | 0.041 |
| Wall thickness deviation of formed component (mm) | 0.066 | 0.056 | 0.038 | 0.05 |
Table 3. Measurements of ovality for formed components at different feed ratio.

| Feed ratio (mm/r) | 0.3  | 0.5  | 0.7  | 0.9  |
|------------------|------|------|------|------|
| Ovality of original tube (mm) | 0.61 | 0.62 | 0.59 | 0.64 |
| Ovality of formed component (mm) | 0.17 | 0.16 | 0.12 | 0.24 |

4. Conclusion

In this paper, the spinnability of high strength steel DP600 in draw-spinning and flow-spinning was investigated in detail. Additionally, the influence of key process parameters on these two spinning modes was also comprehensively studied. The main results of this study are summarized as follows:

1. In draw-spinning process, a limit value of feed ratio which is beneficial to form DP600 is found. Fracture defects may be observed when a wheel with too small fillet radius is used, but a wheel with relatively large fillet radius will result in high manufacturing cost. A wheel with large compound profile face as well as the one with large fillet radius are able to improve the formability of DP600 in draw-spinning.

2. In flow-spinning, the maximum thinning ratio of DP600 with a thickness of 2.0 mm is 64.05%. Feed ratios ranging from 0.3 mm/r, 0.5 mm/r, 0.7 mm/r to 0.9 mm/r are all able to successfully form the desired component, however it indicates that higher feed ratio tends to result in surface indentation. Both of wall thickness deviation and ellipticity of formed component will decrease first and then increase with the increasing of feed ratio.

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