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Coating thickness variation during multistep drawing processes

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Although quite a substantial amount of work on the numerical analysis of sheet metal forming processes has been done by many researchers in the past decade, much of the effort was devoted to the homogeneous material [1]. The solution of inhomogeneous materials problem has been obtained only recently by Wang and Ruan who studied bimetal sheet drawing process by finite element method [2], and Takuda *et al*. predicted the forming limit of Fe/Al laminated composite sheets in deep drawing [3], but they did not consider the interface intensity. As to the drawing of coatings, practical study has not paid sufficient attentions to them [4].

We electrodeposited nickel coating of thickness 3–10 μm on the substrate of low carbon steel sheet, then the coated sheet was handled by special thermal treatment. It was found the coated sheet has high interface intensity, excellent toughness and strength after treatment, and it can be used to form the shells of good quality and high energy-storing battery.

In order to produce a useful sheet metal part, the initially simple geometry of sheet metals has to be transformed into a more complicated geometry without material failure or deterioration in material properties. For sheet metals subjected to the same forming forces, the modes of deformation may differ appreciably due to the differences in the material characteristics and the material-process interactions. Successful forming depends on several factors, thus the knowledge of the deformation mechanics and the mutual interactions between the process parameters are of paramount importance in controlling the metal flow and in providing a better design criterion.

While the electroplated nickel coating was used as the shell material of good quality battery, the coating/substrate composite must be deeply drawn six times separately and sequentially. By numerical simulation of the deep drawing processes, we try to find the coating performance in order to effectively control the processes and design the fabricating parameters. In the paper, we used dynamic explicit formulation DYNA 3D to simulate the processes in the first procedure and the last one, the kinematical work hardening was adopted for the materials of the substrate and coating. Penalty function method was used to treat the contact algorithm, and friction is based on a Coulomb formulation [5].

In the deep drawing processes, the coating/substrate composite may delaminate or crack in the interface. The combination of coating with substrate was considered as a contact in the simulation, defined as "tied with failure contact," that is, before it arrives deterioration, contact surface or node ties with the target, and after arrived deterioration, the contact surface or node separates from the target and may slide each other.

A nickel coating of thickness 3 μm was used in the simulation. The coating and substrate mechanical parameters were obtained by an improved (Jeol)JSM-5600LV SEM. The mechanical parameters of the coating and substrate were as shown in Table I.

The dimensions of the die and punch were supplied by a battery shell factory, and the parameters of the first and sixth working procedures were determined as Table II. In the sixth procedure, the blank was a cylindrical cup formed in the fifth procedure, its inner radius Φ15.4 mm, outer radius Φ15.8 mm, and height 42.5 mm; and the cylindrical cup had a bottom fillet, radius 2 mm. In the first procedure, a blank-holder force of 1800 N was used, and the frictional coefficients were: 0.2 between the punch and sheet, 0.15 between the blank holder and sheet, 0.15 between the die and sheet. In the sixth procedure, the friction coefficients in all contact surfaces were assumed to be 0.15.

The punch, die and the black holder were considered as rigid body in the FE model because their deformation is very small compared to the coated sheet. Belytschko-Wong-Chiang shell element of four nodes was used to divide the model into 12 460 elements in the first procedure, and 15 936 elements in the sixth procedure. The time increment is determined as 0.2×10^{-5} ms. It took in the first procedure 26 h 15 min, in the sixth procedure 25 h 25 min of CPU time for the computation in PIV computer.

Figs 1–2 revealed the thickness variation of the cylindrical cup during the first drawing process. The sheet in the flange would tend to thick, the maximum thickness of the substrate could arrive at 0.28 mm, and the

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TABLE I Mechanical parameters of the substrate and the coating

	Young's modulus (GPa)	Yield strength (MPa)	Hardening modulus (MPa)	Poisson's ratio	Interfacial bonding strength (MPa)	Material density (g/mm^3)
Low carbon steel substrate	200	300	950	0.25	145	0.78×10^{-2}
Nickel coating	254	241	0	0.31		0.78×10^{-2}

TABLE II The procedure parameters in simulation

Procedures	Diameter of punch	Punch fillet radius	Diameter of die hole	Die fillet radius	Blank diameter	Punch stroke	Substrate thickness	Coating thickness
First	Φ31 mm	5 mm	Φ32 mm	5 mm	Φ55 mm	20 mm	0.25 mm	3 μm
Sixth	Φ13.2 mm	2 mm	Φ14.2 mm	5 mm		46.5 mm	0.2 mm	3 μm

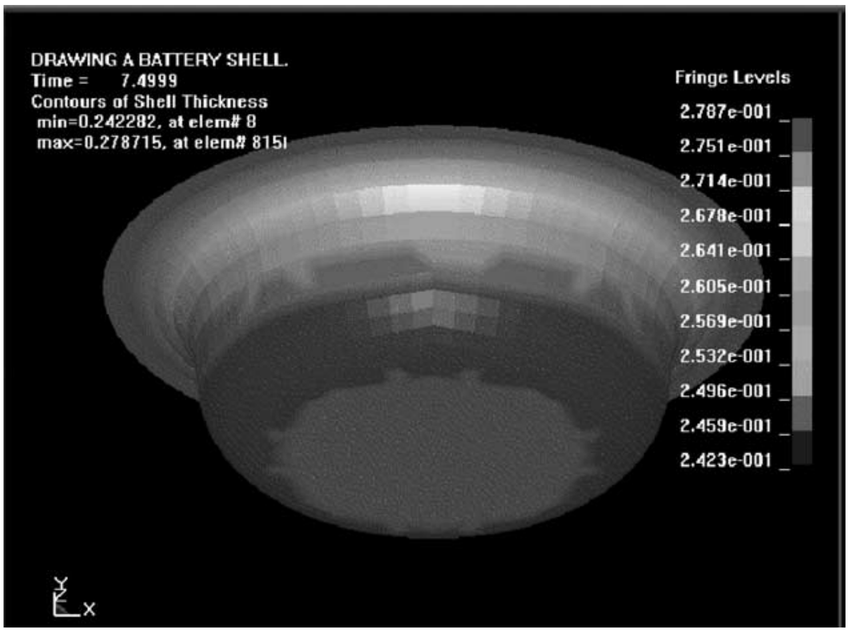

Figure 1 Thickness contours of substrate in first procedure.

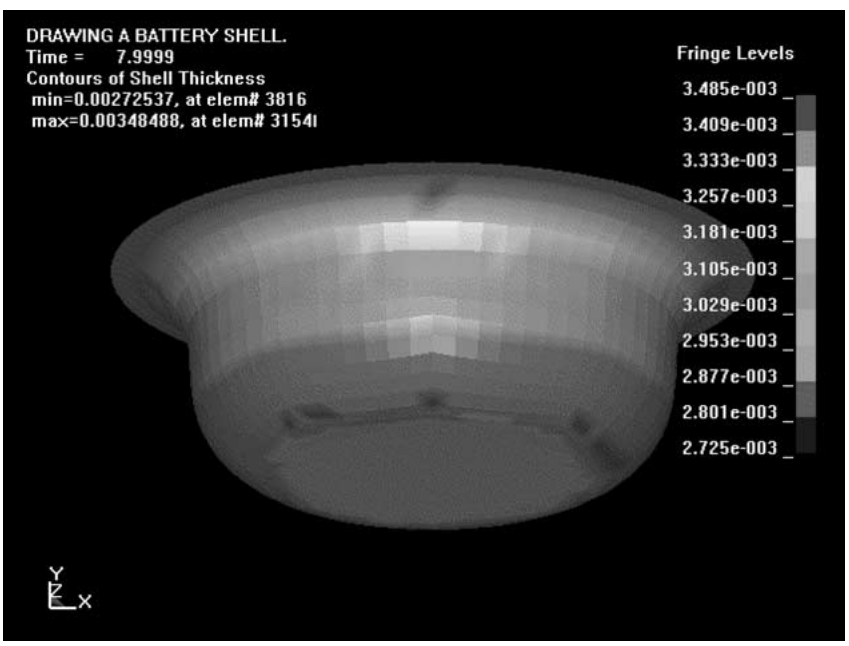

Figure 2 Thickness contours of nickel coating in first procedure.

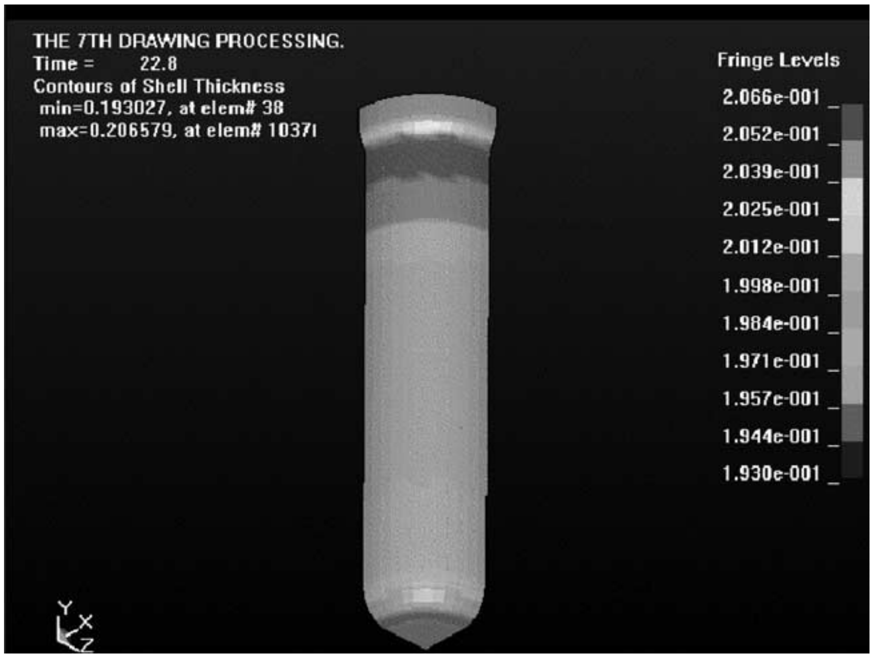

Figure 3 Thickness contours of substrate in sixth procedure.

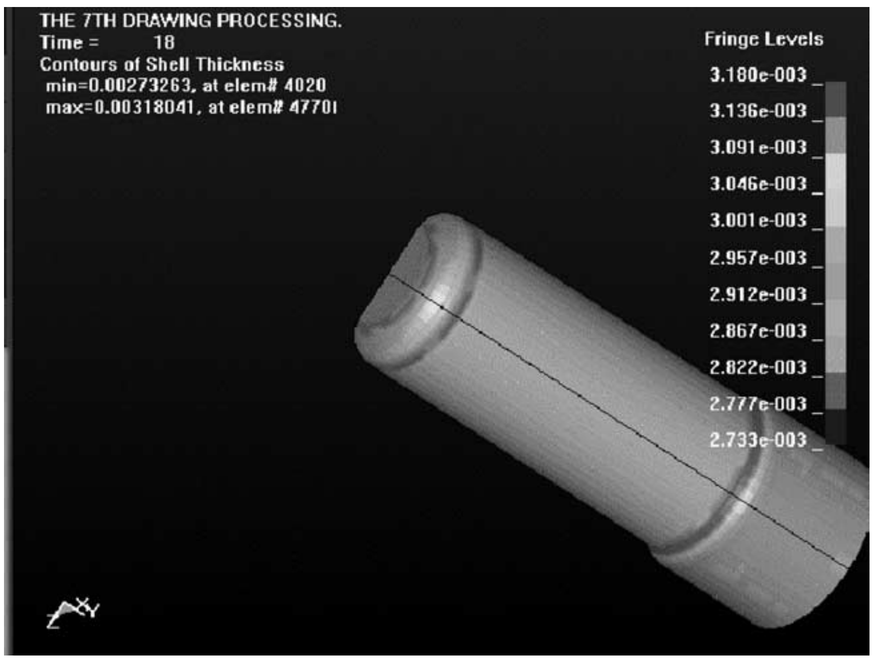

Figure 4 Thickness contours of Ni-coating in sixth procedure.

nickel coating could arrive at 3.3 μm. But the sheet would be drawn and thinned as it passed through the die fillet profile. After formed, the thinnest wall was at the fillet of lower part of the shell, because the thickness of this region was drawn further thinner as the punch advanced forward. The substrate thickness of this region was about 0.24 mm, and the nickel coating thickness of this region was about 2.8 μm. The upper part of the shell would be thicker than the lower part, and at this region the thickness of the substrate was about 0.26–0.27 mm, the thickness of the nickel coating was about 3.1–3.2 μm. In the entire deformation process, the thickness of the substrate and the coating varied consistent, and the limit thinning ratio was 4% for the substrate, 7% for the nickel coating.

Figs 3–4 demonstrate the wall thickness distribution after being formed in the sixth procedure. The blank for this procedure was cylindrical cup, when it passed through the concave die fillet, it was interesting that the wall of the cylindrical cup would tend to thicken, for the substrate to 0.204–0.206 mm, for the coating to 3.15 μm. That may be the case like forming under the flange as the first procedure. But with the punch advanced forward, the cylindrical wall would be thinned, the middle area in the part was 0.195 mm for the substrate. Similarly, the coating thickness would be thinned with the punch advanced forward, the middle area in the part was 2.95 μm. The thinnest wall was near the cup bottom at the area contacted with the punch head fillet, for both nickel coating and substrate,

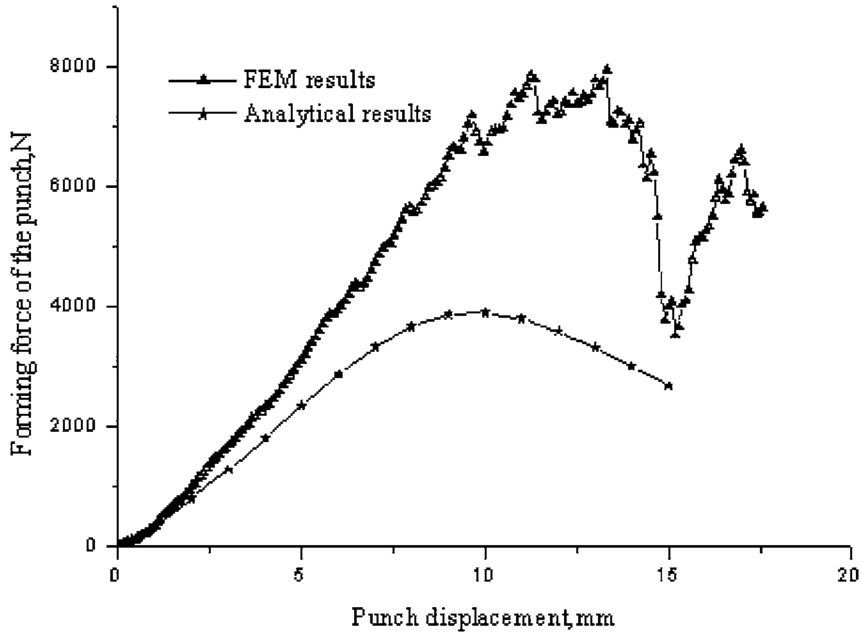

Figure 5 Forming force of the punch.

at this place, coating thickness was 2.75 μm, substrate was 0.195 mm, and limit thinning ratio was 8.3% for the coating, 2.5% for the substrate. It must be noted that near the cup bottom in the wall there was a ring with a thickness of about 3.1 μm even after formed, this was affected by the fillets in the punch head and die entrance, and further more the fillet radius in the die bigger than that in the punch head.

The results of simulation showed that in the drawing processes of the first and sixth procedures, the delamination between the substrate and coating did not occur.

The simulated punch load was compared with the analytical result as shown in Fig. 5. We could see the tendency of the two curves varied similarly before the punch stroke arrived at 15 mm, which the factory test for the value was 16.5–16.8 mm from the formed shell height including earing [6]. The simulated punch load was greater than that of analytical result was because the steel substrate and the nickel coating were considered hardening but analytical method not considered, and the frictional coefficients in the simulation were bigger than in analytical method.

Low carbon steel sheet with electrodeposited nickel coating is a new material for manufacturing good quality battery shell. This investigation showed that the nickel coated sheet can be used in deep drawing process, the thinning of the nickel coating's thickness during the drawing process may be acceptable.

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