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Technical Paper

Development and applications of forming-condition-based formability diagram for split concerns in stamping

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ABSTRACT

This paper introduces an advanced, forming-condition-based formability diagram for accurately assessing the formability of complex stampings. The forming-condition-based formability diagram consists of a formability index that rationally define two curves (marginal line and safe line) and two zones (marginal zone and safe zone). The formability index measures deformation severity, tracks deformation history and predicts deformation trend. The safety factor, defined as the width of the marginal zone by means of the formability index, takes into account the forming conditions including deformation zone size, forming mode, bending process model, deformation history, metal flow pattern and post-necking deformation capacity of sheet metal. It is demonstrated that, rather than the traditional formability limit diagram, this formability diagram can more accurately quantify the formability status and can be used to determine the metal flow adjustment ranges for solving split problems. Its application to an automotive body side outer panel shows that it is a robust tool for formability engineering and troubleshooting through using numerical simulations and/or circle grid analysis.

1. Introduction

When sheet metal is stretched into a certain plastic strain magnitude, its deformation becomes localized until the ductile rupture occurs. The maximum deformation limit at onset of local necking is defined as failure criterion of split, commonly referred to as forming limit curve (FLC) developed by Keeler [1,2] and Goodwin [3]. After several refinements [4–6], FLC was conservatively constructed into a standard FLC for low carbon steel sheets. Furthermore, Keeler and Brazier [7] established an empirical relation between the position of the standard FLC along the major strain axis, *i.e.*, FLD_0, as the function of average strain-hardening exponent $\bar{n}$ and the thickness of sheet metal for the low carbon steel sheets.

In order to avoid sporadic breakage due to strain measurement errors and day-to-day variation in forming conditions, Keeler and Brazier [6,8] suggested a marginal zone under FLC. The marginal zone has the same width in the major strain direction and is quantified as 10% for steels (8% for aluminium) as a safety factor to establish formability limit diagram (FLD). The safety factor does not include effects of strain paths and forming conditions with different rupturing mechanisms. When using FLD, major and minor strains are directly plotted onto FLD as raw data, and forming severity is evaluated with the relative position between the major strain and FLC.

Because of the extensive applications of FLC in stamping industry, tremendous theoretical and experimental studies have been conducted to provide fundamental understanding in mechanical principles and engineering applications. Hill [9] proposed the first theoretical model in which there exists a zero-extension direction during the localized necking and a relationship between the normal anisotropy coefficient $\bar{R}$ and the angle between the through-thickness neck direction and the simple tension axis. Hill's model corresponds to the left-hand side of the FLC. Swift [10], in contrast, developed the diffuse instability model that qualitatively defines the characteristic shape of the right-hand side of the FLC. Both Hill's and Swift's work are based on plane-stress state during proportional loading which is commonly equivalent to proportional straining where the ratio between the principal plastic strains is constant. The latest FLC modeling studies involved more mechanical phenomena including a theoretical FLC for Von Mises material under different orientations of the major strain axis [11], integration of strain- and stress-based FLCs under non-proportional loading [12,13], and a FLC under stretch-bending condition with different relative radii [14]. The recent experimental studies of

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sheet metal forming limits, on the other hand, focused on presentations of real forming conditions regarding both deformation histories [15,16] and strain localizations [17,18].

More robust formability analysis and troubleshooting need more accurate formability diagrams. As reviewed above, theoretical formability studies explore the insights of sheet metal plasticity *versus* material properties; experimental formability studies try to establish FLCs with good engineering approximation to accurately assess the formability through both stamping CAE and circle grid analysis (CGA). Tremendous formability research results are available, but most of them concentrate the FLCs only. In engineering applications, a formability diagram needs to accurately predict and thoroughly evaluate three types of splits in forming processes [19], namely, tension split, bending split, and tension-bending split. The formability diagram, therefore, must have the following sophisticated functions:

(1) Formability zones – the formability diagram includes the failure zone, marginal zone and safe zone that are bordered by the FLC, marginal line and safe line.
(2) Deformation history – a formability scale parameter that incorporates the deformation history is consistently used to quantify the deformation magnitudes and the three formability zones.
(3) Robust assessment – a safety factor presents the deformation history and takes into account different forming conditions.
(4) Assist material selection – the formability diagram can be used to assist selection of an appropriate sheet metal when designing the part.
(5) Troubleshooting capability – when a split occurs in engineering or production, the formability diagram can be used to determine an appropriate range of metal flow adjustment to effectively solve the problem.

In this study, the technique and procedure to develop an advanced formability diagram including the above-mentioned functions are proposed. A formability index that traces the deformation history is established to measure the formability severity. A safety factor that uses the formability index and takes into account the effects of forming conditions is derived. The minimum deformation requirement to ensure good quality is also determined by the formability diagram. As a result, the advanced formability diagram that includes three zones, three lines, one formability scale parameter and one safety factor is established. Taking an automotive body side outer panel as an example, the applications of the forming-condition-based formability diagram are illustrated through using numerical simulation (*a.k.a.* Stamping CAE) and circle grid analysis (CGA). The example shows the capabilities of this new formability diagram is accurate for not only formability assessments but also metal flow adjustments during split problem-solving.

2. Development of the forming-condition-based formability diagram

2.1. Formability index

The deformation at any location in a stamping part needs to be described by combination of the major, minor and thickness strains. In order to measure the deformation severity and compare it with the materials deformation capacity, and to make metal flow adjustments for problem-solving when needed, an engineered formability index is required to quantify the three principal strains for different deformation status. Since the traditional FLC of a sheet metal is established through linear-strain-path doming tests and most deformation histories in stamping are close to linear strain paths [20], a formability index – Remaining Capacity of Material Deformation (denoted as *RCMD*) – is introduced as the deference between the deformation occurred and the corresponding deformation on the FLC. Mechanically, the formability index is the residual formability of sheet metal along the linear strain path determined by the ratio of the minor strain to the major strain at the deformation position, *i.e.*, $\lambda = \varepsilon_2/\varepsilon_1$. The deformation on the FLC along the same linear strain path is the Deformation Capacity (*DC*) of sheet metal, defined as:

$$DC = \frac{\sqrt{1+\bar{R}}}{1+2\bar{R}} \sqrt{\bar{R}(\varepsilon_1^{DC} - \varepsilon_2^{DC})^2 + (\varepsilon_2^{DC} - \bar{R}\varepsilon_3^{DC})^2 + (\bar{R}\varepsilon_3^{DC} - \varepsilon_1^{DC})^2} \quad (1)$$

where the superscript "*DC*" denotes the principal strains on FLC, and $\bar{R}$ is the normal anisotropy coefficient. The formability index *RCMD* is then calculated by using the formulae.

$$RCMD = DC - \varepsilon_e \quad (2)$$

where ε_e is the equivalent strain at the deformation position:

$$\varepsilon_e = \frac{\sqrt{1+\bar{R}}}{1+2\bar{R}} \sqrt{\bar{R}(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \bar{R}\varepsilon_3)^2 + (\bar{R}\varepsilon_3 - \varepsilon_1)^2} \quad (3)$$

2.2. Safety factor

2.2.1. Definition of the safety factor

There are four groups of formability variations in stamping: FLC variations, strain calculation/measurement errors, production environment variations and variations of deformation characteristics. From the robust engineering point of view, a marginal zone is placed between the failure zone and the safe zone to separate the failure status from the safe status. Using the formability index, the marginal zone in linear strain paths is defined as a safety factor that includes a standard safety factor and a fine adjustment factor:

$$\Delta RCMD = \Delta RCMD_o + \delta RCMD \quad (4)$$

where $\Delta RCMD_o$ is the standard safety factor and $\delta RCMD$ is the fine adjustment factor. The standard safety factor $\Delta RCMD_o$ covers the FLC variations, strain calculation/measurement errors and stamping production variations. It is derived through transferring the safety factor ΔFLD_o of the traditional FLD in case the minor strain is zero ($\Delta\varepsilon_1 = \Delta FLD_o$, $\Delta\varepsilon_2 = 0$, $\Delta\varepsilon_3 = \Delta\varepsilon_t = -\Delta FLD_o$). The fine adjustment factor $\delta RCMD$ includes the variations of deformation characteristics. It is determined through the procedure outlined in the next sub-section. Once the safety factor *RCMD* is determined, the marginal line along linear strain paths can be generated and the marginal zone is consequently established.

2.2.2. Determination of the fine adjustment factor

The fine adjustment factor $\delta RCMD$ is determined based upon deformation characteristics. Deformation characteristics [21] include (1) size of deformation zone, (2) forming mode, (3) bending process model, (4) deformation history, (5) metal flow pattern, and (6) post-necking deformation capacity of sheet metal. Being similar to the procedure for other safety factors in stamping, the fine adjustment factor $\delta RCMD$ comes from stamping engineering and production. After multiple iterations of deformation analyses, each component $\delta RCMD_i$ of the fine adjustment factor approaches a reasonable value. The fine adjustment factor $\delta RCMD$ is the sum of the components $\delta RCMD_i$. The specific values presented in Table 1 are obtained through CGA in automotive stamping engineering and production. Following the procedures highlighted below, stamping professionals can use this table as a start point to establish their own component $\delta RCMD_i$ of the fine adjustment factor.

(*1*) *Size of the deformation zone*. Formability analysis is essentially a zone-based formability investigation. The formability index represents the formability severity in an area within small strain variation. This area is defined as the deformation zone. When