Evaluation of fatigue life degradation due to the metal forming processes

J. A. J. El-Sayed
Department of Mechanical Engineering, Kettering University, USA

Abstract

During metal forming processes, localized metal thickness changes occur. These variations in metal thickness due to formation are usually ignored during the design phase. These metal thickness variations can drastically alter the fatigue life of the produced part due to the high nonlinear nature of fatigue life dependence on the applied stress. This paper presents an analytical approach to account for the fatigue life degradation due to formability localized thickness changes. The application and efficiency of the developed approach is studied using a metal forming case study of an automotive rocker section.

1 Introduction

Sheet metal forming is the most common manufacturing process of automotive inner and outer panels. This process is suitable for mass production of sheet metal parts that have complicated geometry. A sheet metal forming process usually has several input variables. These variables relate the sheet blank (geometry and material), the tools (geometry and material), the conditions at the tool-material interface, the mechanics of plastic deformation, the equipment used, the characteristics of the final product, and finally the plant environment in which the process is being conducted [1-3].

During sheet metal forming processes due to stretching of the metal some localized metal thickness changes occur. These changes in metal thickness due are usually ignored during the design phase. One of the major performance criteria impact by these metal thickness changes is structural durability. Reduction in metal thickness can drastically alter the crack initiation and propagation fatigue life of the produced part due to the high nonlinear nature of fatigue life dependence on the localized stress.

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The objective of this study is to investigate the effect of formability on the crack initiation fatigue life of sheet metal components. Some predicted fatigue life reductions of sheet metal forming test cases are discussed.

2 Sheet metal forming process and simulation

In a forming process, binder force is applied to hold the sheet and restrain it from free flow. As a result of the restraining force, the final sheet can have desirable strain to maintain the final shape and have enough stiffness. However, to control the metal flow by only the binder force is not effective due to the limitation on the binder force capacity. In order to add more restraining force, draw bead can be used to control the metal flow [4]. The added metal flow control is achieved from the restraining force induced by the consecutive bending and unbending process along the draw bead geometry. This draw bead effect can be defined by adding draw bead geometry in the right position on the binder, or by applying a force on the draw bead line with a specific draw bead force factor.

The main purpose to use draw beads in the sheet metal forming is to control the metal flow from the binders into the die cavity. It is not so efficient to control the metal flow with only binder forces. Draw beads can be used with the binder force by adding restraining force induced from the bending and unbending process. Also, geometric modeling of draw beads can improve the accuracy of the result by including the effect of variable cross-section beads, end effects, and the work hardening effects within the material. However, geometric draw bead modeling will increase the pre-processing time and computational cost for the solution. An alternative way to simulate the draw bead is to apply restraining forces along the centerlines of the draw beads geometry. This simplified method can reduce computer resources and modeling efforts and became preferred method to simulate complex geometry. In a stamping analysis, the tools such as die, punch, and binder are considered as rigid bodies, so that only the sheet blank has to deform to a final shape throughout the stamping process.

In order to simulate the drawing process using plane strain assumption along the section, only a narrow strip need to be modeled for the finite element simulation. The symmetry condition can be used on both sides to maintain the minor strain equal or nearly equal to zero [5,6]. The restraining forces can be applied to both cross-sectional directions, in opposite direction to the metal flow, to simulate the restraining forces due to the draw bead and the friction effects. Ideally the same boundary condition should be applied to the analysis code so that one can compare the analytical results with the measured results from the actual drawn panel.

In this study, draw-in amount was used as a criterion to obtain the results of the analytical model, because the amount of draw-in is controlled by the amount of restraining forces applied to the model.

The finite element analysis code DYNA2D was used. This code is suitable for deep and stretch forming operations. DYNA2D program is a specially customized program for the sectional plane strain analysis [7,8]. It has to be run with Plane Strain Setup program, which is a user customized sub-program in

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Uni-graphics software, to define the tool and blank geometry, bead location, punch travel, and die information. DYNA2D has a function to directly define the draw-in amount, however the result is more accurate and reliable with the draw bead force. DYNA2D applies restraining force on draw bead location and fixes both sides. Since DYNA2D has no function to separate the closing and drawing processes, whole process is considered as one drawing process.

3 Fatigue life calculations

Detailed discussions for the fatigue life calculation are given in [9,10]. Here, we summarize the basic requirements for a fatigue life calculation routine.

3.1 Cyclic stress-strain relationship

Just as the monotonic stress-strain curve relates static applied stress and the resultant static strain, the cyclic stress-strain curve relates cyclic stress and strain. Of particular importance is the amount of cyclic plastic strain, since this quantity is intimately related to fatigue damage. An equation of the following form is generally used to express the cyclic stress-strain relationship

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2K'}\right)^{1/n'} \tag{1}$$

The Δ, in the above equation, indicates completely reversed ranges of stresses and strains and subscripts e and p stand for elastic and plastic strain. The two material properties, n' and K', are the cyclic strain hardening exponent and cyclic strength coefficient, respectively.

3.2 The strain-life relationship

The cyclic plastic strain and fatigue life were shown by Coffin-Manson to be related by a simple power function, over the entire life range from only a half cycle to millions of cycles. The form of the Coffin-Manson relation is as follows

$$\frac{\Delta\varepsilon_p}{2} = \varepsilon_f' (2N_f)^c \tag{2}$$

Where $2N_f$, indicate reversals or half cycles, while N_f means number of cycles to failure. Similarly, the stress-life relation can be represented as a power function of stress in a form similar to Equation (2), in the form:

$$\frac{\Delta\sigma}{2} = \sigma_f' (2N_f)^b \tag{3}$$

For the calculation of fatigue life, it is convenient to incorporate mean stress effects as an equivalent change in static strength. Equation (3) may then be modified as follows

$$\frac{\Delta\sigma}{2} = (\sigma'f - \sigma_o)((2N_f)^b \tag{4}$$

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To obtain an expression relating total strain, mean stress and life, Equation (4) is divided by Young's modulus, E, to obtain the elastic strain and added to Equation (2) to yield

$$\frac{\Delta\varepsilon}{2} = \frac{\Delta\varepsilon_e}{2} + \frac{\Delta\varepsilon_p}{2} = \left(\frac{\sigma'_f - \sigma_o}{E}\right)(2N_f)^b + \varepsilon_f (2N_f)^c \tag{5}$$

The two exponents and the coefficients are regarded as fatigue properties of the metal, and they are designated as follows

b = Fatigue strength exponent
c = Fatigue ductility exponent
ε_f = Fatigue ductility coefficient
σ'_f = Fatigue strength coefficient

By manipulating Equations (2), (3) and carrying the result to the form of Equation (1), the cyclic strain hardening exponent, n′, is determined by the fatigue strength and ductility exponents as follows:

$$n' = \frac{b}{c} \tag{6}$$

Similarly, it can also be shown that the cyclic strength coefficient can be determined from the fatigue properties as follows

$$K' = \frac{\sigma'_f}{(\varepsilon'_f)^{n'}} \tag{7}$$

3.3 Cycle counting

Some of the counting methods for fatigue analysis are peak, level crossing, range, range-mean, range-pair, and rainflow. Of these various methods, rainflow or its equivalent range-pair has been shown to yield superior fatigue life estimates [11]. The basic idea behind rainflow counting is to treat small events in the load history as interruptions over larger overall events and, in the simplest terms, to match the highest peak and deepest valley, then the next largest and smallest together, etc., until the peaks and valleys of the load history have been paired.

3.4 Simulation of the stress-strain response:

The purpose of simulating the stress-strain response is to determine the parameters necessary for cumulative damage fatigue analysis. Information such as stress amplitude, mean stress, elastic and plastic strain can be determined for each reversal in the load history. The most important feature of any simulation model is its ability to correctly describe the history dependence on cyclic deformation.

Wetzel [12], developed a model, based on an "availability concept," in which the cyclic stress-strain curve is approximated by a series of line segments or elements. The number and size of the elements is arbitrary, depending on the manner in which elements are used. A large number of elements (50-100) can be used where each element is used to its fullest extent. When a smaller number of elements is used, they are usually interpolated to obtain midrange values. The following rules govern these elements use:

(1) Start with the first elements
(2) Use them in order
(3) Skip those elements unavailable for deformation
(4) Continue until the control condition is reached.

Once the cycles have been defined and the stress-strain response determined, the appropriate fatigue parameters can be determined, so that a damage analysis can be performed.

3.5 Notch analysis

In dealing with real components, it is often necessary to relate the nominal loads or strains to the maximum stresses and strains at the critical location. Neuber derived a rule when the material at the notch root deforms nonlinearly. The theoretical stress concentration, K_τ, is equal to the geometric mean of the actual stress and strain concentration factors, K_σ and K_ε

$$K_\tau = (K_\sigma K_\varepsilon)^{\frac{1}{2}} \tag{8}$$

Topper et al. [13] modified Neuber's rule for use in cyclic loading applications by substituting the fatigue notch factor, K_f, for the stress concentration factor and rewriting Equation (8) in the following form

$$K_\sigma = \frac{\Delta\sigma}{\Delta S}$$

$$K_\varepsilon = \frac{\Delta\varepsilon}{\Delta e} \tag{9}$$

$$K_f = \left(\frac{\Delta\sigma\,\Delta\varepsilon}{\Delta S\,\Delta e}\right)^{\frac{1}{2}}$$

$\Delta\sigma$ = Stress range at notch root
ΔS = Nominal stress range
$\Delta\varepsilon$ = Strain range at notch root
Δe = Nominal strain range

This relationship is conveniently used in the following form

$$K_f^2\ \Delta S\ \Delta = \Delta\sigma\ \Delta\varepsilon \tag{10}$$

All terms on the left side are determinable for each reversal from the load history and cyclic stress-strain response of the material, and those terms on the right side represent the local stress-strain behavior of the material at the notch root. The terms on the left side are a determinable constant for each reversal and the result is an equation of the form, xy = c, which is a rectangular hyperbola. When the nominal strains are elastic, Equation (10) is used in the following form

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$$\Delta\sigma\,\Delta\varepsilon = \frac{(K_f\,\Delta S)^2}{E} \qquad (11)$$

Combining this form with Equation (1), the notch stress equation is easily solved using the Newton-Raphson iteration technique.

3.6 Cumulative damage analysis

Cumulative damage fatigue analysis is usually based on the Palmgren-Miner linear damage rule. Fatigue damage is computed by linearly summing cycle ratios for the applied loading history, as indicated in the following equation

$$\text{Damage} = \sum \frac{n_i}{N_{fi}} \qquad (12)$$

n_i = Observed cycles at amplitude, i

N_{fi} = Fatigue life at constant amplitude, i

After the fatigue damage for a representative segment or block of load history has been determined, the fatigue life in blocks, is calculated by taking the reciprocal.

4 Case study

To study the effect of thinning on the crack initiation fatigue life an automotive section from the rocker area was considered. Figure 1, shows the finite element models used in DYNA2D plane strain simulation of the Rocker section. Table 1 contains the boundary condition used in the analytical models for the Rocker section used in the study.

Table 1: Boundary condition of DYNA2D models.

	Rocker section	
Draw bead Location	Top	Bottom
Bead Force (KN/mm)	0.24	0.19

Symmetry Condition: both sides
Friction Coefficient: 0.125 (default)
Sheet Thickness: 0.8 mm

Initial sheet thickness was measured at arbitrary locations on the sheet, and the readings were ranged from 0.78 to 0.80 mm. In the study, the average value was used to calculate the percent thinning, which was 0.79 mm.
The thickness and material information used in the analysis are:

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Thickness	0.8 mm
Yield Strength	174 MPa
Young's Modulus	206 GPa
Poisson's ratio	0.3
Yield Strain	6.153 E-03
n-value	0.221
R-value	1.92
K-value	536 Mpa

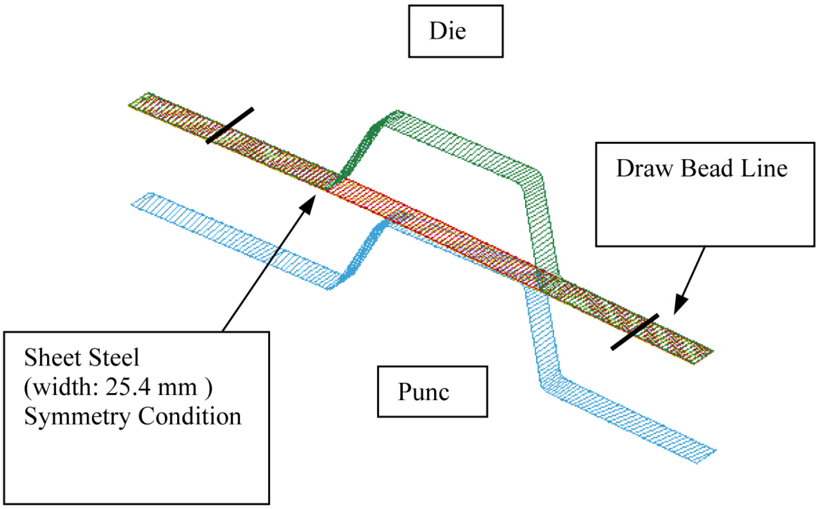

Figure 1: DYNA2D model for rocker section.

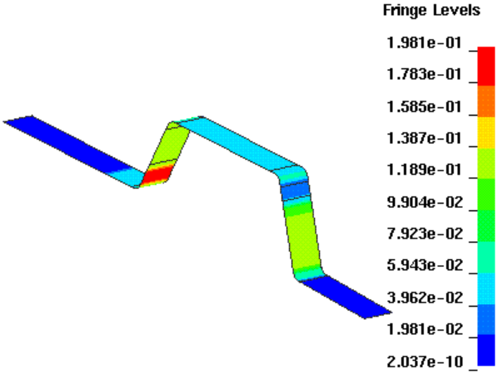

Figure 2: Results for rocker section: % thinning contour – DYNA2D.

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Table 2: Upper and lower bounds of % fatigue life reduction.

Location	A	B	C	D	E	F	G	H	I
% Thinning	11.3	11.5	3.6	4.7	4.1	4.5	11.6	11.0	17.7
Min. % Life Reduction	25.9	26.3	9.0	11.0	10.0	8.9	26.5	25.3	38.6
Max. % Life Reduction	59.0	60.0	24.0	30.0	27.0	29.0	60.3	58.0	76.8

After performing the formability analysis and determining the thinning at different location of the section, fatigue life calculations were performed using the new thickness. A block of a typical load history at the rocker section was used to obtain the stress history for the nominal thickness and the predicted reduced thickness at different locations of the rocker section. The % thinning contours of the section is shown in Figure 2. The % fatigue life reduction upper bounds based on bending mode and lower bounds based on membrane loading are presented with the %thinning for the different locations are presented in Table 2.

5 Conclusion

During design phases of most structures the nominal sheet metal thickness is used to simulate the structural performance. Little or no attention is given to the reduction in the metal thickness during the manufacturing stage.

This paper main objective is to study the effect thinning during metal forming on the structural performance. The crack initiation fatigue life of automotive sections by was the main focus of the study. From the results obtained for a n automotive rocker section under a block of fatigue load history it is clear that at some critical location under the bending mode the crack initiation fatigue life could be reduced by over 75% due to thinning. This explains the formation of unexpected structural cracks at different locations never predicted during the design phases.

Using DYNA2D finite element analysis code to predict the thinning, and a fatigue life code to predict the bounds of fatigue life reductions, demonstrated the ability of taking into account the structural durability performance degradation due to thinning. Having the ability to predict the thinning effect can help in provide design direction to improve structural performance.

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