PREDICTION OF DUCTILE FRACTURE IN FORWARD EXTRUSION WITH SPHERICAL DIES

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ABSTRACT

This paper describes a technique that can be used for the prevention of chevron cracks (or central burst defects) during the cold forward extrusion process with spherical dies. To characterize the behavior of the material and predict the formation of chevron cracks, it is necessary to determine the flow stress and critical damage value (CDV) of the billet material. The flow stress is obtained by homogeneous compression tests. Critical damage value (CDV) is determined from FEM simulations correlated with non-homogeneous compression tests and notched tensile tests. Two different materials are evaluated: SAE 1137 (hot rolled) and SAE 1524 (spheroidized).

The effect of several extrusion parameters (reduction in area, die radius, die land length, and exit radius) on the maximum damage value was examined through FEM simulations. Thus, it was possible to develop a method for prediction of ductile fracture.

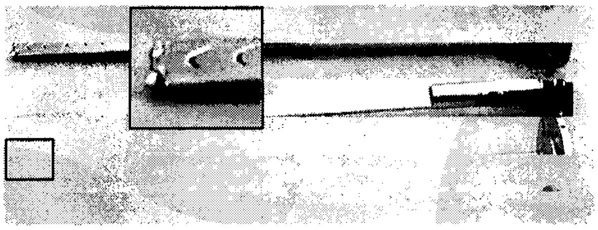
INTRODUCTION

Forward extrusion is a forming process where a round billet is pushed through a die with an exit diameter smaller than that of the billet. The work piece flows through the die in the same direction as the punch, and can either be contained (high reductions) or open (low reductions) prior to entering the deformation zone in the die.

In the automotive industry, many shaft and shaft-like components, including fasteners, are produced by forward extrusion. Some of these components are considered critical for the safe performance of the vehicle and must be free of defects. These defects could be visible external ones, such as laps or cracks, or non-visible internal defects, such as chevrons. See Figures 1 and 2 for examples of chevron defects.

To avoid the use of defective extrusions in automotive assembly, it may be necessary to 100% inspect the parts, either by the manufacturer or by the end user. This process is time consuming and costly. To avoid this expense, DaimlerChrysler developed, in the early 1970's, conservative guidelines to design a forward extrusion sequence using conical dies that would guarantee production of chevron-free components.

Spherical dies, sometimes called radial dies, have been used in the fastener industry for many years. Spherical die designs are sometimes used for safety parts because they provided a more uniform grain flow around corners and improved dimensional controls on net-shaped surfaces. Therefore, it is beneficial to investigate the occurrence of chevron cracks in spherical dies as was done with conical dies.



1. AUTOMOTIVE AXLE SHAFT WITH CHEVRONS.

2. ILLUSTRATION OF DIFFERENT CHEVRON CONFIGURATIONS

Thus, the objectives of the study described in this paper are:

1. Measure critical damage values for typical materials used in cold extrusion
2. Develop criteria or guidelines for designing spherical dies for chevron-free forward extrusions.

DUCTILE FRACTURE

Ductile fracture can be defined as a fracture that occurs after a component experiences a significant amount of plastic deformation [Hosford, 1983]. Fracture is influenced by numerous parameters including the deformation history of the workpiece material and the process conditions (i.e. rate of deformation, lubrication, and friction) [Cerretti, et al., 1996]. Other factors that influence fracture include chemical composition, microstructure, surface conditions, and homogeneity. Several ductile fracture criteria are useful for predicting surface or internal cracks. These can be generally represented by:

$$\int F(deformation)d\bar{\varepsilon} = C \qquad (1)$$

Equation 1 means that ductile fracture is a function of the plastic deformation history and properties of the material. These include the geometry, damage value, C, and strain of the workpiece (or effective strain), $\bar{\varepsilon}$. When the maximum damage value (MDV) of the material exceeds the critical damage value (CDV), crack formation is expected. Different ductile fracture criteria yield different damage values for a given process [Kim, et al., 1994].

Kim, et al., [1995] reviewed the literature and developed a methodology to predict ductile fracture by using FE simulations (see Figure 3). Seven different ductile fracture criteria were implemented in the FE code DEFORM™-2D. Five different processes were selected for the experimental investigation: a) compression test with grooved dies, b) notch tensile test, c) collar test, d) pierce upsetting and e) multi-pass forward extrusion. A review of the literature on ductile fracture in metalforming is given in references by [Kim, et al., 1994].

It was found that the modified Cockroft and Latham's criterion [Oh, et al., 1979] predicts, with good agreement, the location of the maximum damage value. Also predicted is that fracture occurs when the cumulative energy, C, due to the maximum tensile stresses, σ^*, exceeds a certain value (Equation 2):

$$\int^{\bar{\varepsilon}} \frac{\sigma^*}{\bar{\sigma}} d\bar{\varepsilon} = C_b \qquad (2)$$

Cerretti, et al. [1996] further developed the methodology to simulate the fracture of components subject to large amounts of deformation and simulated sucessfully the formation of chevron cracks for the extrusion experiments performed by Kim, et al., [1994].

METHODOLOGY TO PREDICT DUCTILE FRACTURE

Assuming the CDV is a material constant, several tests should be performed to obtain, for a given material, the flow stress and the critical damage value (CDV), as shown in Figure 3. Once the CDV for a specific material is obtained it is possible to predict through FEM simulations the formation of cracks in forming operations.

Two different materials were selected for this study: SAE 1524 (spheroidized), which is a high-manganese carbon steel and SAE 1137 (hot rolled), which is a resulfurized carbon steel. The SAE 1137 material was produced as a coarse grain product, making it more likely to crack. The actual chemical composition, in percent (%) of these steels are shown in Table 1:

SAE	C	Mn	P	S	Si	Cu	Sn	Ni	Mo	Cr	As	Cb	V	N	Al
1524	.22	1.35	.040	.050	.15	---	---	---	---	---	---	.02	---	---	.015
1137	.39	1.48	013	.10	.16	.17	.01	.06	.02	.08	.005	.001	.01	.004	.004

TABLE 1. CHEMICAL COMPOSITION (IN %) FOR SAE 1524 (SPHEROIDIZED) AND SAE 1137 (HOT ROLLED).

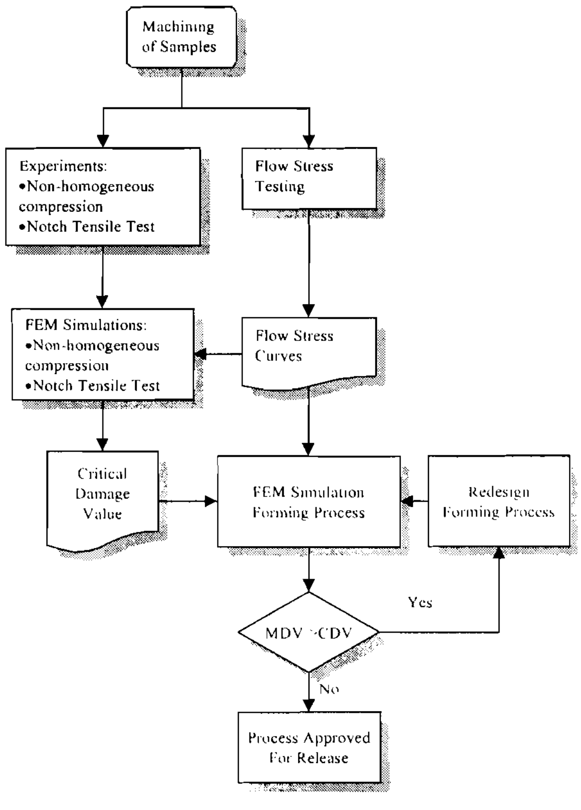
Measurement of Critical Damage Value (CDV)

The critical damage values were obtained by two tests; a non-uniform compression test with grooved dies and a tensile test with a notched specimen.

The non-uniform compression test with grooved dies consists of upsetting a cylinder until a crack is detected near the equatorial surface. The specimen height at which the crack occurs is known as the fracture height, H_f. Then FE simulations are conducted for the compression test up to the fracture height, H_f, to obtain the distribution of the damage value in the workpiece at the time of fracture. In this study, the damage value was obtained by using equation 2. The maximum damage value (MDV) is the critical damage value (CDV) of the material tested.

The non-homogeneous compression tests with grooved dies were conducted with cylindrical specimens to produce cracks on the free or bulged surface. In these tests, the 1.5 in (38.1 mm) high samples were upset in .040 in (1 mm) increments of deformation. At each deformation step the bulged surface of the specimen was inspected for cracks. The fracture height, H_f, was identified as the specimen height where a crack was first visible. The results from these tests are as follows (see Figure 4):

- Vertical cracks were seen in the equatorial surface of the specimens.
- Fractures were observed in SAE 1137 at a lower reduction in height than in SAE 1524.
- At the moment of crack formation, SAE 1524 showed a more sudden tensile failure than 1137.



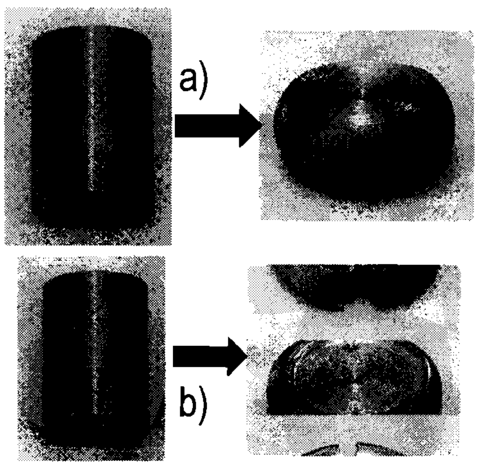
3. METHODOLOGY TO PREDICT & PREVENT THE FORMATION OF CRACKS IN METAL FORMING OPERATIONS

In the tensile test with a notched specimen, the neck diameter is measured continuously until the specimen fractures. Then simulations are conducted to calculate the damage distribution at the instant the neck diameter reaches the fracture diameter, d_f. The MDV determined just before fracture is the CDV.

Tensile tests were conducted to provide information on the average fracture strain at the neck cross section obtained from load vs. neck diameter curves. The tests were performed at the Mechanical Behavior Laboratories at the Ohio State University. An INSTRON Model 1322 servo hydraulic press, capable of pulling 55,000 pounds, was used. During the tests the following information was recorded:

- Neck diameter at fracture (with the help of a clip gage).
- Elongation of the specimen (with extensometer). The gage length of the specimen was 1 inch.
- Tensile force using a load cell

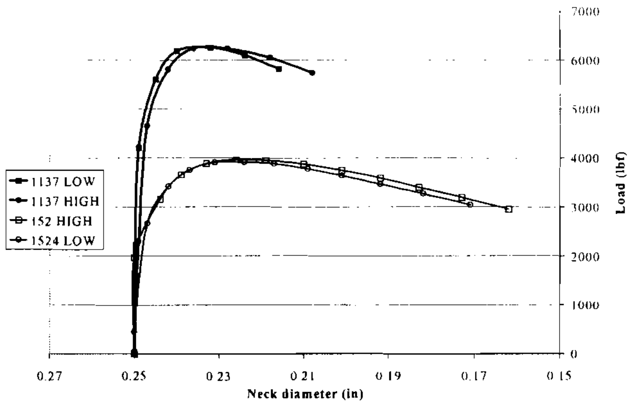
The fracture found in the tension specimens was a cup-and-cone type. This indicates that the fracture begins at the center of the notched specimen. Curves for the load vs. neck diameter for both materials are given in Figure 5. The elongation of the specimen and the reduction of the neck diameter are higher for SAE 1524, indicating higher ductility.



4. SPECIMENS FOR NON-UNIFORM COMPRESSION TEST, **A)** SAE 1137 HOT ROLLED, **B)** SAE 1524 SPHEROIDIZED ANNEALED

Calibration of the Critical Damage Value through Process Simulation

The calibration using FEM analysis was conducted up to the fracture height, H_f, for the compression tests with grooved dies; and up to the final neck diameter for the notched tensile test. The critical damage values obtained from the simulations for both non-homogeneous compression and notched tensile tests are given in Table 2. The critical damage values for the notched tensile tests are higher than the ones obtained from the compression tests with grooved dies. One logical explanation for the difference between compression and tension is the ability to detect the initiation of the crack. During the tensile test, the crack starts at the center and is not visible. This leads to a higher estimation of the CDV. For the compression test, the sensitivity of detecting the crack is in increments of .040 in. (1mm) of ram movement. Therefore, the determination of the CDV at a given reduction in height is within a certain margin of error, i.e. the height at which CDV is given may be up to 1mm smaller than the height where the crack actually occurred.



5. NECK DIAMETER-LOAD CURVE FOR TENSILE TESTS WITH NOTCHED SPECIMENS OF SAE 1137 HOT ROLLED AND SAE 1524 SPHEROIDIZED ANNEALED.

Another possible reason for the difference in the CDV's obtained in tensile and compression tests is that the state of stress is different for each case. In order to use a CDV in practical process evaluations, the average CDV value obtained from the compression and tensile tests was used.

The simulations coincide with the experiments with respect to the location of the CDV as shown in Figure 6. The location of the CDV during the compression with grooved dies is at the equatorial surface, while on the notch tensile test it is at the center of the notched specimen.

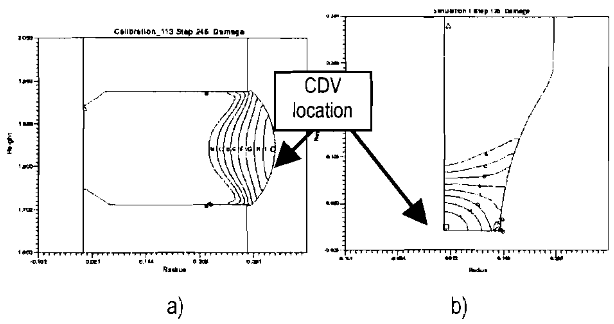
PARAMETRIC EVALUATION OF THE FORWARD EXTRUSION PROCESS WITH SPHERICAL DIES

The objectives of the parametric study were (See Figure 7) to determine:

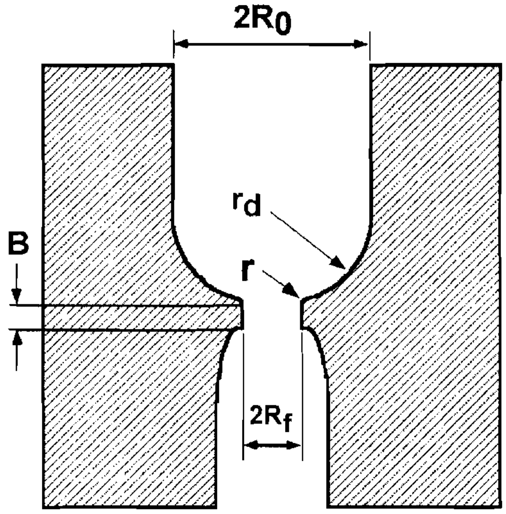
a. the effect of the die land length, B, on damage value
b. the likelihood of forming chevrons for a die radius, $\mathbf{R_0}$, at reductions in area between 30% to 75%
c. the effect of the transition radius, r, on damage value

Material	Method	CDV	Location
SAE 1137	compression with grooved dies	0.44	Equatorial surface
Hot rolled	notch tensile test	0.57	Center of specimen
SAE 1524	compression with grooved dies	0.56	Equatorial surface
Speroidized	notched tensile test	0.65	Center of specimen

TABLE 2. CRITICAL DAMAGE VALUES OBTAINED DURING THE FEM CALIBRATION.



6. DISTRIBUTION OF THE CRITICAL DAMAGE VALUE FOR MATERIAL SAE 1137 (HOT ROLLED) **A)** NON-HOMOGENEOUS COMPRESSION AND **B)** NOTCHED TENSILE TEST.



7. SCHEMATIC REPRESENTATION OF THE PARAMETERS TO BE INVESTIGATED DURING THE FORWARD EXTRUSION WITH SPHERICAL DIE.

Forward extrusion simulations were performed to determine the range of process parameters that assure chevron free forward extrusions. The FEM code DEFORM 2D was used for this purpose. The following are a set of initial values designated by DaimlerChrysler:

2R₀ = entrance (bore) diameter (1 in.)

RR = Reduction ratios: 30%, 45%, and 55%

2Rf = exit (die) diameter: according to reduction ratio

rd = die radius

B = die land length: low: 0.060", high: 0.150"

r = transition radius: 0.005 in., 0.200 in, 0.300 in.

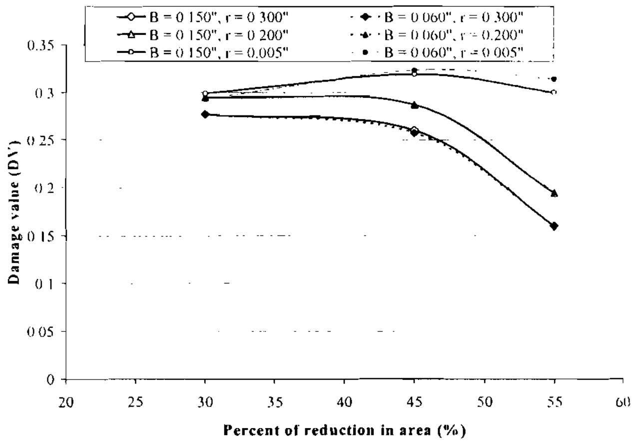
The punch speed was 0.27in/s, with a friction coefficient of m = 0.08. The billet diameter was 1 inch and the billet length was 2 inches. The material selected for the simulations was SAE 1137 hot rolled because it shows less ductility than SAE 1524 spheroidized annealed. This means that SAE 1137 can develop chevron cracks at an earlier stage.

DAMAGE VALUE PREDICTION FOR SINGLE-PASS EXTRUSION

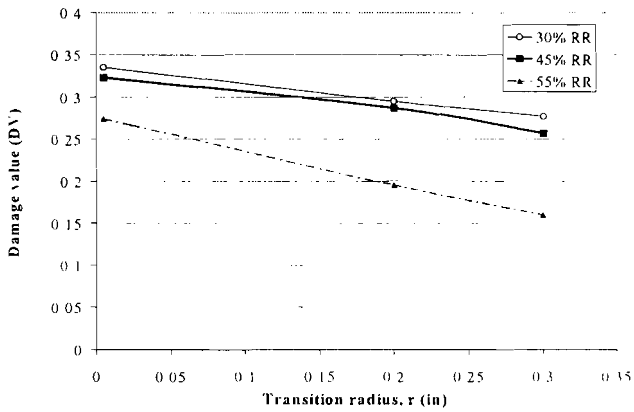
Figure 8 shows the variation of the maximum damage value estimated through simulations for one pass extrusion at several reduction ratios. The material used was SAE 1137. In all simulations the maximum damage value is located along the center of the work piece.

The highest damage value was 0.33, which does not exceed the selected average CDV of 0.51 for SAE 1137. In fact, it is below the conservative value of 0.44. Therefore, under the selected process conditions, chevron cracks would not be expected during one-pass forward extrusion.

Figure 8 also shows that the effect of the die land length (B) is essentially negligible. When the small transition radius (r = 0.005") is used, there is a higher stress concentration and, therefore, the flow of the material is restricted. The variation of the damage value for the given transition radius, r, is seen in Figure 9. This shows that damage value decreases when the transition radius is increased, especially for reductions in area between 45-55%.



8. EFFECT OF REDUCTION RATIO ON DAMAGE VALUE IN SINGLE-PASS FORWARD EXTRUSION



9. EFFECT OF TRANSITION RADIUS ON DAMAGE VALUE FOR SEVERAL REDUCTION RATIOS

The lowest damage values obtained were at the highest reduction in area evaluated. Notice that as the reduction in area increases, the deformation near the center of the work piece becomes more compressive and DV decreases (see Figure 10 for the distribution at 30%, 45%, and 55%).

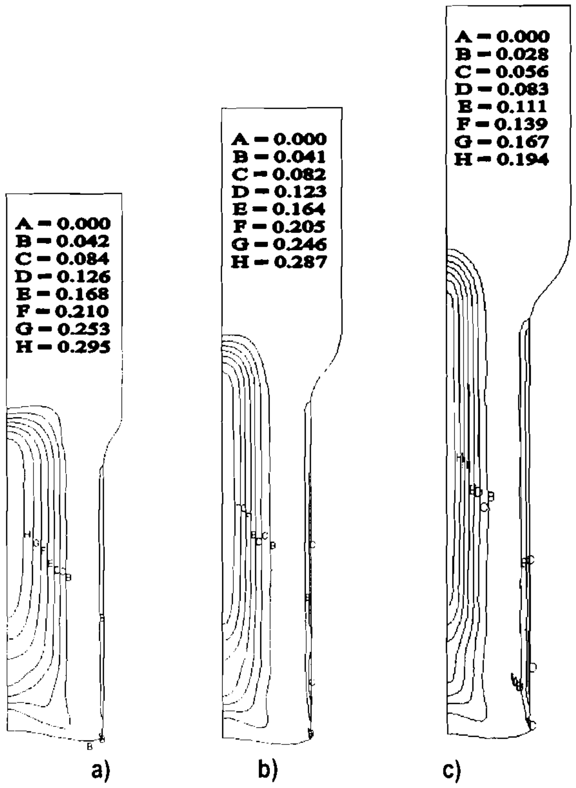
DAMAGE VALUE PREDICTION FOR MULTI-PASS EXTRUSION

The multi-pass extrusion sequence used by Kim [1994] was used in order to validate the premise that the critical damage value can predict the formation of chevron cracks for SAE 1137. The dimensions of the three die inserts used in these simulations are shown in Table 3.

This sequence was selected because, in earlier studies [Kim 1994], the products extruded at the same area reduction ratios and half die angle developed chevron cracks.

After the first pass of the forward extrusion simulation with conical dies, the damage value obtained was 0.25. During the first pass with spherical dies, the damage value obtained was 0.24. The chevron cracks and the damage distribution can be seen in Figure 11 after the third pass.

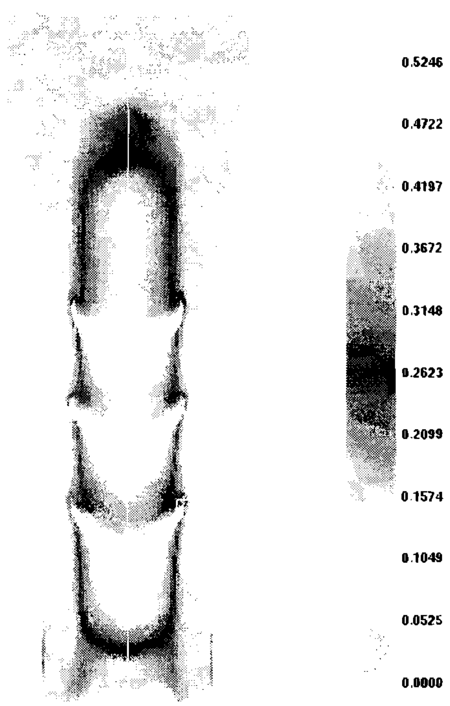
The multi-pass forward extrusion simulations showed that the damage value at the center of the work piece will be much higher than using single-pass extrusion, which leads to higher possibility of chevron cracks. This result showed that the CDV for SAE 1137 and the Cockroft and Latham ductile fracture criterion are capable of predicting chevron defects during three-pass forward extrusion.



10. DISTRIBUTION OF THE DAMAGE VALUE DURING SEVERAL REDUCTIONS IN AREA: (A) 30%, (B) 45% AND (C) 55% (B = 0.150" AND R = 0.200").

Die insert number	Bore Diameter (in)	Exit diameter (in)	Die land length (in)	Die angle
1	1.04	.896	0.125	22
2	1.05	.826	0.143	22
3	1.06	.742	0.146	22

TABLE 3. DIE DESIGN PARAMETERS FOR FORWARD EXTRUSION WITH CONICAL DIES.



11. FORMATION OF CHEVRON CRACKS DURING THREE-PASS FORWARD EXTRUSION USING FIRST PASS AS SPHERICAL DIE WITH MATERIAL SAE 1137 (HOT ROLLED) AND ITS CORRESPONDENT DAMAGE VALUE DISTRIBUTION.

PHYSICAL TESTING/EXPERIMENTS

To evaluate the analytical techniques used for this study, extrusion tests would be needed to support the theoretical work. Even though the ERC/NSM studied SAE 1137 hot rolled, it was decided to run the physical tests with the less formable grades of steel SAE 1215 hot rolled and SAE 1144 normalized; both of these grades had sulfur in the range of 0.30%. Several data points have been tested as shown in Table 4 and none of these were able to generate a chevron defect.

FUTURE WORK

Future work should be performed to generate CDV"s for one or both of these steels (SAE 1215 hot rolled & SAE 1144 normalized). DEFORM simulations could then be run with these lower CDV values to see if the prediction matches actual testing.

A second set of physical experiments is planned to evaluate the ability of developing chevrons when using spherical dies. In this set of

R_o	R_f	R_o / R_f (%RA)	R_o / r_d	SAE grade
0.39	0.31	1.26 (37%)	0.30	1144
0.57	0.40	1.43 (51%)	0.31	1215
0.67	0.53	1.26 (37%)	0.28	1144
0.87	0.49	1.78 (68%)	0.53	1215
0.81	0.44	1.84 (70%)	0.53	1215

All dimensions are in inches
R_o = initial radius of billet R_f = final radius of workpiece
r_d = spherical radius of die R_o / R_f = Reduction Ratio
R_o / r_d = Relative Die Curvature

TABLE 4. EXTRUSION EXPERIMENTS PERFORMED USING SPHERICAL DIES WITH MATERIALS WITH LOWER DUCTILITY THAN SAE 1137 HOT ROLLED – NO CHEVRONS WERE FORMED

experiments, the Relative Die Curvature will be held constant at a value of 1.71 (see Table 5). The Reduction in Area will vary from 50% down to 10%. A die will be manufactured with the largest Reduction Ratio, parts will be extruded, and the die will be modified to the next Reduction in Area. This will continue until all variations are completed as shown below.

If chevrons are found at any stage of this test, a more formable material (higher CDV) will be used to see if chevrons are also found using this material. If chevrons could be developed, it may provide important data for establishing the accuracy of predicting the CDV utilizing the methodology suggested in this paper. Additional experiments may also be conducted for different values of Relative Curvature, such as 1.0 and 2.5.

R_o	R_f	R_o / R_f (%RA)	R_o / r_d	Steel Grade
1.20	0.85	**1.41 (50%)**	1.71	1215, 1144, ZF7B
1.20	0.93	**1.29 (40%)**	1.71	1215, 1144, ZF7B
1.20	1.01	**1.19 (30%)**	1.71	1215, 1144, ZF7B
1.20	1.07	**1.12 (20%)**	1.71	1215, 1144, ZF7B
1.20	1.14	**1.05 (10%)**	1.71	1215, 1144, ZF7B

TABLE 5. FUTURE EXPERIMENTS WITH LOWER DUCTILITY MATERIALS

It will also be useful to compare the results and conclusions, obtained in this study, with criteria proposed by other investigators (Sriram and Van Tyne, 1999).

CONCLUSIONS

- Finite element simulations and a ductile fracture criteria are used to develop design guidelines to avoid the formation of chevron cracks for the forward extrusion process with spherical dies.
- Physical tests were used to determine flow stress and the CDV for SAE 1137 (hot rolled) and SAE 1524 (spheroidized).
- Additional refinement in the procedure for detecting crack initiation in the physical testing procedure will improve the accuracy of predicting defects.
- In the forward extrusion simulations using spherical dies the damage value decreases as reduction in area (RA) increases. The damage value decreases when the transition radius is increased, especially for reductions in area between 45-55. The die land length, B, does not have a significant impact on the MDV.
- None of the maximum damage value (MDV) obtained from simulations for single-pass extrusions exceeded the CDV obtained experimentally for SAE 1137 hot rolled. This means that no chevron cracks will form for the selected process conditions.
- The multi-pass forward extrusion simulations show that the damage value at the center of the work piece will be much higher than the damage value predicted using one-pass extrusion. This leads to a higher possibility of chevron cracks in multi-pass extrusion.
- The CDV used for the materials tested is the average value obtained for non-homogeneous compression and notched tensile testing.
- For the same reduction in a single-pass extrusion, a conical die design has a slightly higher damage value (0.25) than a spherical design (0.24). However, this difference is insignificant for practical purposes.

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