Failure analysis of an automotive shock absorber cup during manufacturing process

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Abstract – A failure investigation was conducted on an automotive shock absorber cup during the manufacturing process. Due to the complexity of the parts, the manufacturing is carried out through multi deep drawing operations. The occurrence of cracks over the hole-flanged edge of the cups was the major problem in the forming process which causes failure. To determine the causes of failure, a detailed method including microscopic and macroscopic inspections were carried out in this study. The mechanical behavior of test specimens was investigated by means of tensile tests and the material was characterized in terms of Vickers micro-hardness. As a result, it was observed that the quality of the cut surface associated with the material work hardening after each sequence of sheet forming is the principal causes of failure. The damage is governed by the generation of micro defects during the punching process. This damage develops further during the hole-flanging step.

Key words: Failure / deep drawing / cracks / quality of the cut surface / work hardening / punching / hole-flanging

1 Introduction

The production of defined standard quality products in a short time and at a low cost is an ultimate goal in the manufacturing of an automotive shock absorber cup. The cup is the product of multiple working steps; such as several shearing, drawings, pre-punching-hole and flanging process which are needed to form the flange suitable for subsequent assembly to a tubular body and then welded. During the sequential forming operations shown in Figure 1 used to manufacture the cup, the damage takes place through the hole-flanging operation which consists in forming an integral collar around the periphery of an initial hole in a sheet metal part. This operation stretches the sheared edge that has already been subject to large amounts of plastic deformation. Therefore, forming problems result frequently. Traditionally, the formability of a product without necking is predicted using the forming limit diagram (FLD) a locus of the limit strain states under different linear strain paths. This diagram is available when the forming of the part is simple, as the cup was prepared through multi operation of deep drawing (complex strain path), failure may not be predictable by this diagram [1].

Among the forming process of the cup, the main focus was on the punching and the flanging process which have a direct influence on the failure.

An earlier overview have been provided by Johson et al. [2] in sheet metal punching-flanging processes, this investigation has reflected the problems and the concerns in the zone involved in cutting of mild steels, high strength steels and non-ferrous metal. The main approach of the study was experimental observation and characterization of sheared edges. Hambli et al. [3,4] were interested to the effect of the process parameters. They conducted an experimental and a numerical investigation to determine the optimum clearance, optimal tool and equipment design in punching process. This study greatly helped the understanding, the control and the improvement of the process. Thipprakmas et al. [5,6] using FEA, focused on the tooling design with the objective to make a clean-cut edge. They proposed a step-tapered-punch shape for the punching process. They also studied the effects of flange-forming direction based on stress distribution analysis. Upward and downward burr orientation of the sheared edge and the flange-forming directions were suitably applied for large and small hole expansion ratios, respectively. Further investigations aimed to understanding the effect of the sheared edge quality on the flanging process were conducted. Sartkulvanich [7] has established a methodology to predict failure by edge cracking in flanging with

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Fig. 1. The experimental setup for forming cup.

considering the sheared edge quality of advanced high-strength steels (AHSS). The result has shown how metal flow, strains and stresses in punching affect the flanged part quality and potential edge cracking in stretch flanging. Thus, the sheared edges quality needs to be better characterized, and their effect on stamping formability needs to be investigated.

Many researchers consider that the difficulty to predict edge cracking, in flanging operation, is related to both the sheared edge quality, as well as, the material properties. A previous work of Leu [8] proved that the onset of necking on the hole edge is influenced by the plastic properties of the material, such as the stress-concentration factor (K), strain-hardening (n) and normal anisotropy (r). Quazi [9] has conducted an optimization of the punching process based on a proper selection of the clearance. He reported that there is no universal optimal clearance value which could minimize the blanking force; the one clear trend noted is that an optimum clearance decreases as the material elongation increases. Kacem et al. [10] studied the limit of the hole flanging process arising from the material failure by a careful identification of the ductile fracture criterion on two aluminum alloys sheets. They have found that the distribution of damage is different whether or not the process is performed with ironing and that the effect of anisotropy is weak on the damage distribution.

Besides the plastic properties of the material, other external influencing factors (the operating conditions) play an important role in deep drawing processes. For example, the friction coefficient influences the flow capacity of the material to move through the die and affects the final stress distribution in the component when the tool is completely closed. A review presented by Chandra Pal Singh reported that the draw-ability of sheet is well dependent on the presence of the adequate lubricating film between contact surfaces [11]. Cao et al. [12] studied the effect of friction variability on the process. They found that the variation of the friction coefficient during the sheet bending process can be as high as 65% resulting in a large variation of the part quality. Rajiv et al. [13] proposed an optimal design of spatially varying frictional constraints to reduce the risk of failure. The results show that compared to the conventional spatially uniform friction case, an overall improvement of 33% in strain distribution is reached and a further 12% improvement can be obtained with a probabilistic design. Huang and Cheng [14] experienced a solid lubricant (zinc stearate powder) and a liquid

one (press oil) to improve the friction condition. Comparing the results of limit drawing ratio (LDR), punch load and sheet thickness distribution; it was found that the solid lubricant has better lubricating effect than the liquid.

The study presented hereafter was devoted to determine the main causes of failure of an automotive shock absorber cup during the manufacturing process. A description of the product and the two industrial processes involved in the preparation of the product were introduced in Section 2. In Section 3 we described the experimental procedure used in this study. The fourth section was devoted to the results of the tensile tests and the SEM observations conducted on punched and flanged cup. In addition, the effect of the deformation history on the mechanical properties of the drawn-part is examined by micro-hardness tests. We drew our conclusion in final section of this paper.

2 Industrial inspection

The work pieces are disk substrates with an expanded hole at the center (Fig. 2a). The cup sheet material was a 3 mm low-carbon steel (DC01). The first main step was to focus on defects occurring over the neck of the cup. Failure was determined visually and defined as necking thinning and fractures. The defects are highlighted in Figure 2b. They vary in size and depth, and occur on the expanded-hole. Defects with relatively large depths are located near the ribs.

Generally, the applied tensile stress in the circumferential direction at the edge of the expanded hole is the main reason of failure [15, 16]. Cups failure may be attributed to the three following factors: sheet material selection and quality, tool design and manufacturing process especially punching and hole flanging processes.

2.1 Punching process

Hole punching is the most important step in forming process as it strongly affects the final results. It consists in cutting process in which the material is removed from a work piece by applying a great enough shearing force. The press drives the punch downward at a high speed through the sheet and into the die below. Initially the material tends to be pulled into the die, and then the

Fig. 2. (a) Definition of near and transient surfaces. (b) A stretch flange sample fractured by edge necking.

Fig. 3. Schematic illustration of cups punching process.

punch forces the sheet to penetrate in shearing. There is a small clearance between the edge of the punch and the die causing the material to bend quickly and ultimately fracture. All tests were performed with the burr up configuration at 10% of thickness cutting clearance. A schematic representation of the punching tools is given in Figure 3.

2.2 Flange forming process

The flange forming operation consists in expanding a hole with a cylindrical punch into a die, in order to produce a hollow cylinder; a schematic representation is given in Figure 4. The sheet is retained between the blank-holder and the die. During the first phase, the punch moves down until it reached a close contact with the inner edge of the work-piece, and induces the deformation of the component edge. In the second phase, the punch goes down, and the work sheet is punched down towards the die cavity. The punch forces the material, in the third phase, to fill the narrow gap between the die and the punch. In the final phase, the punch moves up and the elastic deformation is recovered. The real components are prepared for some laboratory experiments, in order to check the effect of the punching on the component response after hole-flanging.

Fig. 4. Crosscut view of the flanging device tool for cups.

Fig. 5. Shape and dimensions of the tensile specimen $\Psi = 0, 45^\circ, 90^\circ$ (dimensions in mm).

3 Laboratory experiments

3.1 Materials characterization

Three materials were considered to perform this study: (a) DC01 mild steel as highly ductile, (b) DD13 as ductile material with low cost and (c) S355MC high strength steel for its high lightweight potential and high security responses at the same time [17]. Their chemical compositions are listed in Table 1.

All specimens were extracted from 3 mm thick sheets and performed at $0^\circ, 45^\circ$ and 90° to the rolling direction. The specimen geometry is shown in Figure 5. A standard tensile machine has been used for the experiments. The result of a test is normally an average of three test results for the three considered materials.

Table 1. Chemical compositions of mild steels; DD13, DC01 and HSS; S355MC.

	C _(max)	Mn _(max)	P _(max)	S _(max)	Si _(max)	Al _(min)	Nb _(max)	Ti _(max)	V _(max)
DC01	0.12	0.6	0.045	0.045	0.03	0.02	–	–	–
DD13	0.08	0.4	0.03	0.03	–	–	–	–	–
S355MC	0.12	1.5	0.025	0.020	0.5	0.015	0.09	0.15	0.20

Fig. 6. Typical locations of the micro-hardness measurements for; (a) flanged cup, (b) punched cup.**Table 2.** Tensile mechanical properties of; DD13, DC01 and S355MC materials: E – Young Modulus, YS – Yield Stress; TS – Tensile Strength; EL – Elongation; and n – strain hardening exponent

Material	DD13			DC01			S355MC		
ψ (°)	45	90	0	45	90	0	45	90	0
E (GPa)	201	201	219	211	221	147	195	254	200
YS (MPa)	215	270	260	180	150	145	420	445	420
TS (MPa)	322	320	330	300	260	255	475	500	490
YS/TS	0.7	0.8	0.8	0.6	0.6	0.6	0.9	0.9	0.9
EL (%)	56	28	45	54	58	62	32	40	42
n	0.19	0.17	0.18	0.19	0.22	0.21	0.16	0.16	0.17

3.2 Failure analysis

3.2.1 Macroscopic and microscopic examination

An optical microscope (OM) and a scanning electron microscopic (SEM) equipped with an EDX microanalysis system were used in order to assess the underlying failure mechanisms in the cups. For a better understanding of the damage mechanisms, the surfaces of the flanged hole are classified into three main types surfaces (Fig. 2a):

- On the flange forming direction, called “tangential surface”.
- Perpendicular to the flange forming direction, called “normal surface”.
- On the circumferential of the die, called “lateral surface”.

To investigate the effect of the sheared surface morphology on the features and the flanged edge shape, the punched parts were sectioned and further processed by observing and capturing the cut surfaces using macro and microscopic analyses. All the steels in this study were tested in the received conditions for the following experiments.

3.2.2 Micro-hardness examination

To follow the mechanical variations which may occur during the forming cycle around the cold-worked

hole, micro-hardness measurements with 200 g load were performed. Small test specimens were sectioned with robofil machining from DC01 cold rolled steel; virgin, pre-punched cup and flanged hole cup. The result for micro-hardness measurements is normally the mean of the three tests. A detailed view of measurements region is presented in Figure 6.

4 Results and discussions

4.1 Tensile properties

The onset of necking on the deep drawn components is mostly influenced by the plastic properties of the sheet material. Figure 7 shows the stress-strain curves for steels; DC01, DD13, S355MC. The mechanical properties are in Table 2.

The strain hardening behaviors show the anisotropy of the Yield Stress, the Tensile Strength, and the Elongation which prove the anisotropy of the studied materials. The results prove a very satisfying performance of the cold rolled steel material (DC01). In fact, it shows the highest elongation to failure so the best ductility, the largest values of strain-hardening exponent “n” which improves the consolidation of the material and increases the distribution of deformations during the drawing operation, thus better hole-flanging formability. It shows the lowest ratio YS/TS which improves its formability. The S355MC

Fig. 7. Strain- stress curves for analyzed material in different orientations with respect to the rolling direction.

Fig. 8. Hole-expansion sample showing necking and fracture.

presents the maximum tensile strength; this can reduce the risk of plasticizing in case of shock, then minimizing the possibility of generating cracks. But it presents the lowest elongation at fracture which affects its performance compared to the extra mild steel. The hot rolled steel DD13 and the high-strength steel S355MC show short gap between the yield strength and the ultimate tensile strength compared to the DC01, which promote difficulties during the forming process. Therefore, they exhibit poor formability compared to the cold rolled steel. This material assures formability and promotes a structural stiffness associated with elevated strength properties.

Because of the above mentioned reasons the microstructure and micro-hardness characterization at and around the edge were achieved only for the DC01 material for the rest of the work.

4.2 Characterization of surface defects

4.2.1 Flanged edge damage

The general appearance of the shock absorber cups provides a real picture of failure; the cracks covered the

flanged edge, and they usually initiate in the vicinity of the lateral surface and traverse through the thickness in a line perpendicular to the load axis (Fig. 8). Necking and fractures appear and grow normally due to the severe straining according to the applied tensile stress during the hole-flanging process. An overview on the fracture surface displays a very heterogeneous morphology; the presence of dimples is a typical characteristic of a ductile fracture (Fig. 9a).

The presence of dimples in Figures 9b and 9c which appear as oblate hollow regions called voids at the lateral surface produces the fibrous appearance in the graph. The elongated dimple is a characteristic of a tensile failure mode. Their occurrence and shape are largely influenced by the state of stress/strain conditions. Voids nucleation, growth and linkage are the fundamental cause of dimple fracture in high stress triaxiality [18]. The existence of second-phase particles shown in Figure 9d as small circular particles that act as a source for crack nucleation affects the failure mechanism [19]. The inner surface of the obtained hollow cylinder is free from apparent macro defect (Fig. 10a). This suggests that the material failure first occurs at outer region.

Fig. 9. Surface of failure through-hole wall: (a) normal surface, (b–d) lateral surface of failure.

Fig. 10. (a) SEM observation of the analyzed area, (b) EDX analysis of the mentioned area.

Thus, the fault cracks are considered to have been caused principally by a large stress that results from the impact of a shearing action and promoted by the stretching one. The cracks were formed during the punching operation, then they were developed during the hole flanging process.

During the forming operation, a superficial local oxidation occurs on the substrate especially at the inner surface as evidenced by EDX analysis. Figure 10a taken from the tangential surface shows some clear and dark areas proving the superficial oxidation of the steel sheet. The dark areas correspond to iron oxide formed during the drawing steps by heating with the presence of air oxygen. This is confirmed by EDX analysis which depicts the presence of oxygen in the EDX spectrum (Fig. 10b). Since the analysis was performed on crude sample, foreign elements (Ca, Mg, K) occurring on the spectrum may originate from dirt, soil covering the surface and the tools-sheet interaction.

4.2.2 Sheared edge damage

According to Saxena et al. [1], the sheet metal may have inherent voids/imperfections present because of pre-processing. These voids/imperfections grow under the applied load resulting in a final fracture. Thereby, the extent of cracks developed in the cut surface was clarified by OM and SEM observations after the punching operation. The cut surface reveals three main zones; a rollover zone, a burnished zone and a fracture zone (Fig. 11a). The fracture zone will have some burrs from being sheared. The

height of each of these portions of the cut depends on several factors, including the sharpness of the tools and the clearance between the tools [3].

From micrographs inspection (Figs. 11b–11d), it can be seen that porosity occurs within all of the zones; voids are randomly distributed specially within the fracture zone and the rollover one. Qualitatively, porosity appears to be nucleated and coalesced voids. The fracture area exhibits a ductile fracture surface.

The area affected by the shearing process called shear affected zone (SAZ) has a large influence on the edge flange-ability. The state of damage in the SAZ due to the quality of the sheared edge (roughness, imperfections) and the effect of the plastic deformation and the resulting work hardening will have a major influence on the formability of the sheared edge and the parts performance.

A secondary finishing operation was performed to eliminate SAZ. The samples were initially shear cut, and then reamed. Figure 12 shows achieved samples of each of these two types of hole.

The reamed hole presents a homogeneous zone of parallel streaks. After flanging, a significant difference was observed compared to the conventional punched hole. In fact, the reamed parts were free from necking and cracks. A local thinning of about 20% is detected near the rib, but it doesn't cause failure of parts. In fact, obtaining a good quality requires achieving smoother edges. This implies a different critical state of the sheared edge for the sheet formability. These results suggest that the imperfections as porosity and surface roughness within the SAZ play a major role in edge forming.

Fig. 11. Microscopic observations of the punched profile; (a) sheared edge, (b) rollover zone, (c) burnished zone and (d) fracture zone.

Fig. 12. Characteristic of cut surface after; (a) punching operation, (b) punching and finishing operations. Characteristic of flanged edges for the, (c) sheared edge and (d) finished edge.

4.3 Characterization of material work hardening

To characterize the work hardening in the sheared edge, a micro-hardness measurement was conducted. The hardness distributions measured as a function of the distance from the hole-edge are presented in Figure 13. The micro-hardness measurement performed on a virgin sheet was approximately uniform within the sheet depth. While those attributed to the punched and flanged samples are

non-uniform; highest values are located close to surface where the plastic strain is important. The width of the SAZ is of approximately 1 mm, it is defined as the distance from the edge to the depth where the hardness measurements decrease and become uniform. Experimental results confirm that the state of hardening of the cut edge, which is related to the deformation history of the sheet, affects the parts flangeability.

Fig. 13. Micro-hardness measurement performed on a virgin sheet, pre-punched samples and stretched samples.

5 Conclusion

An experimental investigation was conducted to gain a thorough understanding of the failure mechanism during the manufacturing of automotive shock absorber cups. The main failure process was the occurrence of crack and necking above the hole-flanged edge. The influence of the punching and the hole-flanging processes on the failure was clarified.

The principal conclusions of these experiments are:

1. The mild steel “DC01” presents a stress-strain behavior which exhibits the lowest YS, the highest EL% and a region where the strain hardening rate increased with strain which makes it the most appropriate material for the manufacturing of cups.
2. The sheared surface quality (roughness, nucleated voids, imperfections) is the principal cause of the sheet material damage.
3. Work hardening of the sheet material within the SAZ seems to have an influence on edge failure.
4. The pre-straining associated with the shearing operation affects the edge formability.
5. The rupture mechanism varied from necking and shearing between voids.
6. The superficial oxidation of the steel sheet caused by heating during deep drawing operations doesn't significantly affect the formability during manufacturing but may cause problems in future.

Further investigation is needed to explore more parameters and operating conditions of punching and hole expansion processes. An experimental work is being developed to perform a punching process that helps us to achieve an optimal set of parameters and improve its output quality.

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