16 Edge Formability in Sheet Metal Forming

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16.1 INTRODUCTION

In today's industry, marked by fierce competition, companies face a growing demand for high-quality products, driving them to minimize losses to the lowest possible level. In this context, the edge formability of metal sheets plays a crucial role. Understanding and controlling this property has become essential for ensuring efficient manufacturing processes, minimizing losses, and maximizing the quality of the final products.

The consequences of manufacturing losses are diverse and impactful. In addition to the material waste itself, waste consumes considerable energy and ultimately increases greenhouse gas emissions. Understanding and controlling the edge formability of metal sheets is essential for addressing these challenges and ensuring the efficiency and sustainability of industrial processes. Minimizing losses by reducing failures and waste not only enhances energy efficiency and preserves natural resources but also directly impacts the profitability of companies by reducing costs associated with rework and waste. This chapter aims to delve deeply into the edge formability of metal sheets, providing valuable insights on how to comprehend, evaluate, and control this fundamental property.

16.2 FLANGING

Modern sheet metal manufacturing methods primarily involve cutting, bending, and stretching. Among these processes is bending around holes. This operation, known as flanging, is incorporated into designs to reinforce edge regions. Flanged holes find application in bolted connections or serve as strengthening components within mechanical joints and bushings. The conventional flanging process is schematically represented in Figure 16.1. This operation typically consists of a die, a punch, and a blank holder. The blank-holder pressure is fine-tuned to effectively grip the sheet, while the punch impels the hole's outer edge into the die.

Flanging can be executed with or without an ironing stage. In flanging without ironing (Figure 16.1(a)), the sheet is held in place between the die and the blank holder using suitable force, and the flange is shaped by stretching the edge. In contrast, flanging with ironing (Figure 16.1(b)) involves regulating a minor gap

DOI: 10.1201/9781003441755-16

between the punch and the die. Through this approach, metal is extruded between the punch and the die, yielding elongated flanges.

The edges of a part can exhibit different geometric arrangements as a result of flanging (Figure 16.2); during strain, the flange edge can experience tension or compression or remain undeformed. Concave bending is particularly prominent because it is commonly incorporated in stamping processes and because of the possibility of crack formation. Failure is usually linked to the material's elongating tangentially to the open edge, concomitant with contraction in the direction perpendicular to the open edge.

Forming a flange in conventional mild steels is relatively simple, but flanging high-strength steels is a more complex task that requires precautions; they have a high tendency to crack, which has restricted their use. Over the past few decades, these materials have gradually increased in use, leading to a heightened focus on fracture analysis within edge regions. Researchers have extensively explored the subject.

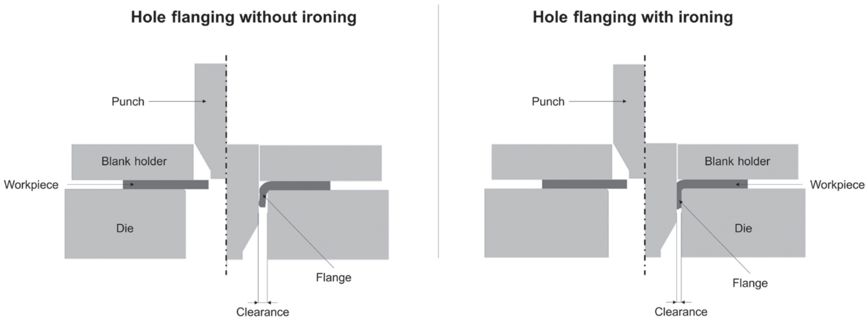

FIGURE 16.1 Conventional hole flanging: (a) without ironing; (b) with ironing.

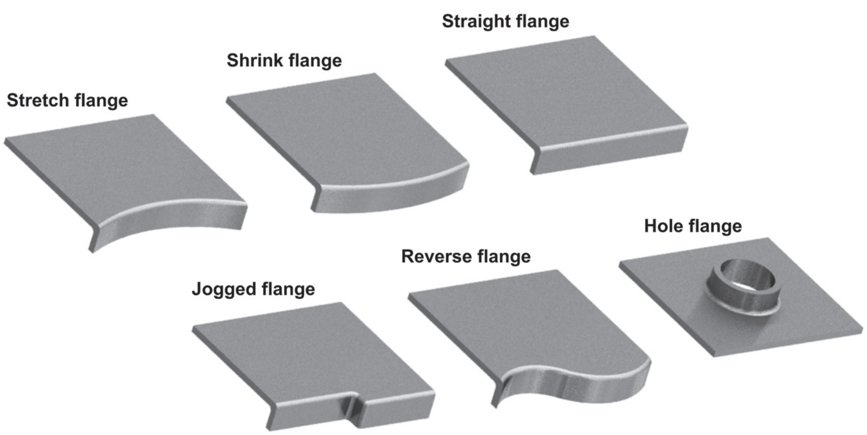

FIGURE 16.2 Different flanging geometries.

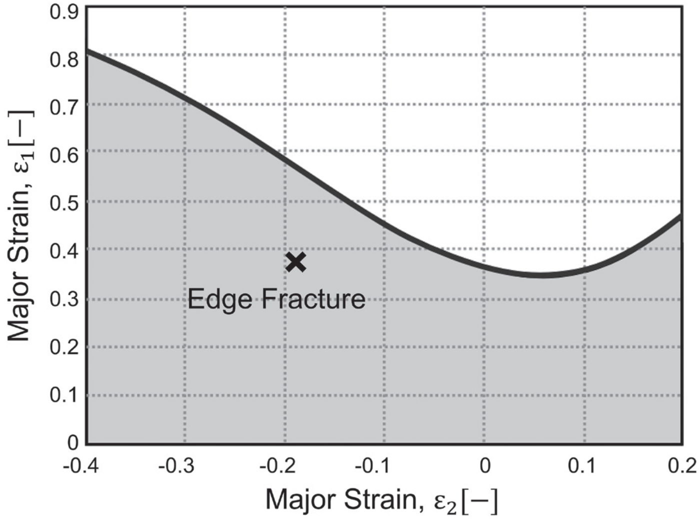

FIGURE 16.3 Comparison of edge fracture results with the FLC of AISI 1008 steel.

16.3 EDGE FORMABILITY

Sheet formability can be classified as bulk or edge formability. Bulk formability, also known as global formability, refers to the ability of a sheet to be deformed without failure in the body of the part. Edge formability, also referred to as local formability, encompasses the material's capacity to undergo deformation in edge regions or perforations without experiencing failure.

Global formability can be ascertained through techniques such as forming limit curves (FLC), deep-drawing experiments, stretching tests, and ductility assessments derived from standard tensile tests. However, these tools are not efficient for analyzing edge formability. In Figure 16.3, the results of edge fracture are plotted on the forming limit diagram of AISI 1008 steel. The fracture of the punched-hole sheet occurs below the FLC, demonstrating that the FLC cannot successfully predict fracture in flanging.

16.4 EDGE FORMABILITY TEST

The hole expansion test is the prevalent approach for quantifying edge formability. The strain state imposed by the test is equivalent to that developed in concave flanging under production conditions. This makes the test ideal for predicting the behavior of a material subjected to edge stretching. The test quantifies the edge formability of a material class with a specific edge condition. ISO 16630 is the commonly used standard for this test, but other test standards have also been developed such as JFS T 1001-96 and IISI–AHSS Guidelines Hole Expansion-2004.

The hole expansion test encompasses subjecting a flat sheet featuring a circular hole to the progressive penetration of a conical punch until cracks emerge at the edge (Figure 16.4). The test is halted at the initial indication of a crack extending through the sheet's entire thickness (Figure 16.5). The outcome of this test yields the hole expansion ratio (λ), a widely employed parameter for appraising the edge formability of sheet metal. This ratio is expressed by Equation 16.1:

$$\lambda = \frac{d_1 - d_0}{d_0}.100 \quad (16.1)$$

where d_0 and d_1 correspond, respectively, to the initial hole diameter and the diameter after test.

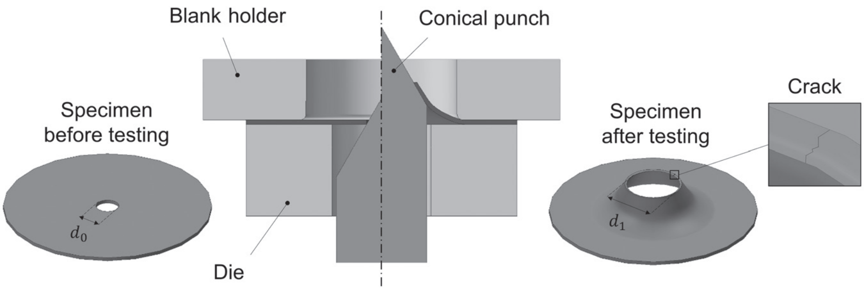

FIGURE 16.4 Schematic drawing of the hole expansion test.

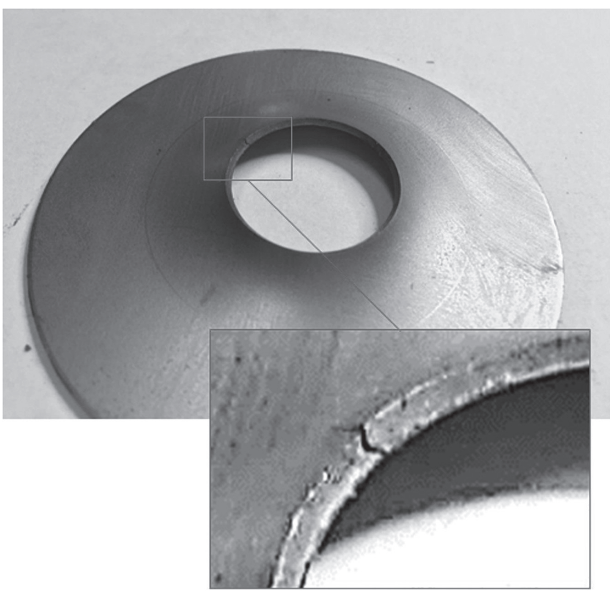

FIGURE 16.5 Hole expansion test specimen after the test.

Sample preparation involves shearing a hole through the sheet, and as previously mentioned, the cutting operation for hole fabrication influences edge formability. For this reason, the standard defines specific conditions for fabricating the hole in the samples. The standard also stipulates the clearance between the punch and the cutting die, along with the permissible tolerances for tool dimensions.

16.5 PARAMETERS THAT INFLUENCE EDGE FORMABILITY

Edge formability is a function of sheet properties and process design. Steel mills have made continuous efforts to enhance hole expansion capability by developing new high-performance products. At the same time, designers must evaluate whether a specific steel grade is compatible with the desired manufacturing route. If they are not compatible, the material may need to be replaced or the process modified, or possibly both. Edge formability is influenced by a number of factors: material microstructure; mechanical properties; hole preparation (shearing, laser cutting, water jet, etc.); hole diameter; burr position relative to the punch; and punch shape (conical, hemispherical, flat, etc.).

16.5.1 Microstructure

From a microstructural perspective, the volumetric fraction and, more importantly, the type of microconstituents significantly affect the hole expansion capability. As a result, the same steel grade produced by different steel mills may exhibit significantly different edge formability. This aspect is critical in modern high strength steels. The complex microstructure of these steels generates an optimized balance of properties and influences edge formability.

Materials such as dual-phase (DP) steels, which differ greatly in hardness owing to their microconstituents (martensite and ferrite), tend to exhibit inferior performance. This is due to the concentration of strain in the softer and more ductile phase and the occurrence of microcracks at the ferrite/martensite interface (Figure 16.6). The edge formability of DP steels can be improved by achieving a fine and uniform distribution of martensite colonies.

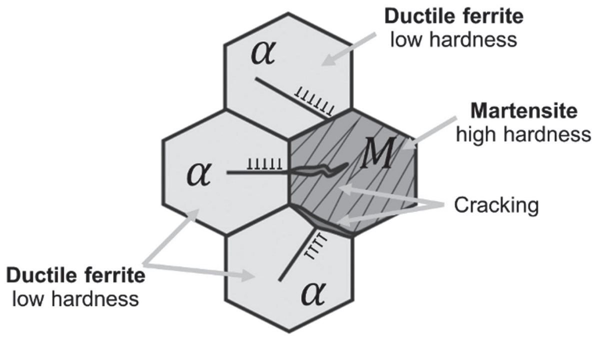

FIGURE 16.6 Failure mechanism of DP steels subjected to hole expansion.

Complex-phase (CP) steels exhibit better edge formability than DP steels. In CP steels, the stronger phase consists of a mixture of bainite and tempered martensite, and the relatively smaller difference in strength between the phases results in higher λ values. Due to bainite's higher ductility compared with martensite, in steels comprising this microconstituent, strain doesn't localize exclusively in the ferrite. Rather, the strain dispersion becomes more even, resulting in enhanced hole expansion potential.

In TRIP (transformation-induced plasticity) steels, the prematurely retained austenite that transforms into martensite during strain is detrimental to formability. The retained austenite tends to transform into martensite during the hole execution through the punching process. Consequently, the presence of low stability and a significant fraction of retained austenite tends to diminish the λ values.

16.5.2 Mechanical Properties

Experimental and numeric results from the hole expansion test of AISI 1008 carbon steel are used to enhance understanding of the stress and strain states developed during the forming process. The distribution of equivalent stress in the sample at the moment of failure is illustrated in Figure 16.7(a), while Figure 16.7(b) shows the distribution of the algebraically larger principal stress. Upon test completion, the stress condition at the edge of the central hole within the sample is primarily tensile in nature, analogous to the stress state generated during uniaxial tensile testing.

Figure 16.8(a) displays the pattern of equivalent strain dispersion within a hole expansion sample made from AISI 1008 steel posttest. Meanwhile, Figure 16.8(b) depicts a side-by-side representation of the experimental and numeric outcomes showcasing the fluctuations in principal strains, ε_1 and ε_2, across the sample.

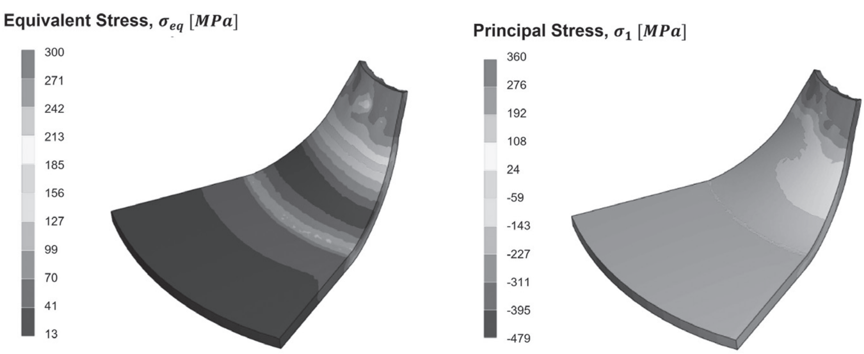

FIGURE 16.7 Distributions of (a) equivalent stress, σ_{eq}, and (b) algebraically larger principal stress, σ_1, in the sample at the moment of failure obtained through finite element analysis using FORGE software.

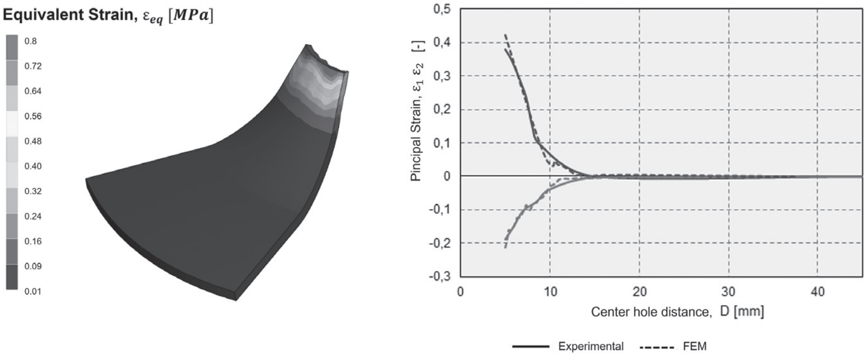

FIGURE 16.8 (A) Distribution of equivalent strain, ε_{eq}, in the AISI 1008 sample at the moment of failure obtained through finite element analysis using FORGE software. (b) Variation of principal strains, ε_1 and ε_2, along the sample.

It is evident that in the hole expansion process, strains are concentrated in the edge region, while the periphery of the sheet undergoes minimal plastic deformation. The maximum strain coincides with the location of material failure, namely at the edge of the sheet. The analysis of principal strains demonstrates that during hole expansion, the strain near the hole edge follows the path of uniaxial tension, where $\varepsilon_1 = -2\,\varepsilon_2$. As a result of the tensile stress and strain states in the edge region, material stretching occurs, leading to failure.

Figure 16.8(a) shows that expansion generates a strain gradient along the geometry. Therefore, despite the fundamentally tensile stress and strain states and the deformation path that coincides with uniaxial tension, the hole expansion test differs from the uniaxial tensile test due to the heterogeneous distribution of strain along the material. In a tensile test, at the macro scale, strain is homogeneous until the onset of necking. Furthermore, in a tensile test, fracture becomes noticeable solely within the necking zone, whereas within the hole expansion sample, multiple cracks can become apparent along the central edge. In other words, even though the edge presents a deformed state analogous to uniaxial tension, tensile tests and hole expansion tests have a significant difference that prevent obtaining precise correlations between uniform elongation and hole expansion ratio. An example is TRIP steels, which, despite exceptional uniform elongation in tension, exhibit limited formability in terms of hole expansion.

Several researchers have sought to relate other properties to the hole expansion. Recent studies have shown that nonuniform elongation is a relevant parameter for edge formability. Materials showcasing heightened elongation post-necking typically yield enhanced outcomes in the hole expansion test. Moreover, increased hole expansion should correlate with a higher strain-hardening exponent and a higher coefficient of normal anisotropy. These properties restrict deformation in the thickness direction, enhancing resistance to necking and delaying premature failure in the thickness direction induced by flanging.

16.5.3 Hole Preparation

The procedure for creating the central hole in the samples assumes a pivotal role in shaping the outcomes of the hole expansion test. Diverse hole preparation techniques are utilized in industrial applications, including punching, milling, wire-EDM cutting, laser cutting, and more. Each of these methods imparts varying degrees of damage to the hole edge, subsequently impacting the material's local formability.

Typically, for reasons of cost-efficiency, components are fabricated from steel sheets derived from coil cutting. Within these sheets, a single edge is shaped during the shearing stage, followed by subsequent stamping. In the course of punching, the material is essentially subjected to catastrophic shearing failure. However, the process doesn't perfectly achieve pure shear; instead, it engenders stress and strain gradients. The heterogeneous distribution of strain in the edge region results in strain hardening. Consequently, compared with other cutting processes, punching results in more damage to the material edge.

A punching operation yields a cutting edge characterized by three distinct zones and the presence of a burr (Figure 16.9), and the extension of each of these regions fluctuates based on punching conditions and material mechanical properties. The slope of shear and the sheared surface are influenced by the cut's clearance. The extent of the fracture region and the height of the burr are regulated by the sheet's tensile strength.

In contemporary steels, an edge featuring a well-defined shear zone and a seamless transition to the fracture zone yields improved hole expansion outcomes. The fracture zone should be sleek and devoid of secondary shearing

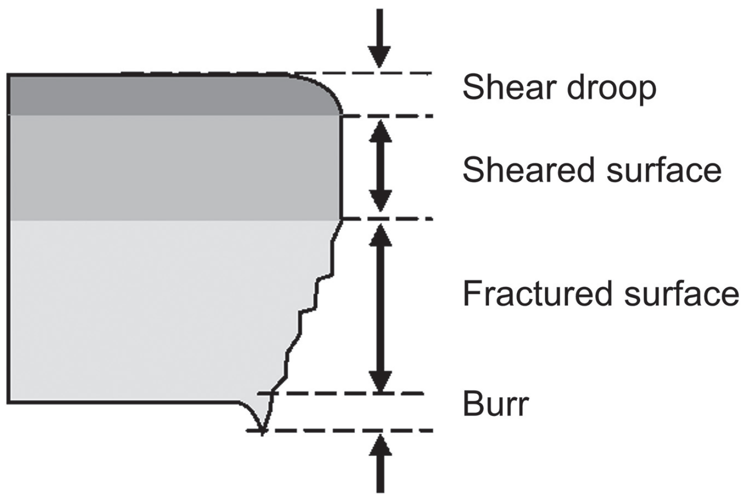

FIGURE 16.9 Schematic drawing showing the characteristic zones of a punched cutting edge; AHSS: advanced high-strength steel.

or impairment. If clearances are too low, secondary shearing might transpire, escalating fracture susceptibility due to the intricate microstructure. Likewise, a nonuniform shift from the shear zone to the fracture zone, as depicted in Figure 16.10, is undesirable.

To ensure the quality of the cutting surface and prevent degradation of the edge formability, control of tool wear is crucial. Over time, the quality of the punch edge decreases and the clearance changes due to wear mechanisms. The progression of tool wear damages the edge of the holes. The edges become unevenly work-hardened, and the flangeability is dramatically affected.

16.5.4 Hole Diameter

While ISO 16630 designates a 10 mm diameter hole for hole expansion tests, it's important to note that the initial hole diameter directly impacts the achievable expansion extent. That is, the initial diameter should be considered when selecting the work material for a specific process. Tests should be conducted on sheets with hole diameters close to those used in the production process.

16.5.5 Burr Position

The positioning of the cutting burr in relation to the punch significantly influences the outcomes of a hole expansion test. The negative impacts are mitigated when the burr is situated on the punch side (as illustrated in Figure 16.11). This effect is primarily due to the reduced tension exerted on the surface near the punch during expansion. Correct burr positioning can increase edge expansion capability by up to 20%. This factor should be duly acknowledged in designs that are susceptible to edge expansion issues.

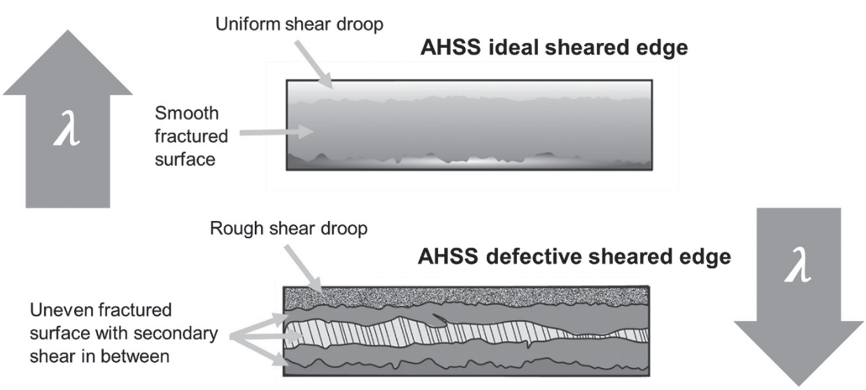

FIGURE 16.10 Schematic drawings of cut surface of advanced high-strength steel sheets.

In the standardized test according to ISO 16630, the test specimens are positioned with the burr on the opposite side of the punch. In this way, the material is evaluated under the most critical condition in terms of edge formability.

16.5.6 Punch Geometry

The geometry of the flanging punch affects the metal flow during forming and, consequently, the extent to which the steel can be deformed before fracture. Figure 16.12 shows the numeric results of Cockcroft–Latham damage obtained in QFORM software for different punch geometries with the same hole expansion.

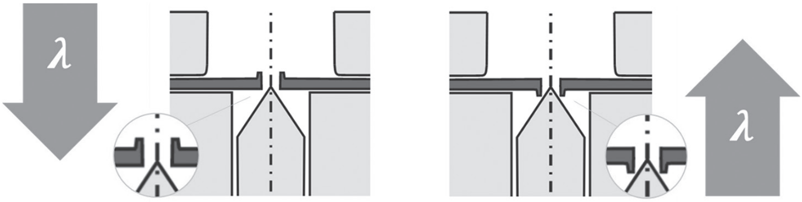

FIGURE 16.11 Effects of burr position on the hole expansion ratio.

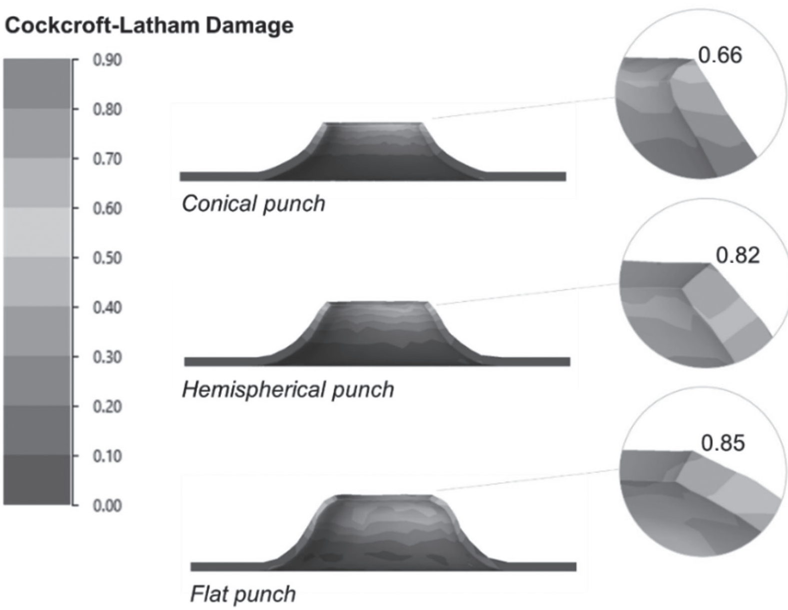

FIGURE 16.12 Numeric result of Cockcroft–Latham damage distribution for hole expansion with different punch geometries.

The use of a conical punch results in bending and stretching of the material edge. On the other hand, the use of a flat or hemispherical punch eliminates bending, and all deformation occurs only in the form of edge stretching. These differences in strain state lead to different levels of damage; sheets deformed with a conical punch show the least damage. This indicates that conical punches can expand holes farther than can other geometries.

While hole expansion tests utilizing hemispherical and flat punches are not standardized techniques, they have been explored in research. Investigations indicate that in these punch geometries, the point of failure occurs slightly removed from the edge. This observation suggests that the edge condition's impact is diminished when employing flat and hemispherical punches.

16.6 CONCLUSION

Understanding the edge formability of sheet metal is crucial for the design and manufacturing of stamped components. Accurate quantification of this property allows for proper material selection and optimization of forming processes, resulting in high-quality end products.

When analyzing edge formability, the cutting process plays a crucial role in maximizing local formability characteristics. The geometry and cutting conditions can influence the hole expansion capability of the material, directly impacting edge formability. Therefore, careful design of preflanging operations is necessary to maximize the deformation properties of sheet edges.

Another important factor to consider is the influence of the microstructural characteristics of each type of steel on hole expansion capability. Variations in chemical composition and heat treatments can significantly alter edge formability, making a detailed analysis of the microstructural properties of the materials used essential. The success of a flanging operation depends on the precise control of factors from the metallurgical properties of the materials to the adopted manufacturing route. In summary, in quantifying edge formability, processing conditions, proper design of the cutting process, analysis of microstructural characteristics, and careful control of involved factors are key to achieving excellence in flanging operations.

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