

FATIGUE AND SIMULATION STUDIES IN REINFORCED-POLYURETHANE-BASED SHEET METAL FORMING DIES

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ABSTRACT

Fatigue in metal forming dies is an important issue in the manufacturing industry. Fatigue failure leads to repair or replacement of the die, which interrupts and slows down the manufacturing process. The proposed work is to analyze fatigue failure of V-bending dies machined from a polyurethane-based tooling. Despite their advantages in lead time and cost reductions, polymer dies for sheet metal forming applications have several drawbacks. Due to their lack of strength as compared to conventional die materials, the use of polymer dies is often limited to prototype or short-run production. The damage analysis of V-bending dies involved the stress-strain analysis of the forming process using the FEA and applying the damage parameters to the materials data to predict die life. To improve the fatigue life of dies the profile of die in stress concentrated areas are to be varied and replaced with some damping materials. The objective of this work is to predict the failure and the life of a polyurethane die and to reduce the stress concentration at the bend radius of the die.

1.INRODUCTION

Sheet metal forming is one of the most commonly practiced fabrication processes in industry. Throughout the years, the sheet metal forming industry experienced technological advances that allowed the production of complex parts. However, the advances in die design and fabrication progressed at a much slower rate, and they still depend heavily on trial-and-error and the experiences of skilled workers. Fatigue in metal forming dies is an important issue in the manufacturing industry.

Fatigue failure leads to repair or replacement of the die, which interrupts and slows down the manufacturing process. Fatigue of bulk metal forming (such as, forging and extrusion) dies has been the focus of most die failure studies because the nature of the process tends to subject the die to high stresses, thus increasing the likelihood of die failure. However, as polymer composite tooling materials are making inroads into rapid tooling technologies, die failure in sheet metal forming, in which the dies are subjected to significantly lower stresses, is drawing attention.

This work focus on the fatigue failure analysis of V-bending dies machined from polyurethane and to improve it by changing the geometry of the die. The mechanical properties of the tooling materials are characterized to identify the underlying failure mechanisms. Various fatigue failure criteria, namely, maximum tensile principal stress, effective stress and critical plane approaches are investigated as die life prediction methods, among which

the latter two approaches were most accurate. Finite element analyses and experiments are performed to verify the results.

1.1 POLYURETHANES

Ever since their discovery by Otto Bayer and co-workers in 1937, polyurethanes have developed as a unique class of materials and have found use in a wide variety of applications. The name polyurethane was derived from ethyl carbonate, also known as urethane. Besides incorporating the urethane linkage, these materials also sometimes contain several other types of linkages such as amide, urea, ether, and ester. The urethane linkage is formed by the reaction of an isocyanate group of one reactant with the alcohol group of another component. By controlling variables such as the functionality, chemical composition, and the molecular weight of the different reactants, a wide class of materials with significantly varying properties can be obtained. This flexibility has led polyurethanes to find use as synthetic polymers in foams, elastomers, coatings, sealants, and adhesive based products. Some of the applications of polyurethanes lie in the automotive, furniture, construction, thermal insulation, and footwear industries. The 2000 urethanes market was estimated to be of the order of 8.2 million metric tons worldwide.

The mechanical properties of urethane allow for excellent resilience, toughness and load bearing capacity. These properties can be specifically controlled through different mixtures of the rubber's ingredients. Urethane also has high resistance to mechanical fatigue, shear, and corrosion, impact and mould contamination.

Unlike any other engineering material, Cast Polyurethanes have an extraordinary combination of physical, mechanical, and environmental properties in the same material. The ratio between the resin and the curative can be varied to optimize some of these properties (though some times at the cost of other properties). So, a properly engineered compound can outlast an identical hardness part by a factor of several times.

In any application, opting for urethane offers number of advantages includes Excellent resilience, Extra toughness and durability, very high load bearing capacity etc.

Urethane casting material is very popular for product prototypes. It can be formulated to imitate elastomers, and can have structural properties similar to high-impact styrene. It can mimic production parts in material properties, thermal properties, colour, and surface texture. It can also be machined, sanded, glued, and painted readily.

1.2 FATIGUE

Fatigue is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. The nominal maximum stress values are less than the ultimate tensile stress limit, and may be below the yield stress limit of the material.

Fatigue occurs when a material is subjected to repeated loading and unloading. If the loads are above a certain threshold, microscopic cracks will begin to form at the stress concentrators such as the surface, persistent slip bands (PSBs), and grain interfaces. Eventually a crack will reach a critical size, and the structure will suddenly fracture. The shape of the structure will significantly affect the fatigue life; square holes or sharp corners will lead to elevated local stresses where fatigue cracks can initiate. Round holes and smooth transitions or fillets are therefore important to increase the fatigue strength of the structure.

ASTM defines fatigue life, N_f , as the number of stress cycles of a specified character that a specimen sustains before failure of a specified nature occurs.

One method to predict fatigue life of materials is the Uniform Material Law (UML). UML was developed for fatigue life prediction of aluminium and titanium alloys by the end of 20th century and extended to high-strength steels and cast iron. For some materials, there is a theoretical value for stress amplitude below which the material will not fail for any number of cycles, called a fatigue limit, endurance limit, or fatigue strength.

1.3 FINITE ELEMENT ANALYSIS

FEA uses a complex system of points called nodes which make a grid called a mesh. This mesh is programmed to contain the material and structural properties which define how the structure will react to certain loading conditions. Nodes are assigned at a certain density throughout the material depending on the anticipated stress levels of a particular area. Regions which will receive large amounts of stress usually have a higher node density than those which experience little or no stress. Points of interest may consist of: fracture point of previously tested material, fillets, corners, complex detail, and high stress areas. The mesh acts like a spider web in that from each node, there extends a mesh element to each of the adjacent nodes. This web of vectors is what carries the material properties to the object, creating many elements.

The FEA method is a Computer Aided Engineering (CAE) technique to determine the behaviour of components under external loads. At first the component is divided into a large number of small pieces (elements) that are connected at their corner points by nodes. Next the finite element approach results in a large number of coupled equations where the unknowns are the degrees of freedom in the nodes. In a mechanical analysis these unknowns are the displacements and rotations. Finally, these nodal unknowns are determined by solving the total system of equations. The FEA method can be used to determine the behavior of a rubber component. However, proper analysis of rubber components requires special material modeling and non-linear finite element analysis tools that are quite different than those used for metallic components. The unique properties of rubber are such that:

- It can undergo large deformations under load, sustaining strains of up to 500% elongation in engineering applications.
- Its load-extension curve shows a markedly non-linear behaviour.
- Its visco-elastic behaviour exhibits significant damping properties, unlike with other materials its behaviour is time- and temperature dependent.
- It is nearly incompressible. This means that its volume does not change appreciably under stress.

II. EXPERIMENTAL

2.1 MATERIAL CHARACTERISATION:

This study deals with a polymer composite tooling material developed for metal forming applications by Swagath Urethane Pvt. Ltd. The material is supplied in the form of a block from which metal forming dies can be machined in a relatively short amount of time. The material has a thermoset polyurethane base. The material has a high hardness of 75 Shore D to increase the overall compressive strength and to improve tribological characteristics.

2.1.1 BASIC MECHANICAL BEHAVIOR

Fundamental mechanical properties of the polyurethane composite were measured from tension, compression, flexure and fatigue tests. Using an UTM of 2 tonne capacity tension, compression, flexure and fatigue tests are done. The measured tensile, compressive, and flexural properties are summarized. The general conclusion that can be drawn from the tests is that the polyurethane composite is not brittle and that little plastic deformation takes place before failure. Table 2.1 shows the various mechanical properties of polyurethane. Figure 2.1 shows the die machined from polyurethane.

Table 2.1 Various mechanical properties of polyurethane

PROPERTY	ASTM	VALUE
Ultimate tensile strength(MPa)	D 638	33.55
Youngs modulus(GPa)	D 638	1.211
Flextural strength(MPa)	D 790	35
Flextural modulus(MPa)	D 790	612.41
Compression strength(MPa)	D 695	72.9
Compression modulus(MPa)	D 695	839.9



Figure 3.1 Die machined from polyurethane

Sheet metal properties:

- ▶ Sheet material 1100-O Al
- ▶ Sheet thickness 1 mm
- ▶ Sheet width 50 mm
- ▶ Ultimate tensile strength 89.6 MPa
- ▶ Youngs modulus 68.9GPa

2.2 FATIGUE ANALYSIS

Fatigue is generally defined as the material failure at low values when it is subjected to cyclic loads. Fatigue is a time dependent phenomenon. The fatigue characters are generally represented as stress versus number of cycles diagram.

The polyurethane composite material whose fatigue strength is to be determined by Fatigue test is machined to a dog-bone shaped specimen according to ASTM-3039 standard, as shown in Figure 2.1.

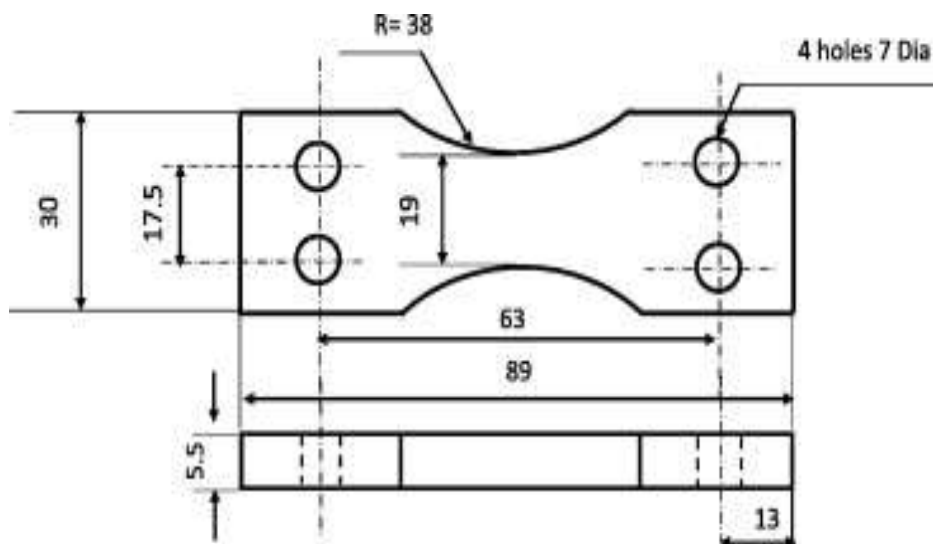


Figure 2.1 ASTM-3039 fatigue test specimen.

The specimen is measured for its thickness and breath using vernier caliper. Then by using the formula bending moment is calculated

$$\text{Bending moment } M = \sigma \times b \times h^2 / 6$$

Where,

σ = stress applied in Pascal (N/m²)

b = lowest breath of the specimen (m)

h = thickness of the specimen (m)

M = bending moment (Nm)

In accordance with the bending moment calculated, corresponding dial gauge reading is noted from the standard graph now the reading is set on the dial gauge by adjusting the eccentric flywheel. The specimen is marked with

some powder to find the initiation of fracture clearly. The specimen is mounted on the fatigue machine the angle of the flywheel is set so that the calculated bending moment can be applied to the specimen. The test setup is shown in figure 2.2. Setup is allowed to run until the fracture initiate in the specimen. The time for fracture initiation is noted and number of cycle is calculated by following formula

$$\text{Number of cycles} = \text{time of fracture} \times \text{motor rpm}$$

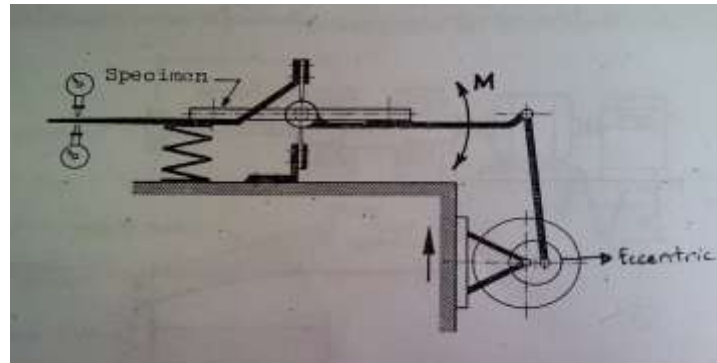


Figure 2.2 Fatigue test setup

2.3 ANALYSIS USING FEA

Finite Element Analysis is a numerical tool where a physical problem is modeled into a mathematical model and that model is solved by Numerical technique. The physical domain under consideration is discretized into sub-domains of finite dimensions known as finite elements that are made up of nodes. The elements are interconnected at a discrete number of nodal points on the boundaries. The appropriate boundary conditions and the loads are applied at the nodes. The element mathematical equation of each element are assembled and solved to get the total global solution.

Characterizing the capability of a material to survive the many cycles a component may experience during its lifetime is the aim of fatigue analysis. In this ANSYS Fatigue Module is used to simulate the fatigue behavior of composite for dynamic behavior.

The boundary conditions for analysis is given below

III.PUNCH PROPERTIES

- ▶ Punch travel distance 12.929 mm
- ▶ Punch speed 120 mm/min
- ▶ Load on punch 994 N

DIE SPECIFICATION

- ▶ Bend radius 5 mm
- ▶ Die shoulder radius 5 mm
- ▶ Die opening 30 mm
- ▶ Die width 100 mm

► Die height 45 mm

IV. RESULT AND DISCUSSION

4.1 FATIGUE RESULTS

For fatigue test the dog-bone shaped specimen according to ASTM-3039 standard is tested in alternating bending fatigue tester. The test input values are shown in table 4.1.

Table 4.1 Fatigue test input values

SAMPLE	BREATH (b) mm	HEIGHT (h) mm	STRESS TO BE APPLIED MPa	BENDING MOMENT (M) Nm	DIAL GAUGE READING
1	18.8	3.3	33	2.0286	281
2	19	3.3	20	1.126	221
3	18.4	3.4	15	0.5172	100
4	18.8	3.2	11	0.3744	63

The fatigue test results for the specimen are shown in table 4.2 and the S-N curve is plotted with the values as shown in figure 4.1.

Table 4.2 Fatigue test result

SAMPLE	STRESS (MPa)	NO OF CYCLES (N)
1	33	0
2	20	41880
3	15	96560
4	11	∞

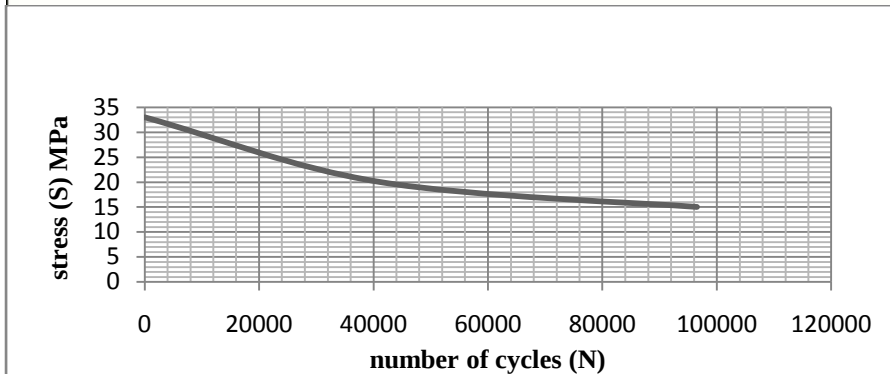


Figure 4.1 S-N curve

4.2 FINITE ELEMENT ANALYSIS

Characterizing the capability of a material to survive the load during the v bending operation is the aim of fatigue analysis. The CAD model of the die is done in SOILDWORKS and it is imported to ANSYS for analysis. Screen shot of simulation is shown in following figures. Figure 4.2 shows the mesh model of the polyurethane die.

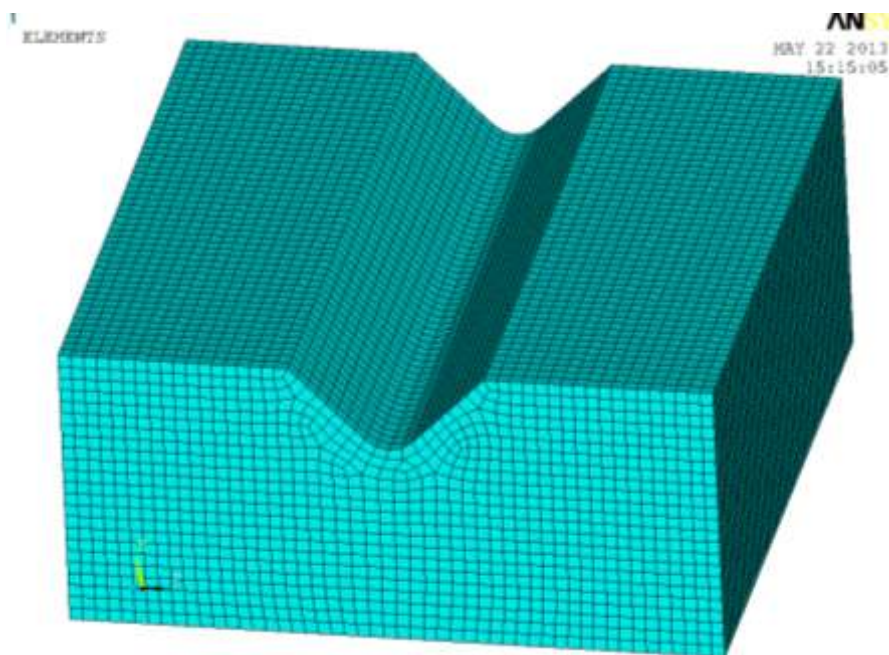


Figure 4.2 Mesh model of die

Total no. of elements : 60384.
Total no. of nodes : 55350

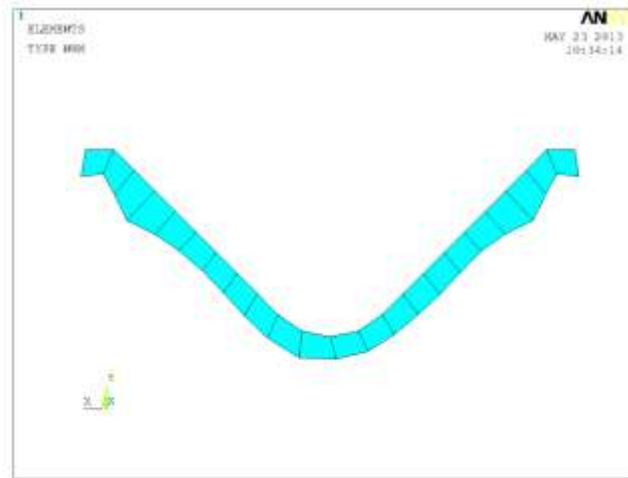


Figure 4.3 Bend radius plot

The bend radius plot of the die is shown in figure 4.3 and the boundary conditions for analysis are shown in figure 4.4.

Total no. of elements in bend radius	:	2346
Total no. of nodes in bend radius	:	1100

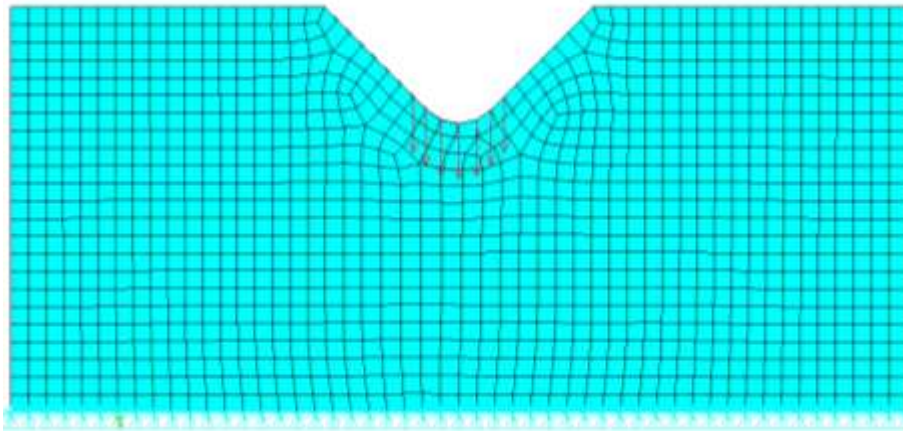


Figure 4.4 Boundary conditions

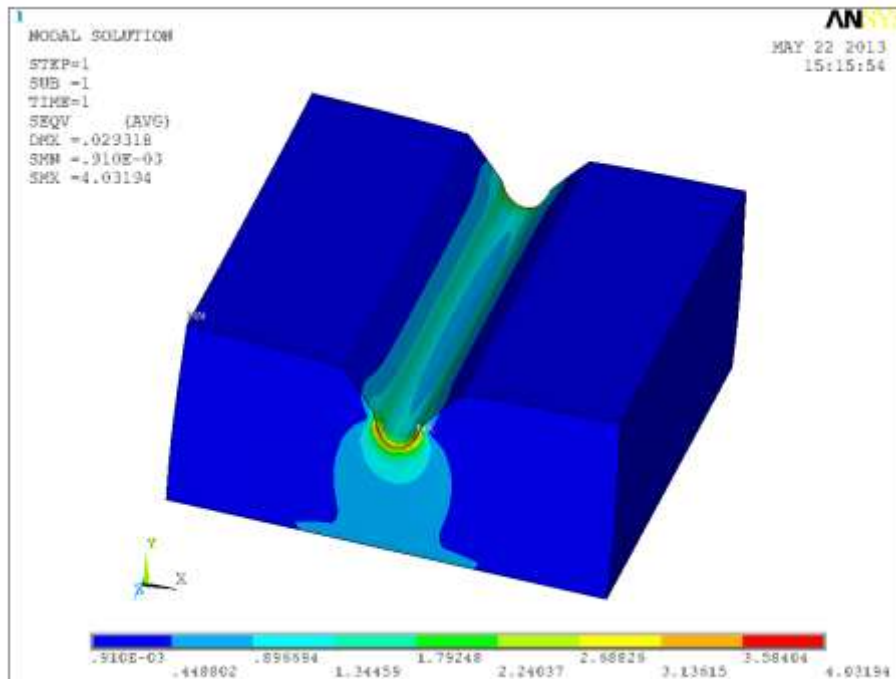


Figure 4.5 Stress plot

Figure 4.5 shows the stress distribution in the die. The maximum stress generated at the bend radius when the punch is at the exact bottom of its stroke is 4.03 Mpa for a maximum load of 994 N.

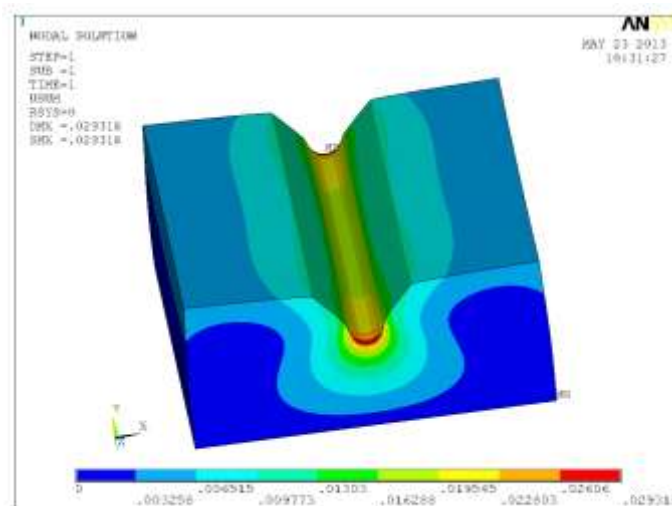


Figure 4.6 Deformation plot

The maximum deformation occurs at the bend radius of the die when the punch is at the exact bottoming position of 12.929mm. Maximum deformation at the bend radius is .0293mm which is negligible during bending operation. The deformation plot is shown in figure 4.6.

The max stress is around 4MPa which is almost three times lesser than the endurance limit of 11MPa. This means the component can perform infinite number of load cycles under controlled loading of 994N.

V. CONCLUSION

In this work, a failure analysis is done to estimate the fatigue life of a 90° V-bending die fabricated from polyurethane board was analyzed. The properties of the tooling material were thoroughly characterized in various aspects, including fatigue behavior. Based on the nature of the tooling material it was found that the low stress-based fatigue approach was appropriate for die life prediction. The damage analysis of V-bending dies involved the stress-strain analysis of the forming process using the FEA and applying the damage parameters to the materials data to predict die life.

A parametric study revealed that punch over-travel is the most significant parameter, followed by bend radius, sheet thickness and strength, and volume of material under the bend radius. These results establish the generic guidelines for V-bending die design for polymer composite tooling materials.

The designed die in this work can perform infinite number of cycles under controlled loading of 994N. The advantages of the die designed from polyurethane are Light Weight (14% of steel tool weight), Less Setup Time - minimal or no shimming, will not damage press bed, more economical than steel dies and noise reduction during bending operation. This type of dies can be used for bending sheets with less thickness or less tensile strength since the polyurethane material has less modulus compared to steel dies.

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