冲压变形

冲压变形工艺可完成多种工序，其基本工序可分为分离工序和变形工序两大类。

分离工序是使坯料的一部分与另一部分相互分离的工艺方法，主要有落料、冲孔、切边、剖切、修整等。其中有以冲孔、落料应用最广。变形工序是使坯料的一部分相对另一部分产生位移而不破裂的工艺方法，主要有拉深、弯曲、局部成形、胀形、翻边、缩径、校形、旋压等。

从本质上看，冲压成形就是毛坯的变形区在外力的作用下产生相应的塑性变形，所以变形区的应力状态和变形性质是决定冲压成形性质的基本因素。因此，根据变形区应力状态和变形特点进行的冲压成形分类，可以把成形性质相同的成形方法概括成同一个类型并进行系统化的研究。

绝大多数冲压成形时毛坯变形区均处于平面应力状态。通常认为在板材表面上不受外力的作用，即使有外力作用，其数值也是较小的，所以可以认为垂直于板面方向的应力为零，使板材毛坯产生塑性变形的是作用于板面方向上相互垂直的两个主应力。由于板厚较小，通常都近似地认为这两个主应力在厚度方向上是均匀分布的。基于这样的分析，可以把各种形式冲压成形中的毛坯变形区的受力状态与变形特点，在平面应力的应力坐标系中(冲压应力图)与相应的两向应变坐标系中(冲压应变图)以应力与应变坐标决定的位置来表示。也就是说，冲压应力图与冲压应变图中的不同位置都代表着不同的受力情况与变形特点

(1)冲压毛坯变形区受两向拉应力作用时，可以分为两种情况：即$\sigma_\gamma>\sigma>0\sigma_t=0$和$\sigma_\theta>\sigma_\gamma>0$，$\sigma_t=0$。再这两种情况下，绝对值最大的应力都是拉应力。以下对这两种情况进行分析。

1)当$\sigma_\gamma>\sigma_\theta>0$且$\sigma_t=0$时，安全量理论可以写出如下应力与应变的关系式：

(1-1) $\varepsilon_\gamma/(\sigma_\gamma-\sigma_m)=\varepsilon_\theta/(\sigma_\theta-\sigma_m)=\varepsilon_t/(\sigma_t-\sigma_m)=k$

式中 ε_γ，ε_θ，ε_t——分别是轴对称冲压成形时的径向主应变、切向主应变和厚度方向上的主应变；

σ_γ，σ_θ，σ_t——分别是轴对称冲压成形时的径向主应力、切向主应力和厚度方向上的主应力；

σ_m——平均应力，$\sigma_m=(\sigma_\gamma+\sigma_\theta+\sigma_t)/3$；

k——常数。在平面应力状态，式（1—1）具有如下形式：

$3\varepsilon_\gamma/(2\sigma_\gamma-\sigma_\theta)=3\varepsilon_\theta/(2\sigma_\theta-\sigma_t)=3\varepsilon_t/[-(\sigma_t+\sigma_\theta)]=k$ （1—2）

因为$\sigma_\gamma>\sigma_\theta>0$，所以必定有$2\sigma_\gamma-\sigma_\theta>0$与$\varepsilon_\theta>0$。这个结果表明：在两向

拉应力的平面应力状态时，如果绝对值最大拉应力是σ_γ，则在这个方向上的主应变一定是正应变，即是伸长变形。

又因为$\sigma_\gamma>\sigma_\theta>0$，所以必定有-（$\sigma_t+\sigma_\theta$）<0 与$\varepsilon_t<0$，即在板料厚度方向上的应变是负的，即为压缩变形，厚度变薄。

在σ_θ方向上的变形取决于σ_γ与σ_θ的数值：当$\sigma_\gamma=2\sigma_\theta$时，$\varepsilon_\theta=0$；当$\sigma_\gamma>2\sigma_\theta$时，$\varepsilon_\theta<0$；当 $\sigma_\gamma<2\sigma_\theta$ 时，$\varepsilon_\theta>0$。

σ_θ 的变化范围是 $\sigma_\gamma>=\sigma_\theta>=0$ 。在双向等拉力状态时，$\sigma_\gamma=\sigma_\theta$，有式（1—2）得 $\varepsilon_\gamma=\varepsilon_\theta>0$ 及 $\varepsilon_t<0$；在受单向拉应力状态时，$\sigma_\theta=0$，有式（2—2）可得，$\varepsilon_\theta=-\varepsilon_\gamma/2$。

根据上面的分析可知，这种变形情况处于冲压应变图中的 AON 范围内（见图 1—1）；而在冲压应力图中则处于 GOH 范围内（见图 1—2）。

(1) 当$\sigma_\theta>\sigma_\gamma>0$且$\sigma_t=0$时，有式（1—2）可知：因为$\sigma_\theta>\sigma_\gamma>0$，所以

1）定有 $2\sigma_\theta>\sigma_\gamma>0$与$\varepsilon_\theta>0$。这个结果表明：对于两向拉应力的平面应力状态，当$\sigma_\theta$的绝对值最大时，则在这个方向上的应变一定时正的，即一定是伸长变形。

又因为$\sigma_\gamma>\sigma_\theta>0$，所以必定有-（$\sigma_t+\sigma_\theta$）<0 与$\varepsilon_t<0$，即在板料厚度方向上的应变是负的，即为压缩变形，厚度变薄。

在σ_θ方向上的变形取决于σ_γ与σ_θ的数值：当$\sigma_\theta=2\sigma_\gamma$时，$\varepsilon_\gamma 0$；当$\sigma_\theta>\sigma_\gamma$，$\varepsilon_\gamma<0$；当 $\sigma_\theta<2\sigma_\gamma$ 时，$\varepsilon_\gamma>0$。

σ_γ的变化范围是 $\sigma_\theta>=\sigma_\gamma>=0$ 。当$\sigma_\gamma=\sigma_\theta$ 时，$\varepsilon_\gamma=\varepsilon_\theta>0$，也就是在双向等拉力状态下，在两个拉应力方向上产生数值相同的伸长变形；在受单向拉应力状态时，当$\sigma_\gamma=0$时，$\varepsilon_\gamma=-\varepsilon_\theta/2$，也就是说，在受单向拉应力状态下其变形性质与一般的简单拉伸是完全一样的。

这种变形与受力情况，处于冲压应变图中的 AOC 范围内（见图 1—1）；而在冲压应力图中则处于 AOH 范围内（见图 1—2）。

上述两种冲压情况，仅在最大应力的方向上不同，而两个应力的性质以及它们引起的变形都是一样的。因此，对于各向同性的均质材料，这两种变形是完全相同的。

(1)冲压毛坯变形区受两向压应力的作用，这种变形也分两种情况分析，即$\sigma_\gamma<\sigma_\theta<$
$\sigma_t=0$和$\sigma_\theta<\sigma_\gamma<0$，$\sigma_t=0$。

1）当$\sigma_\gamma<\sigma_\theta<0$且$\sigma_t=0$时，有式（1—2）可知：因为$\sigma_\gamma<\sigma_\theta<0$，一定有$2\sigma_\gamma-\sigma_\theta<0$ 与$\varepsilon_\gamma<0$。这个结果表明：在两向压应力的平面应力状态时，如果

绝对值最大拉应力是$\sigma_\gamma<0$，则在这个方向上的主应变一定是负应变，即是压缩变形。

又因为$\sigma_\gamma<\sigma_\theta<0$，所以必定有$-(\sigma_t+\sigma_\theta)>0$ 与$\varepsilon_t>0$，即在板料厚度方向上的应变是正的，板料增厚。

在σ_θ方向上的变形取决于σ_γ与σ_θ的数值：当$\sigma_\gamma=2\sigma_\theta$时，$\varepsilon_\theta=0$；当$\sigma_\gamma>2\sigma_\theta$时，$\varepsilon_\theta<0$；当 $\sigma_\gamma<2\sigma_\theta$ 时，$\varepsilon_\theta>0$。

这时σ_θ 的变化范围是 σ_γ与 0 之间 。当$\sigma_\gamma=\sigma_\theta$时，是双向等压力状态时，故有 $\varepsilon_\gamma=\varepsilon_\theta<0$；当$\sigma_\theta=0$ 时，是受单向压应力状态，所以$\varepsilon_\theta=-\varepsilon_\gamma/2$。这种变形情况处于冲压应变图中的 EOG 范围内（见图 1—1）；而在冲压应力图中则处于 COD 范围内（见图 1—2）。

2) 当$\sigma_\theta<\sigma_\gamma<0$且$\sigma_t=0$ 时，有式（1—2）可知：因为$\sigma_\theta<\sigma_\gamma<0$，所以一定有 $2\sigma_\theta\sigma_\gamma<0$ 与$\varepsilon_\theta<0$。这个结果表明：对于两向压应力的平面应力状态，如果绝对值最大是σ_θ，则在这个方向上的应变一定时负的，即一定是压缩变形。

又因为$\sigma_\gamma<\sigma_\theta<0$，所以必定有$-(\sigma_t+\sigma_\theta)>0$ 与$\varepsilon_t>0$，即在板料厚度方向上的应变是正的，即为压缩变形，板厚增大。

在σ_θ方向上的变形取决于σ_γ与σ_θ的数值：当$\sigma_\theta=2\sigma_\gamma$时，$\varepsilon_\gamma=0$；当$\sigma_\theta>2\sigma_\gamma$，$\varepsilon_\gamma<0$；当 $\sigma_\theta<2\sigma_\gamma$ 时，$\varepsilon_\gamma>0$。

这时，σ_γ的数值只能在$\sigma_\theta<=\sigma_\gamma<=0$ 之间变化。当$\sigma_\gamma=\sigma_\theta$ 时，是双向等压力状态，所以$\varepsilon_\gamma=\varepsilon_\theta<0$；当$\sigma_\gamma=0$ 时，是受单向压应力状态，所以有$\varepsilon_\gamma=-\varepsilon_\theta/2>0$。这种变形与受力情况，处于冲压应变图中的 GOL 范围内（见图 1—1）；而在冲压应力图中则处于 DOE 范围内（见图 1—2）。

(1)冲压毛坯变形区受两个异号应力的作用，而且拉应力的绝对值大于压应力的绝对值。这种变形共有两种情况，分别作如下分析。

1）当$\sigma_\gamma>0$，$\sigma_\theta<0$及$|\sigma_\gamma|>|\sigma_\theta|$时，由式（1—2）可知：因为$\sigma_\gamma>0$，$\sigma_\theta<0$ 及$|\sigma_\gamma|>|\sigma_\theta|$，所以一定有 $2\sigma_\gamma-\sigma_\theta>0$ 及$\varepsilon_\gamma>0$。这个结果表明：在异号的平面应力状态时，如果绝对值最大应力是拉应力，则在这个绝对值最大的拉应力方向上应变一定是正应变，即是伸长变形。

又因为$\sigma_\gamma>0$，$\sigma_\theta<0$及$|\sigma_\gamma|>|\sigma_\theta|$，所以必定有$\varepsilon_\theta<0$，即在板料厚度方向上的应变是负的，是压缩变形。

这时σ_θ 的变化范围只能在$\sigma_\theta=-\sigma_\gamma$与$\sigma_\theta=0$ 的范围内 。当$\sigma_\theta=-\sigma_\gamma$时，$\varepsilon_\gamma>0\varepsilon_\theta<0$ 且$|\varepsilon_\gamma|=|\varepsilon_\theta|$；当$\sigma_\theta=0$ 时，$\varepsilon_\gamma>0$，$\varepsilon_\theta<0$，而且$\varepsilon_\theta=-\varepsilon_\gamma/2$，这是

受单向拉的应力状态。这种变形情况处于冲压应变图中的 MON 范围内（见图1—1）；而在冲压应力图中则处于 FOG 范围内（见图 1—2）。

2）当$\sigma_\theta>0$，$\sigma_\gamma<0$，$\sigma_t=0$ 及$|\sigma_\theta|>|\sigma_\gamma|$时，由式（1—2）可知：用与前项相同的方法分析可得$\varepsilon_\theta>0$。即在异号应力作用的平面应力状态下，如果绝对值最大应力是拉应力σ_θ，则在这个方向上的应变是正的，是伸长变形；而在压应力σ_γ方向上的应变是负的（$\varepsilon_\gamma<=0$），是压缩变形。

这时σ_γ 的变化范围只能在$\sigma_\gamma=-\sigma_\theta$与$\sigma_\gamma=0$ 的范围内 。当$\sigma_\gamma=-\sigma_\theta$时，$\varepsilon_\theta>0$，$\varepsilon_\gamma<0$ 且$|\varepsilon_\gamma|=|\varepsilon_\theta|$；当$\sigma_\gamma=0$ 时，$\varepsilon_\theta>0$，$\varepsilon_\gamma<0$，而且$\varepsilon_\gamma=-\varepsilon_\theta/2$。这种变形情况处于冲压应变图中的 COD 范围内（见图 1—1）；而在冲压应力图中则处于 AOB 范围内（见图 1—2）。

虽然这两种情况的表示方法不同，但从变形的本质看是一样的。

(1)冲压毛坯变形区受两个方向上的异号应力的作用，而且压应力的绝对值大于拉应力的绝对值。以下对这种变形的两种情况分别进行分析。

1）当$\sigma_\gamma>0$，$\sigma_\theta<0$ 而且$|\sigma_\theta|>|\sigma_\gamma|$时，由式（1—2）可知：因为$\sigma_\gamma>0$，$\sigma_\theta<0$ 及$|\sigma_\theta|>|\sigma_\gamma|$，所以一定有 $2\sigma_\theta-\sigma_\gamma<0$ 及$\varepsilon_\theta<0$。这个结果表明：在异号的平面应力状态时，如果绝对值最大应力是压应力σ_θ，则在这个方向上应变是负的，即是压缩变形。

又因为$\sigma_\gamma>0$，$\sigma_\theta<0$，必定有 $2\sigma_\gamma-\sigma_\theta<0$ 及$\varepsilon_\gamma>0$，即在拉应力方向上的应变是正的，是伸长变形。

这时σ_γ的变化范围只能在$\sigma_\gamma=-\sigma_\theta$与$\sigma_\gamma=0$ 的范围内 。当$\sigma_\gamma=-\sigma_\theta$时，$\varepsilon_\gamma>0\varepsilon_\theta<0$ 且$\varepsilon_\gamma=-\varepsilon_\theta$；当$\sigma_\gamma=0$ 时，$\varepsilon_\gamma>0$，$\varepsilon_\theta<0$，而且$\varepsilon_\gamma=-\varepsilon_\theta/2$。这种变形情况处于冲压应变图中的 DOF 范围内（见图 1—1）；而在冲压应力图中则处于 BOC 范围内（见图 1—2）。

2）当$\sigma_\theta>0$，$\sigma_\gamma<0$，$\sigma_t=0$ 及$|\sigma_\gamma|>|\sigma_\theta|$时，由式（1—2）可知：用与前项相同的方法分析可得$\varepsilon_\gamma<\sigma_\gamma 0$。即在异号应力作用的平面应力状态下，如果绝对值最大应力是压应力σ_γ，则在这个方向上的应变是负的，是压缩变形；而在拉应力σ_θ方向上的应变是正的，是伸长变形。

这时σ_θ 的数值只能介于$\sigma_\theta=-\sigma_\gamma$与$\sigma_\theta=0$ 的范围内 。当$\sigma_\theta=-\sigma_\gamma$时，$\varepsilon_\theta>0$，$\varepsilon_\gamma<0$ 且$\varepsilon_\theta=-\varepsilon_\gamma$；当$\sigma_\theta=0$ 时，$\varepsilon_\theta>0$，$\varepsilon_\gamma<0$，而且$\varepsilon_\theta=-\varepsilon_\gamma/2$。这种变形情况处于冲压应变图中的 DOE 范围内（见图 1—1）；而在冲压应力图中则处于 BOC 范围内（见图 1—2）。

这四种变形与相应的冲压成形方法之间是相对的，它们之间的对应关系，

用文字标注在图 1—1 与图 1—2 上。

上述分析的四种变形情况，相当于所有的平面应力状态，也就是说这四种变形情况可以把全部的冲压变形毫无遗漏地概括为两大类别，即伸长类与压缩类。

当作用于冲压毛坯变形区内的拉应力的绝对值最大时，在这个方向上的变形一定是伸长变形，称这种变形为伸长类变形。根据上述分析，伸长类变形在冲压应变图中占有五个区间，即 MON、AON、AOB、BOC 及 COD；而在冲压应力图中则占有四个区间 FOG、GOH、AOH 及 AOB。

当作用于冲压毛坯变形区内的压应力的绝对值最大时，在这个方向上的变形一定是压缩变形，称这种变形为压缩类变形。根据上述分析，压缩类变形在冲压应变图中占有五个区间，即 LOM、HOL、GOH、FOG 与 DOF；而在冲压应力图中则占有四个区间 EOF、DOE、COD、BOC。

MD 与 FB 分别是冲压应变图与冲压应力图中两类变形的分界线。分界线的右上方是伸长类变形，而分界线的左下方是压缩变形。

由于塑性变形过程中材料所受的应力和由此应力所引起的应变之间存在着相互对应的关系,所以冲压应力图与冲压应变图也一定存在着一定的对应关系。每一个冲压变形都可以在冲压应力图上和冲压应变图上找到它固定的位置。根据冲压毛坯变形区内的应力状态或变形情况，利用冲压变形图或冲压应力图中的分界线（MD 或 FB）就可以容易地判断该冲压变形的性质与特点。

概括以上分析结果，把各种应力状态在冲压应变图和冲压应力图中所处的位置以及两个图的对应关系列于表 1—1。从表 1—1 中的关系可知，冲压应力图与冲压应变图中各区间所处的几何位置并不一样，但它们在两个图中的顺序是相同的。最重要是一点是：伸长类与压缩类变形的分界线，在两个图里都是与坐标轴成 45°角的一条斜线。表 1—2 中列出了伸长类变形与压缩类变形在冲压成形工艺方面的特点。

从表 1—2 可以清楚地看出，由于每一类别的冲压成形方法，其毛坯变形区的受力与变形特点相同，而与变形有关的一些规律也都是一样的，所以有可能在对各种具体的冲压成形方法进行研究之外，开展综合性的体系化研究工作。体系化研究方法的特点是对每一类别冲压成形方法的共性规律进行研究工作，体系化研究的结果对每一个属于该类别的成形方法都是适用的。这种体系化的研究工作，在板材冲压性能、冲压成形极限等方面，已有一定程度的开展。应用体系化方法研究冲压成形极限的内容可用图 1—3 予以说明。

表 1—1　冲压应力状态与冲压变形状态的对照

应力状态		冲压应变图中位置	冲压应变图中位置	在绝对值最大的应力方向上		变形类别
				应力	应变	
双向受拉 $\sigma_\theta>0,\sigma_\gamma>0$	$\sigma_\gamma > \sigma_\theta$	AON	GOH	+	+	伸长类
	$\sigma_\theta>\sigma_\gamma$	AOC	AOH	+	+	伸长类
双向受压 $\sigma_\theta<0,\sigma_\gamma<0$	$\sigma_\gamma < \sigma_\theta$	EOG	COD	—	—	压缩类
	$\sigma_\theta<\sigma_\gamma$	GOL	DOE	—	—	压缩类
异号应力 $\sigma_\gamma>0,\sigma_\theta<0$	$\lvert\sigma_\gamma\rvert>\lvert\sigma_\theta\rvert$	MON	FOG	+	+	伸长类
	$\lvert\sigma_\theta\rvert>\lvert\sigma_\gamma\rvert$	LOM	EOF	—	—	压缩类
异号应力 $\sigma_\theta>0,\sigma_\gamma<0$	$\lvert\sigma_\theta\rvert>\lvert\sigma_\gamma\rvert$	COD	AOB	+	+	伸长类
	$\lvert\sigma_\gamma\rvert> \lvert\sigma_\theta\rvert$	DOE	BOC	—	—	压缩类

表 1—2　伸长类成形与压缩类成形的对比

项目	伸长类成形	压缩类成形

变形区质量问题的表现形式	变形程度过大引起变形区产生破裂现象	压力作用下失稳起皱
成形极限	1．主要取决于板材的塑性，与厚度无关 2．可用伸长率及成形极限 DLF 判断	1．主要取决于传力区的承载能力 2．取决于抗失稳能力 3．与板厚有关
变形区板厚的变化	减薄	增厚
提高成形极限的方法	1．改善板材塑性 2．使变形均匀化，降低局部变形程度 3．工序间热处理	1．采用多道工序成形 2．改变传力区与变形区的力学关系 3．采用防起皱措施

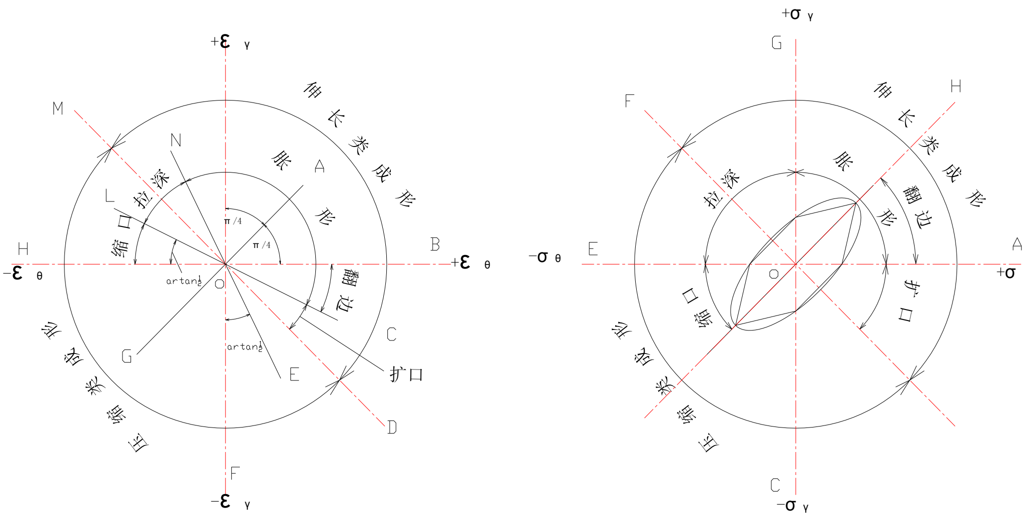


图 1—3 冲压应变图

图 1—3　　体系化研究方法举例

Categories of stamping forming

Many deformation processes can be done by stamping, the basic processes of the stamping can be divided into two kinds: cutting and forming.

Cutting is a shearing process that one part of the blank is cut form the other .It mainly includes blanking, punching, trimming, parting and shaving, where punching and blanking are the most widely used. Forming is a process that one part of the blank has some displacement form the other. It mainly includes deep drawing, bending, local forming, bulging, flanging, necking, sizing and spinning.

In substance, stamping forming is such that the plastic deformation occurs in the deformation zone of the stamping blank caused by the external force. The stress state and deformation characteristic of the deformation zone are the basic factors to decide the properties of the stamping forming. Based on the stress state and deformation characteristics of the deformation zone, the forming methods can be divided into several categories with the same forming properties and to be studied systematically.

The deformation zone in almost all types of stamping forming is in the plane stress state. Usually there is no force or only small force applied on the blank surface. When it is assumed that the stress perpendicular to the blank surface equal to zero, two principal stresses perpendicular to each other and act on the blank surface produce the plastic deformation of the material. Due to the small thickness of the blank, it is assumed approximately that the two principal stresses distribute uniformly along the thickness direction. Based on this analysis, the stress state and the deformation characteristics of the deformation zone in all kind of stamping forming can be denoted by the point in the coordinates of the plane principal stress(diagram of the stamping stress) and the coordinates of the corresponding plane principal stains (diagram of the stamping strain). The different points in the figures of the stamping stress and strain possess different stress state and deformation characteristics.

(1)When the deformation zone of the stamping blank is subjected toplanetensile stresses, it can be divided into two cases, that is $\sigma_\gamma>\sigma_\theta>0,\sigma_t=0and\sigma_\theta>\sigma_\gamma>0,\sigma_t=0$.In both cases, the stress with the maximum absolute value is always a tensile stress. These two cases are analyzed respectively as follows.

2)In the case that $\sigma_\gamma>\sigma_\theta>0and\sigma_t=0$, according to the integral theory, the relationships between stresses and strains are:

$$\varepsilon_\gamma/(\sigma_\gamma-\sigma_m)=\varepsilon_\theta/(\sigma_\theta-\sigma_m)=\varepsilon_t/(\sigma_t-\sigma_m)=k \qquad 1.1$$

where, ε_γ, ε_θ, ε_t are the principal strains of the radial, tangential and thickness directions of the axial symmetrical stamping forming; σ_γ, $\sigma_\theta$and $\sigma_t$are the principal stresses of the radial, tangential and thickness directions of the axial symmetrical stamping forming;σ_m is the average stress,$\sigma_m=(\sigma_\gamma+\sigma_\theta+\sigma_t)/3$; k is a constant.

In plane stress state, Equation 1.1

$$3\varepsilon_\gamma/(2\sigma_\gamma-\sigma_\theta)=3\varepsilon_\theta/(2\sigma_\theta-\sigma_t)=3\varepsilon_t/[-(\sigma_t+\sigma_\theta)]=k \quad 1.2$$

Since $\sigma_\gamma>\sigma_\theta>0$,so $2\sigma_\gamma-\sigma_\theta>0$ and $\varepsilon_\theta>0$.It indicates that in plane stress state with two axial tensile stresses, if the tensile stress with the maximum absolute value is σ_γ, the principal strain in this direction must be positive, that is, the deformation belongs to tensile forming.

In addition, because $\sigma_\gamma>\sigma_\theta>0$，therefore -（$\sigma_t+\sigma_\theta$）<0 and $\varepsilon_t<0$. The strain in the thickness direction of the blankε_t is negative, that is, the deformation belongs to compressive forming, and the thickness decreases.

The deformation condition in the tangential direction depends on the values ofσ_γ and σ_θ. When $\sigma_\gamma=2\sigma_\theta$,$\varepsilon_\theta=0$； when $\sigma_\gamma>2\sigma_\theta$,$\varepsilon_\theta<0$； and when $\sigma_\gamma<2\sigma_\theta$,$\varepsilon_\theta>0$.

The range of σ_θ is $\sigma_\gamma>=\sigma_\theta>=0$. In the equibiaxial tensile stress state $\sigma_\gamma=\sigma_\theta$ ，according to Equation 1.2,$\varepsilon_\gamma=\varepsilon_\theta>0$ and $\varepsilon_t<0$. In the uniaxial tensile stress state$\sigma_\theta=0$，according to Equation 1.2 $\varepsilon_\theta=-\varepsilon_\gamma/2$.

According to above analysis, it is known that this kind of deformation condition is in the region AON of the diagram of the diagram of the stamping strain (see Fig .1.1), and in the region GOH of the diagram of the stamping stress (see Fig.1.2).

2)When $\sigma_\theta>\sigma_\gamma>0$ and $\sigma_t=0$, according to Equation 1.2 , $2\sigma_\theta>\sigma_\gamma>0$ and $\varepsilon_\theta>0$,This result shows that for the plane stress state with two tensile stresses, when the absoluste value of σ_θ is the strain in this direction must be positive, that is, it must be in the state of tensile forming.

Also because$\sigma_\gamma>\sigma_\theta>0$，therefore -（$\sigma_t+\sigma_\theta$）<0 and $\varepsilon_t<0$. The strain in the thickness direction of the blankε_t is negative, or in the state of compressive forming, and the thickness decreases.

The deformation condition in the radial direction depends on the values ofσ_γ and σ_θ. When $\sigma_\theta=2\sigma_\gamma$,$\varepsilon_\gamma 0$;when $\sigma_\theta>\sigma_\gamma$,$\varepsilon_\gamma<0$;and when $\sigma_\theta<2\sigma_\gamma$,$\varepsilon_\gamma>0$.

The range of σ_γ is $\sigma_\theta >= \sigma_\gamma >= 0$ .When $\sigma_\gamma=\sigma_\theta, \varepsilon_\gamma=\varepsilon_\theta>0$, that is, in equibiaxial tensile stress state, the tensile deformation with the same values occurs in the two tensile stress directions; when $\sigma_\gamma=0$, $\varepsilon_\gamma=-\varepsilon_\theta /2$, that is, in uniaxial tensile stress state, the deformation characteristic in this case is the same as that of the ordinary uniaxial tensile.

This kind of deformation is in the region AON of the diagram of the stamping strain (see Fig.1.1), and in the region GOH of the diagram of the stamping stress (see Fig.1.2).

Between above two cases of stamping deformation, the properties of$\sigma_\theta$andσ_γ, and the deformation caused by them are the same, only the direction of the maximum stress is different. These two deformations are same for isotropic homogeneous material.

(1)When the deformation zone of stamping blank is subjected to two compressive stresses$\sigma_\gamma$andσ_θ($\sigma_t=0$), it can also be divided into two cases, which are $\sigma_\gamma<\sigma_\theta<0, \sigma_t=0$ and $\sigma_\theta<\sigma_\gamma <0, \sigma_t=0$.

1）When $\sigma_\gamma<\sigma_\theta<0$ and $\sigma_t=0$, according to Equation 1.2,　$2\sigma_\gamma-\sigma_\theta<0$ 与 $\varepsilon_\gamma=0$.This result shows that in the plane stress state with two compressive stresses, if the stress with the maximum absolute value is $\sigma_\gamma<0$, the strain in this direction must be negative, that is, in the state of compressive forming.

Also because $\sigma_\gamma<\sigma_\theta<0$, therefore -（$\sigma_t +\sigma_\theta$）>0 and $\varepsilon_t>0$.The strain in the thickness direction of the blankε_t is positive, and the thickness increases.

The deformation condition in the tangential direction depends on the values ofσ_γ and σ_θ.When $\sigma_\gamma=2\sigma_\theta$,$\varepsilon_\theta=0$;when $\sigma_\gamma>2\sigma_\theta$,$\varepsilon_\theta<0$;and when $\sigma_\gamma<2\sigma_\theta$,$\varepsilon_\theta>0$.

The range of σ_θ is $\sigma_\gamma<\sigma_\theta<0$.When $\sigma_\gamma=\sigma_\theta$,it is in equibiaxial tensile stress state, hence$\varepsilon_\gamma=\varepsilon_\theta<0$; when $\sigma_\theta=0$,it is in uniaxial tensile stress state, hence $\varepsilon_\theta=-\varepsilon_\gamma/2$.This kind of deformation condition is in the region EOG of the diagram of the stamping strain (see Fig.1.1), and in the region COD of the diagram of the stamping stress (see Fig.1.2).

2）When $\sigma_\theta<\sigma_\gamma<0$and $\sigma_t=0$, according to Equation 1.2,$2\sigma_\theta-\sigma_\gamma<0$ and $\varepsilon_\theta<0$. This result shows that in the plane stress state with two compressive stresses, if the stress with the maximum absolute value is σ_θ, the strain in this direction must be negative, that is, in the state of compressive forming.

Also because$\sigma_\theta<\sigma_\gamma<0$, therefore $-(\sigma_t+\sigma_\theta)>0$ and $\varepsilon_t>0$.The strain in the thickness direction of the blankε_t is positive, and the thickness increases.

The deformation condition in the radial direction depends on the values ofσ_γ and σ_θ. When $\sigma_\theta=2\sigma_\gamma$, $\varepsilon_\gamma=0$; when $\sigma_\theta>2\sigma_\gamma$,$\varepsilon_\gamma<0$; and when $\sigma_\theta<2\sigma_\gamma$,$\varepsilon_\gamma>0$.

The range of σ_γ is $\sigma_\theta<=\sigma_\gamma<=0$. When $\sigma_\gamma=\sigma_\theta$, it is in equibiaxial tensile stress state, hence $\varepsilon_\gamma=\varepsilon_\theta<0$; when $\sigma_\gamma=0$, it is in uniaxial tensile stress state, hence $\varepsilon_\gamma=-\varepsilon_\theta/2>0$.This kind of deformation is in the region GOL of the diagram of the stamping strain (see Fig.1.1), and in the region DOE of the diagram of the stamping stress (see Fig.1.2).

(3) The deformation zone of the stamping blank is subjected to two stresses with opposite signs, and the absolute value of the tensile stress is larger than that of the compressive stress. There exist two cases to be analyzed as follow:

1)When $\sigma_\gamma>0$, $\sigma_\theta<0$ and $|\sigma_\gamma|>|\sigma_\theta|$, according to Equation 1.2, $2\sigma_\gamma-\sigma_\theta>0$ and $\varepsilon_\gamma>0$.This result shows that in the plane stress state with opposite signs, if the stress with the maximum absolute value is tensile, the strain in the maximum stress direction is positive, that is, in the state of tensile forming.

Also because $\sigma_\gamma>0$, $\sigma_\theta<0$ and $|\sigma_\gamma|>|\sigma_\theta|$, therefore $\varepsilon_\theta<0$. The strain in the compressive stress direction is negative, that is, in the state of compressive forming.

The range of σ_θ is $0>=\sigma_\theta>=-\sigma_\gamma$. When $\sigma_\theta=-\sigma_\gamma$, then $\varepsilon_\gamma>0,\varepsilon_\theta<0$, and $|\varepsilon_\gamma|=|\varepsilon_\theta|$;when $\sigma_\theta=0$, then $\varepsilon_\gamma>0,\varepsilon_\theta<0$, and $\varepsilon_\theta=-\varepsilon_\gamma/2$, it is the uniaxial tensile stress state. This kind of deformation condition is in the region MON of the diagram of the stamping strain (see Fig.1.1), and in the region FOG of the diagram of the stamping stress (see Fig.1.2).

2)When $\sigma_\theta>0$, $\sigma_\gamma <0,\sigma_t=0$ and $|\sigma_\theta|>|\sigma_\gamma|$, according to Equation 1.2, by means of the same analysis mentioned above, $\varepsilon_\theta>0$, that is, the deformation zone is in the plane stress state with opposite signs. If the stress with the maximum absolute value is tensile stress σ_θ, the strain in this direction is positive, that is, in the state of tensile forming. The strain in the radial direction is negative （$\varepsilon_\gamma<=0$）, that is, in the state of compressive forming.

The range of σ_γ is $0>=\sigma_\gamma>=-\sigma_\theta$. When $\sigma_\gamma=-\sigma_\theta$, then $\varepsilon_\theta>0,\varepsilon_\gamma <0$ and $|\varepsilon_\gamma|=|\varepsilon_\theta|$; when $\sigma_\gamma=0$, then $\varepsilon_\theta>0,\varepsilon_\gamma <0$, and$\varepsilon_\gamma=-\varepsilon_\theta /2$. This kind of deformation condition is in the region COD of the diagram of the stamping strain (see Fig.1.1), and in the region AOB of the diagram of the stamping stress (see Fig.1.2).

Although the expressions of these two cases are different, their deformation essences are the same.

(4) The deformation zone of the stamping blank is subjected to two stresses with opposite signs, and the absolute value of the compressive stress is larger than that of the tensile stress. There exist two cases to be analyzed as follows:

1)When $\sigma_\gamma>0,\sigma_\theta<0$ and $|\sigma_\theta|>|\sigma_\gamma|$, according to Equation 1.2, $2\sigma_\theta-\sigma_\gamma<0$ and $\varepsilon_\theta<0$.This result shows that in plane stress state with opposite signs, if the stress with the maximum absolute value is compressive stress σ_θ, the strain in this direction is negative, or in the state of compressive forming.

Also because $\sigma_\gamma>0$ and $\sigma_\theta<0$, therefore $2\sigma_\gamma-\sigma_\theta<0$ and $\varepsilon_\gamma>0$. The strain in the tensile stress direction is positive, or in the state of tensile forming.

The range of $\sigma_\gamma$is $0>=\sigma_\gamma>=-\sigma_\theta$.When $\sigma_\gamma=-\sigma_\theta$, then $\varepsilon_\gamma>0,\varepsilon_\theta<0$, and $\varepsilon_\gamma=-\varepsilon_\theta$;when $\sigma_\gamma=0$, then $\varepsilon_\gamma>0,\varepsilon_\theta<0$, and $\varepsilon_\gamma=-\varepsilon_\theta/2$. This kind of deformation is in the region LOM of the diagram of the stamping strain (see Fig.1.1), and in the region EOF of the diagram of the stamping stress (see Fig.1.2).

2)When $\sigma_\theta>0$, $\sigma_\gamma<0$ and $|\sigma_\gamma|>|\sigma_\theta|$, according to Equation 1.2 and by means of the same analysis mentioned above,$\varepsilon_\gamma<0$.This result shows that in plane stress state with opposite signs, if the stress with the maximum absolute value is compressive stress σ_γ,the strain in this direction is negative, or in the state of compressive forming, The strain in the tensile stress direction is positive, or in the state of tensile forming.

The range of σ_θ is $0>=\sigma_\theta>=-\sigma_\gamma$.When $\sigma_\theta=-\sigma_\gamma$, then $\varepsilon_\theta>0,\varepsilon_\gamma<0$, and $\varepsilon_\theta=-\varepsilon_\gamma$;when $\sigma_\theta=0$, then $\varepsilon_\theta>0,\varepsilon_\gamma<0$, and $\varepsilon_\theta=-\varepsilon_\gamma/2$. Such deformation is in the region DOF of the diagram of the stamping strain (see Fig.1.1), and in the region BOC of the diagram of the stamping stress (see Fig.1.2).

The four deformation conditions are related to the corresponding stamping forming methods. Their relationships are labeled with letters in Fig.1.1 and Fig.1.2.

The four deformation conditions analyzed above are applicable to all kinds of plane stress states, that is, the four deformation conditions can sum up all kinds of stamping forming in to two types, tensile and compressive. When the stress with the maximum absolute value in the deformation zone of the stamping blank is tensile, the deformation along this stress direction must be tensile. Such stamping deformation is called tensile forming. Based on above analysis, the tensile forming occupies five regions MON, AON, AOB, BOC and COD in the diagram of the stamping stain; and four regions FOG, GOH, AOH and AOB in the diagram of the stamping stress.

When the stress with the maximum absolute value in the deformation zone of the stamping blank is compressive, the deformation along this stress direction must be compressive. Such stamping deformation is called compressive forming. Based on above analysis, the compressive forming occupies five regions LOM, HOL, GOH, FOG and DOF in the diagram of the stamping strain; and four regions EOF, DOE, COD and BOC in the diagram of the stamping stress.

MD and FB are the boundaries of the two types of forming in the diagrams of the stamping strain and stress respectively. The tensile forming is located in the top right of the boundary, and the compressive forming is located in the bottom left of the boundary.

Because the stress produced by the plastic deformation of the material is related to the strain caused by the stress, there also exist certain relationships between the diagrams of the stamping stress and strain. There are corresponding locations in the diagrams of the stamping stress and strain for every stamping deformation. According to the state of stress or strain in the deformation zone of the forming blank, and using the boundary line in the diagram of the stamping stress MD or the boundary line in the diagram of the stamping strain FB, it is easy to know the properties and characteristics of the stamping forming.

The locations in the diagrams of the stamping stress and strain for various stress states and the corresponding relationships of the two diagrams are listed in Table 1.1.It shows that the geometrical location for every region are different in the diagrams of the stamping stress and strain, but their sequences in the two diagrams are the same. One key point is that the boundary line between the tensile and the compressive forming is an inclined line at 45°to the coordinate axis. The characteristics of the stamping technique for tensile and compressive forming are listed in Table 1.2.

Table 1.2 clearly shows that in the deformation zone of the blank, the characteristics of the force and deformation, and the patterns relevant to the deformation for each stamping method are the same. Therefore, in addition to the research on the detail stamping method, it is feasible to study stamping systematically and comprehensively. The characteristic of the systematic research is to study the common principle of all different types of stamping methods. The results of the systematic research are applicable to all stamping methods. The research on the properties and limit of the sheet metal stamping has been carried out in certain extent. The contents of the research on the stamping forming limit by using systematic method are shown in Fig.1.3.

Table 1.1 Comparison between states of stress and strain in stamping

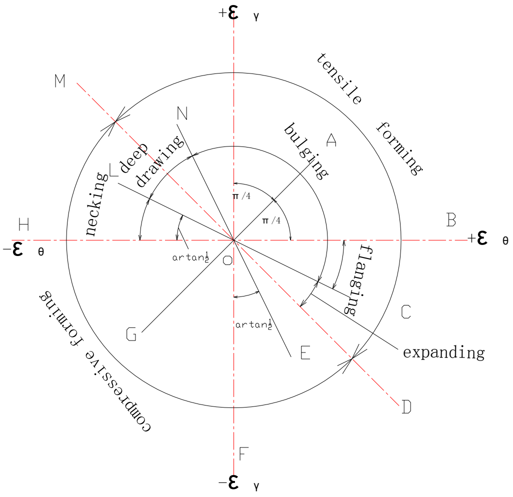
State of stress		Location in the diagram of the stamping strain	Location in the diagram of the stamping stress	Stress	Strain	Types of deformation
Biaxial tensile stress state $\sigma_\theta>0,\sigma_\gamma>0$	$\sigma_\gamma > \sigma_\theta$	AON	GOH	+	+	Tensile
	$\sigma_\theta>\sigma_\gamma$	AOC	AOH	+	+	Tensile
Biaxial compressive stress state $\sigma_\theta<0,\sigma_\gamma<0$	$\sigma_\gamma < \sigma_\theta$	EOG	COD	—	—	Compressive
	$\sigma_\theta<\sigma_\gamma$	GOL	DOE	—	—	Compressive
State of stress with opposite signs $\sigma_\gamma>0,\sigma_\theta<0$	$\lvert\sigma_\gamma\rvert>\lvert\sigma_\theta\rvert$	MON	FOG	+	+	Tensile
	$\lvert\sigma_\theta\rvert>\lvert\sigma_\gamma\rvert$	LOM	EOF	—	—	Compressive
State of stress with opposite signs $\sigma_\theta>0,\sigma_\gamma<0$	$\lvert\sigma_\theta\rvert>\lvert\sigma_\gamma\rvert$	COD	AOB	+	+	Tensile
	$\lvert\sigma_\gamma\rvert> \lvert\sigma_\theta\rvert$	DOE	BOC	—	—	Compressive

Table 1.2 Comparison between tensile and compressive forming

Item	Tensile forming	Compressive forming
Representation of the quality problem in the deformation zone	Fracture in the deformation zone due to excessive deformation	Instability wrinkle caused by compressive stress
Forming limit	3. Mainly depends on the plasticity of the material, and is irrelevant to the thickness 4. Can be estimated by extensibility or the forming limit DLF	4. Mainly depends on the loading capability in the force transferring zone 5. Depends on the anti-instability capability 6. Has certain relationship to the blank thickness
Variation of the blank thickness in the deformation zone	Thinning	Thickening
Methods to improve forming limit	4. Improve the plasticity of the material 5. Decrease local	4. Adopt multi-pass forming process 5. Change the mechanics

	deformation, and increase deformation uniformity 6. Adopt an intermediate heat treatment process	relationship between the force transferring and deformation zones 6. Adopt anti-wrinkle measures

Fig.1.1 Diagram of stamping strain



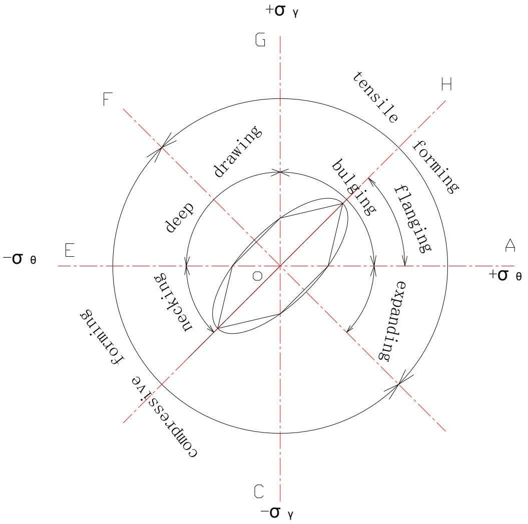


Fig.1.2 Diagram of stamping stress

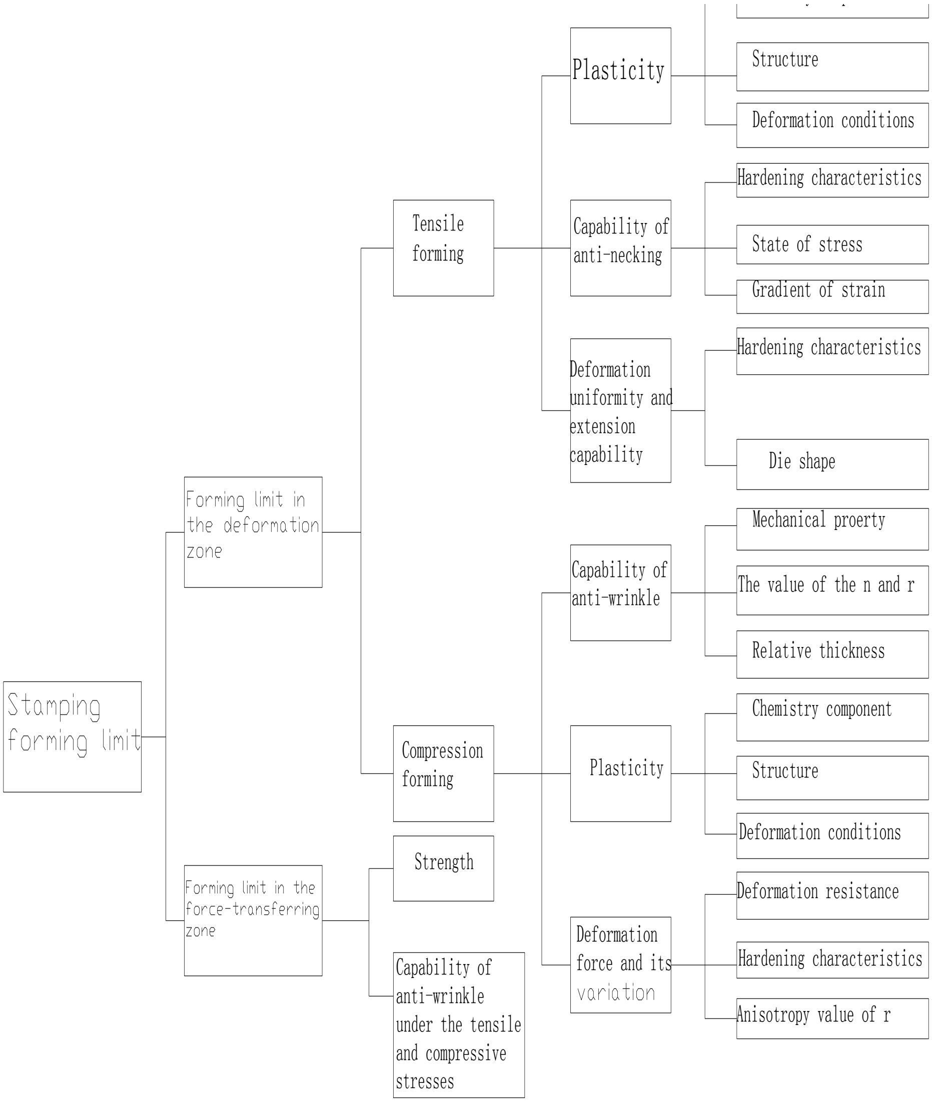


Fig.1.3 Examples for systematic research methods