CHAPTER II

LITERATURE SURVEY

HILL'S ANISOTROPY PLASTICITY THEORY(1950)

Hill had formulated a quantitative treatment of plastic anisotropy without regard to its crystallographic origin. He assumed a homogeneous material characterized by three orthogonal axes of anisotropy, x, y, and z, about which the properties have two-fold symmetry (Equivalently, the x-y, y-z, and z-x planes are planes of mirror symmetry). In rolled sheet, it was conventional to take x, y, and z to be the rolling, transverse, and through-thickness directions respectively. The theory also assumed that in any given direction the tensile and compressive yield strengths are equal. The proposed anisotropy yield criterion had the form of:

$$\begin{aligned} 2f\ (\sigma_{ij}) &= F\ (\sigma_y - \sigma_z)^2 + G\ (\sigma_z - \sigma_x)^2 + H\ (\sigma_x - \sigma_y)^2 \\ &\quad + 2L\ (\tau_{yz})^2 + 2M\ (\tau_{zx})^2 + 2N\ (\tau_{xy})^2 \\ &= 1 \end{aligned}$$

where

σ - effective stress

τ - shear stress

F, G, H, L, M, and N - constants

JOHN R. NEWBY (1970) showed a method of strain analysis of formed sheet metal parts. The electrochemical etched grid pattern on sheet metals was useful for tailoring the various grades of sheet which were commercially available to the requirements of fabricators. Application of strain grids and their measurement to give accurate value of e_1 or principal strain, and e_2, the strain at 90 deg to e_1 on the surface of the formed part had been described. It was concluded that strain analysis can be powerful diagnostic approach in the solution of sheet metal forming problems.

ROBERT H. WAGONER AND NENG-MING WANG(1979) gave a method to choose the specimen shape in plane-strain tensile test. In their test, sheet aluminum alloy (2036-T4) specimens of several geometry were photogrided and pulled in a tensile testing machine while precision photographs were taken of the photogrid. This technique allowed determination of strain distributions and load-displacement points. These results were compared with corresponding results obtained by Finite Element Modeling based on Hill's anisotropy plasticity theory and experimental tensile stress-strain data. FEM predictions and experimental results were in excellent agreement; verifying Hill's model for the case of in-plane deformation of 2036-T4 aluminum alloy between the strain states of plane-strain tension and uniaxial tension.

In another test of theirs(1980), a technique for measurement of plane-strain work hardening characters had been developed which used tensile experiments and computer analysis for interpretation, and which eliminated the experimental uncertainties of large strain gradients, friction, and out-of-plane bending inherent in the usual plane-strain deformation modes. Plane-strain and tensile work hardening curves had been measured for 2036-T4 aluminum alloy using several types of sheet specimens. The work hardening rate in plane-strain was lower than that in uniaxial tension. In each case a Voce-type empirical work hardening law represented the data well. Hill's theories could not account for these data because the isotropic hardening assumption is violated. A method of analysis was introduced to determine Hill's new m parameter as a function of strain and m was found to vary from 1.6 to 2.0 in the strain range $0.02 < \varepsilon < 0.18$.

MANABU GOTOH, ATUYUKI MIURA AND KOZO TANAKA (1988) gave the forming limit diagrams of proportionally pre-strained brass sheets which were experimentally determined for a combination of uniaxial and equi-biaxial tensions. From these FLDs and the theoretical ones predicted using a new plastic constitutive equation previously proposed by one of the authors (Gotoh) and a local necking condition, the n-th power hardening, Voce and modified Voce hardening laws were compared to determine the most suitable one for the brass sheet. Furthermore, the dependence of the FLDs on sheet thickness of the brass sheet was discussed. Their study showed that the secondary limit strains of brass sheets depend on the strain path. As a result, the limit strains for the case of uniaxial tension-unloading-equiaxial tension were slightly higher than the proportional limit strains, while the limit strains in uniaxial tension with pre-equibiaxial tension were only slightly higher than that in the vicinity of plane-strain conditions. For the strain path of equibiaxial tension-unloading-uniaxial tension, the secondary FLDs of the 60/40 soft brass sheet used in their study were much higher than those of other materials. One could not observe such a tendency in a steel sheet for which breakage occurs immediately after the strain-path change. The second limit and proportional strains were depended on the thickness of the sheet, increasing with the thickness, though the experimental limit strains of a 0.6 mm sheet were merely a little higher than those of a sheet of thickness 0.3 mm. As for the hardening law which was employed for predicting the theoretical FLDs, it was found that the Voce hardening law, which had been so far reported to be very effective for brass sheet, was not so effective. Instead, the conventional n-th power law or the modified Voce law proposed here were recommended for that purpose. It was noted, however, that the material constants employed on the basis of the critical strain in the plane-strain state.

YASUYOSHI FUKUI AND KENJI NAKANISHI (1988) studied the formability of two steel sheets by means of a plane-strain tensile test and an in-plane stretching test. The parameter m of Hill's nonpolynomial yield function was calculated by applying Wagoner's method. The assumption m=2 was recognized for the sheets because the difference between effective stress-strain curves of the uniaxial and plane-strain test could almost be neglected. The fracture mechanism of the plane-strain specimen was initiated at the center of the specimen by shear deformation and then propagated in the manner of a mode I-type crack.

MANABU GOTOH, MASAYUKI MISAWA AND CHEAL ROK LIM(1993) performed the experiments on the forming limit strains of several metal sheets under the plane-strain tension by using Gotoh's equation. Sheets break generally due to localized necking (localized - type instability or bifurcation). All theories predicted that any sheet would break at the tensile strain comparable with its n-value (strain hardening exponent) under such conditions. It was clarified why there exist so many materials whose forming limit strains for plane-strain tension were not coincident with their n-value. It was verified that the theoretical critical condition for localized necking was basically correct, in which the first-order derivative of the stress-strain relation (the strain hardening character) of the material played the decisive role. The conventional n-th power law approximation of the strain hardening characters was not reliable when its first-order derivative must be used. It was emphasized that the strain hardening character had to be formulated precisely up to its first-order derivative when determining the forming limit strain.

HIROSHI KATOH, KAZUO KOYAMA, AND KUNIHIKO KOMIYA (1985) studied the behaviour of cementite precipitation in continuous annealing. In their report, recovery yield-point elongation (YP-El) was selected for the characteristics to the deterioration by strain-aging, and the relations between natural and artificial aging, and between the degree of deterioration by strain aging and solute carbon content or aging index (AI) were investigated. The value of AI would be within 30 MPa to suppress recovery of YP-El below 0.2% by the artificial aging. This condition corresponds to the value of solute carbon content within 4.5 ppm. Furthermore, under a condition of AI within 15 MPa, or solute carbon content within 1-1.5 ppm, recovery of YP-El was never observed.

R.A.MIRSHAMS, H.P.MOHAMADIAN, AND K.E.CROSBY (1994) gave the equation to evaluate stability ratio (SR), a measure of the degree to which the interstitial atoms are free, by the following relationship: $SR = \{(Nb)/92.9 + [(Ti) - 48/32(S) - 48/14(N)]/47.9\}/[(C)/12.01]$, where ( ) is weight percent of the alloying element. A calculated value of $SR>1$ implies there are no free interstitial atoms, and the steel is thus referred to as stabilized; $SR<1$ refers to an unstabilized steel.

MILL HEAT TREATMENT OF COLD ROLLED LOW-CARBON STEEL SHEET (METALS HANDBOOK, AMERICAN SOCIETY FOR METALS, P153, 1987)

Unless a hard temper is desired, cold rolled sheet is always softened to improve formability. This is accomplished at the mill by a recrystallization heat treatment such as annealing or normalizing.

Annealing. Low-temperature recrystallization annealing, or process annealing, may be used to soften cold rolled low-carbon steel. When done as a batch process, this type of annealing is known as box annealing. It is carried out by placing coils or stacks of sheets on a bottom plate and then enclosing them with a cover within which a protective gas atmosphere is maintained. A bell-type heating furnace is then placed over the atmosphere container. After heating to approximately 690 to 730°C, the charge is allowed to soak 30 to 90 hours until the temperature is uniform throughout, after which the heating furnace is removed and the charge is allowed to cool in the protective atmosphere before being uncovered.

At the present time, cold rolled steel is batch annealed in coils under a protective atmosphere more than by any other methods. In addition to box annealing, a small percentage of coils are treated by continuous annealing. This process is intended to provide a fully recrystallized grain structure.

Open-coil annealing is used when uniform heating and/or gas contact across the entire width of the coil is required; for example, to obtain decarburization over the entire surface during production of material for porcelain enameling. In this process, the coils are wound loosely, permitting gas to flow freely between the coil convolutions. Annealing temperatures may be higher than those used in conventional box annealing.

Temper Rolling. The purpose of temper rolling depends upon the type of products desired. In some sheet products, the main purpose is to develop the proper stiffness or temper by cold working the steel to a controlled extent. This is also true with respect to the temper rolling of black plate for tin plate manufacture. In addition, however, temper rolling may be used to improve the flatness of annealed strip, to develop desired mechanical properties and to impart a desired finish to the strip surface.

For tinplate, the temper designations are as listed in Table 2-1.

Table 2-1 Temper Designation

Designation	Expected average control hardness Rockwell 30-T	Characteristic	Example of usage
T-1	46-52	Soft for drawing	Drawn requirement, nozzles, spouts, closures
T-2	50-56	Moderate drawing where some stiffness is required	Rings and plugs, pie pans, closures, shallow drawn and specialized can parts
T-3	54-60	Shallow drawing, general purpose with fair degree of stiffness to minimize fluting	Can ends and bodies large diameter closures, crown caps
T-4	58-64	General purpose where increased stiffness desired	Can ends and bodies, crown caps
T-5	62-68	Stiffness, rephosphorized steel used for hardness to resist buckling	Can ends and bodies
T-6	67-73	Rephosphorized steel for great stiffness	Beer can ends

Sheet temper mills are used only when it is necessary to process the steel in sheet form, otherwise coil temper mills are used. The changes in the mechanical properties given to the sheet or strip depend on the reduction which is usually referred to in temper rolling as extension. Sheets intended for deep drawing applications received 0.25 to 1 percent extension, whereas sheets having lesser ductility requirements are given 1.0 to 1.5 percent extension.

STRAIN ANALYSIS (J.R.NEWBY, 1979)

Most formable metal sheets behave in a similar manner when stretched biaxially or drawn by a combination of tension and compression force. However, the relative amounts of stretch and draw (especially in regions of plane-strain where one principal dimension remains unchanged) can differ appreciably among metals subjected to the same forming forces. These differences are caused by differences in material characteristics (strain hardening capacity, fracture strain and plastic anisotropy) and in material-process interaction (gage effects, sheet-to-die friction, press speed, and the like).

The strain level, and hence closeness to plastic instability during forming, can be evaluated by measuring the change in distance between gage markings on the surface of the metal that results from one or more forming operations. The markings must be located in areas that undergo critical amounts of deformation; strain measurements are made both parallel and perpendicular to the direction of maximum extension. Because it is difficult to measure thickness changes without cutting into the part, it is convenient to assume that the volume of the metal remains constant, and then to calculate the through-thickness strain from the two principal surface strains.

The major strain (value of strain in the plane of the sheet along the direction of maximum stretching) is customarily referred to as ε_1 and the minor strain (value of strain in the plane of the sheet perpendicular to the direction of maximum stretching) as ε_2. Through-thickness strain is sometimes identified as ε_3.

Because the location of the critical area and the orientation of the maximum strain relative to the rolling direction are seldom known before a part is formed, a pattern of circular gage markings is especially useful. A grid of such gage markings may be applied to a sample sheet by electrochemical etching or by ink, paint or photographic printing. Scribing is not recommended, because it requires reading both before and after forming, and because the scribed markings can affect the deformation process. Narrow lines and small circles should be used where critical deformation occurs over a small area of the part. Larger gage markings may be used to observe gross metal flow patterns or on parts where deformation is moderate. Areas at some distance from the critical strain site may be important in showing directions and magnitudes of metal movement.

FORMING LIMIT DIAGRAMS (FLD) (J.R.NEWBY, 1979)

The forming limit diagram, also known as the forming limit curve, is a direct and useful representation of the formability of steel sheet. It illustrates the biaxial combinations of strain that can occur without failure.

Determination of FLD can be obtained by measuring the deformation of the metal that occurs during deformation operations. An array of circles is imprinted by photoprinting, photoetching or electroetching on the surface of the steel sheet before it is formed. The individual circles become ellipses wherever deformation occurs, except in areas where pure biaxial stretching occurs. The major and the minor axes of the ellipses are compared with the circles of the original grid to determine the major and the minor strains at each location. The area immediately adjacent to failures are of particular concern when evaluating the forming capabilities of the metal. Failure can be defined by several criteria, but the onset of the visible neck is the most widely used definition of failure. The locus of strain combinations that produce failures is the forming limit. The area below the FLD encompasses all the combinations of strain that the metal can withstand.