

Chapter 2

Cross Rolling: A Metal Forming Process

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Abstract The chapter deals with cross rolling where the workpiece is rotated by 90° in the rolling plane after each rolling pass. The chapter begins with basics of metal rolling, and later on focuses on cross rolling. A short introduction to texture and its representation is presented followed by an overview of the formation of deformation texture in various materials after cross rolling. Review of some of the research works on cross rolling in last few decades has also been included. A case study has been provided at the end of this chapter.

2.1 Introduction

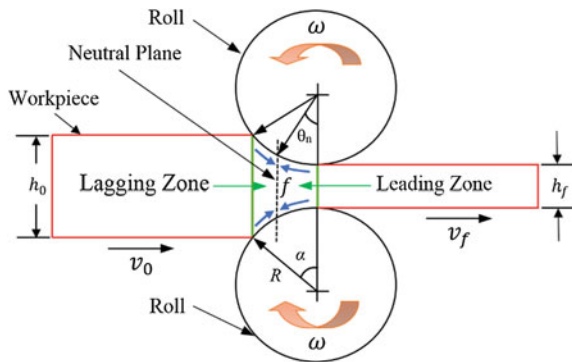
Rolling is one of the bulk metal forming processes, where metal is deformed plastically by allowing it to flow between two rollers, rotating in opposite directions. Plastic deformation reduces the initial thickness of the workpiece to a pre-defined final thickness, and the gap between the two rotating rolls, which is less than the initial thickness, determines the final thickness. Because of the constancy of volume of material before and after rolling, the amount of reduction in material thickness governs the elongation in length. The change in width is negligible since it is much larger as compared to its thickness. Frictional force, f between workpiece and rolls is responsible for dragging the workpiece into the roll gap. Rolling process not only reduces the thickness, but also enhances material properties like strength, toughness, surface morphology, etc. Contour of the rolls governs the shape of the rolled product. Rolling is the most widely used forming process, which produces

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Fig. 2.1 Flat rolling process

products like bloom, billet, slab, plate, strip, sheet, etc. In order to increase the flowability of the metal during rolling, the process is generally performed at high temperature and consequently the load requirement reduces. Figure 2.1 shows a schematic diagram of a rolling process, where a strip of thickness, h_0 enters the roll gap and is reduced to h_f by a pair of rolls, rotating in opposite directions. The surface speed of the roll is $V_r (= \omega \times R)$. The linear speed of the workpiece increases from its initial value, V_0 as it moves through the roll gap and attains a highest value, V_f at the exit of the roll gap.

Friction plays an important role in rolling as it always opposes relative movement between two surfaces sliding against each other. At the point where workpiece enters the roll gap, the surface speed of the rolls is higher than that of the workpiece. So, the direction of friction is in the direction of the workpiece movement and this friction force drags it into the roll gap. During rolling, velocity of the workpiece increases as material flow rate remains same all throughout the deformation. Material velocity is equal to the surface speed of the rolls at a plane, called the *neutral plane*. From the entry point to the neutral point, the deformation zone is named as the *lagging zone*. Beyond the neutral plane, i.e., in the *leading zone*, the speed of the deforming workpiece is faster than the peripheral speed of the rolls and direction of friction quickly changes to oppose this. In order to make the analysis of flat rolling process simple, assumptions like plane strain deformation, volume constancy principle, constant coefficient of friction, constant surface velocity of the rolls, etc., are considered. Out of all varieties of the rolling processes, the flat rolling is the most practical one which produces around 40–60 % of the total rolled products [1]. This attracts several researchers to work in this area to improve the quality and quantity of products through optimizing the process parameters. Cross rolling, by changing the workpiece orientation and hence changing the deformation path, is a way of tailoring texture development to reduce the anisotropic properties of the workpiece.

2.1.1 Cross rolling

Cross rolling (CR) is normally done on samples of comparatively lesser dimension, by changing the rolling direction (RD). The sample, on the rolling plane, is rotated by 90° about the normal direction (ND). There is no standardized sequence of stages of cross rolling but the sequences followed by most of the researchers are mainly of two types: Two-step cross rolling (TSCR), also known as pseudo-cross-rolling, where direction is changed after achieving 50 % of the total reduction (Fig. 2.2a). Second, Multistep cross rolling (MSCR), also known as true cross rolling, where direction is changed after each pass (Fig. 2.2b) [2]. Clock rolling (Fig. 2.2c) may be one more way of achieving cross rolling, by continuously changing the rolling direction by 90° about ND, and if the rotation is 180° instead of 90° , it is called as reverse rolling. Change in rolling direction or deformation path changes the substructure formed in the previous path of deformation, and hence affects the deformation texture. Cross rolling leads to rolled product of comparatively uniform mechanical properties in all directions (Fig. 2.3).

Schmitt et al. [3] have studied the effect of critical resolved shear stress (CRSS) value on yield locus for polycrystalline material. Different values of CRSS were obtained by prestraining the material in different directions and the degree of change in strain path, is defined by a scalar parameter, $\alpha = d\varepsilon_p \cdot d\varepsilon$, where $d\varepsilon_p$ and $d\varepsilon$ are the unit vectors in two different strain paths. They have observed that the yield stress value increases with α varying from 1 to 0 and decreases when α varies from 0 to -1 . Gurao et al. [4] defined the above-mentioned parameter in a different way as $\theta = (\varepsilon_p : \varepsilon) / (\|\varepsilon_p\| \|\varepsilon\|)$, where ε_p is strain tensor in the prestrain path and ε

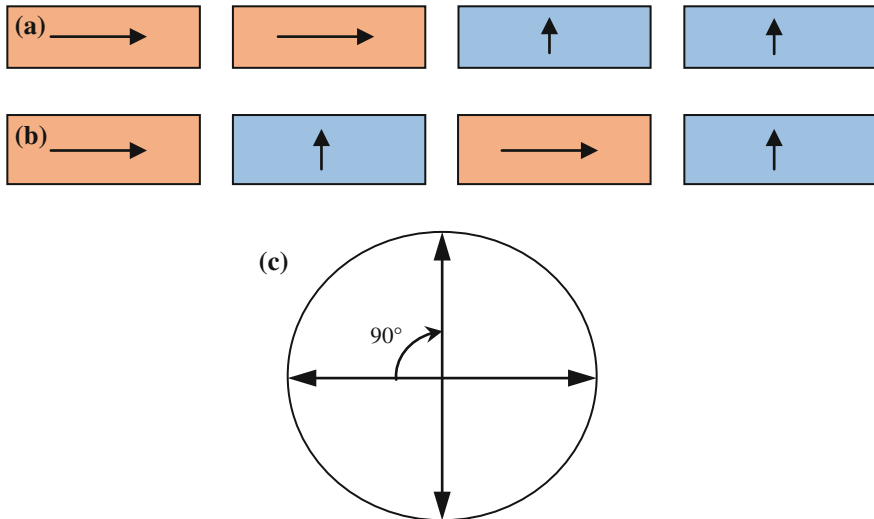
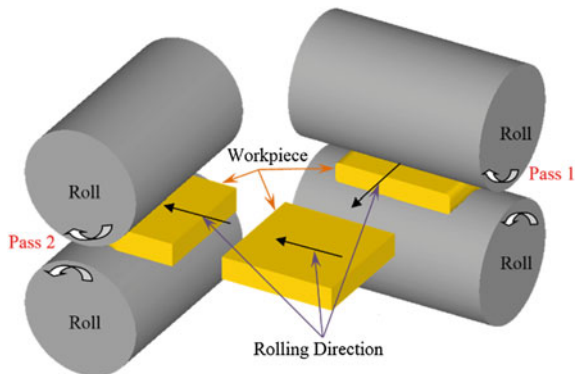


Fig. 2.2 Cross rolling sequences; **a** Two-step cross-rolling (TSCR), **b** Multistep cross-rolling (MSCR) and **c** Clock rolling

Fig. 2.3 Rolling mill arrangement for cross rolling



is the strain tensor in successive strain path. For no change in strain path, $\varepsilon_p = \varepsilon$ and $\theta = 1$, while $\theta = 0$ corresponds to orthogonal strain path change. As the parameter θ is defined for change of strain path during rolling, it leads to a value of 0.5 for both MSCR, TSCR and 1 for reverse rolling, as reported by Suwas and Gurao [5].

For unidirectional or straight rolling, where it is considered as a plane strain deformation, the sample has an orthorhombic symmetry. Symmetry is something that when certain operations are performed on the sample it will bring the sample into coincidence with itself. Orthorhombic symmetry means all the three viz. rolling, transverse, and normal directions of the sample are axes of twofold symmetry. Now, for cross rolling, where the sample is rotated by 90° after each pass, the sample symmetry becomes tetragonal having one fourfold axis which is parallel to the normal direction [2, 6].

2.1.1.1 Applications

Cross rolling is a way of reducing the directional dependency of different properties of the rolled plate. An application of this process can be for the sheets used for making cup by deep drawing processes. The value of \bar{R} and ΔR (described in Sect. 2.1.2.2) can be controlled by cross rolling, which may be needful in reducing the ear formation during a deep drawing process. In another application, it can be used for producing non-grain-oriented electrical steels used in transformers, motors, generators, etc., to get similar magnetic properties in all directions. Bohler-Uddeholm of USA is one of the industries [7] which is currently using this process to make stainless steel sheets for manufacturing of knives.

2.1.1.2 Limitations

As the plate is rotated, i.e., width and length of the plate are altered, it cannot be applicable for products of longer dimensions. Initial cost of the set up may increase

due to the placing of the rolls in two different angles and due to the required material handling equipment.

2.1.2 Effects of Cross Rolling

Cross rolling can affect the material properties in many ways; possible effects on the material due to change in rolling directions are

- Microstructural changes and changes in crystallographic texture
- Changes in plastic anisotropy
- Changes in residual stress distribution

2.1.2.1 Crystallographic Texture

Almost all materials of interest are made up of aggregates of single crystals (also known as grains). Single crystals are solid aggregates where the crystal lattice is continuous, i.e., without grain boundaries. Most commercial metals are polycrystals, composed of aggregates of single crystals, with different atomic orientations with respect to a predetermined external frame of reference and hence have the grain boundaries. The main differences among the grains of the polycrystalline materials are: the shape and the orientation. Shape of the grains depends on type of the solidification and the subsequent thermomechanical processes, whereas orientation largely depends on the processing that a material experiences during deformation. In a plastic deformation process of polycrystalline metals, crystallographic orientation of each grain changes which is known as texture evolution. This texture evolution needs to be controlled as it has a significant effect on the anisotropy of the properties [8]. Texture, generally characterized by a crystallographic plane and a crystallographic direction, can be represented graphically in pole figures and orientation orientation distribution functions (ODF). Basically this representation indicates the intensity of an orientation or texture component, which depends on the number of grains having same orientation [9].

2.1.2.2 Plastic Anisotropy

Plastic anisotropy means that in plastic deformation materials are not isotropic, which is normally the directional independency of the properties. Most of the materials available are polycrystalline and exhibit anisotropic behavior. During manufacturing, some forms of textures are developed in the material and it may enhance anisotropy. The form of texture pattern depends on the type of deformation and depending on that it may enhance or reduce the level of anisotropy. In case of rolling, high intense textures are formed in the direction of rolling, which may lead to significantly different properties in the rolling and transverse directions.

Lankford coefficient, R , defines plastic anisotropy by the ratio of strain in width direction (ε_w) to the strain in thickness direction (ε_t) in the uniaxial tensile test. Higher value of R indicates high resistance of the material to thinning and hence the material can be drawn into a greater height. The Lankford coefficient depends on the orientation of tensile axis with reference to the rolling direction, in the rolling plane and defined by the angle α , and hence $R = R_\alpha$. In general, materials are anisotropic and defined by average \bar{R} (ASTM E517):

$$\bar{R} = \frac{1}{4} (R_{0^\circ} + 2R_{45^\circ} + R_{90^\circ}) \quad (2.1)$$

Variation of the R_α in the plane of the sheet is also important and it is described by the coefficient of planar anisotropy,

$$\Delta R = \frac{1}{2} (R_{0^\circ} - 2R_{45^\circ} + R_{90^\circ}) \quad (2.2)$$

Planar anisotropy relates to the formation of ears in deep drawn cups or in other words ΔR is the degree of the tendency of the sheet to form ears. If $\Delta R > 0$, then ears form at 0° and 90° to the rolling direction, and if $\Delta R < 0$, ears form at 45° . These two coefficients are dependent on crystallographic texture.

2.1.2.3 Residual Stress

Stresses which remain in the solid material even after the removal of the cause of stress are called as residual stress. The cause of the stress may be external mechanical load or it may be the thermal load and for the latter case, the residual stress is normally called as thermal stress. During hot rolling, the material is subjected to both the types of loading; and due to the nonuniformity in deformation and presence of temperature gradients; the residual stress distribution in the material after rolling is not uniform. Residual stress may distort the shape of the rolled material and it also has significant effect on further processing of the rolled product. Thus, the residual stresses distribution in rolled sheet cannot be ignored. Residual stresses, which may be a compressive or a tensile type, are sometimes desirable also. For brittle fracture by crack propagation in a material having compressive residual stress is little difficult. Now for cross rolling, where the deformation path changes, the temperature and plastic strain distribution in the material will be different to that of a material rolled in a single direction and hence the residual stress distribution will also change. Very few literatures are available on residual stress distribution for the cross-rolled material. Nature of the residual stress developed in the rolled product can be changed, i.e., from tensile to compressive, by cross rolling [10].

2.2 Texture or Preferred Orientation

Texture is a measure of the similarity in orientation of the crystal lattice within the constituent grains of a polycrystalline. In simple words, texture is the orientation or arrangement of the grains in the material with respect to a fixed coordinates. This can be clarified using the following figures. In Fig. 2.4a, the grains in the plate are placed randomly and gives rise to a random texture, whereas in Fig. 2.4b the grains are arranged in a similar fashion and forms a preferred orientations, as normally seen in the rolled sheets made through unidirectional rolling.

Texture development or changes in texture in a material normally occurs due to any one or combination of any of the reasons; (i) solidification, (ii) plastic deformation, (iii) annealing, and (iv) phase transformation. This chapter deals with deformation texture (rolling texture). Texture or orientation of grains, in rolling, is normally represented by set of Miller indices $\{hkl\}\langle uvw \rangle$, where $\{hkl\}$ specifies the crystallographic planes of the grains parallel to the plane of the sample and $\langle uvw \rangle$ shows crystallographic direction parallel to the rolling direction. For polycrystalline material, different grains have different orientations which give rise to a complex texture. In such cases, the overall texture can be statistically represented by the following fundamental equation [11]:

$$\text{Texture}_{\text{Overall}} = \sum w_i \{hkl\}_i \langle uvw \rangle_i, \quad (2.3)$$

where w_i is a weighting factor. Texture can be broadly classified into two types: macrotexture and microtexture. Macrotexture gives information about how much volume fraction of the sample has a specific orientation and does not give any idea about how the grains are spread within the sample. Microtexture is the combination of microstructure and texture. It gives information about the orientation of an individual grain and its neighbors as well. X-ray diffraction is the commonly used method for bulk texture measurement; whereas, electron back scatter diffraction (EBSD) is used for microtexture measurement. The other method used for texture measurement is by Neutron diffraction. Details regarding texture formation, measurement, and representation can be found elsewhere (Engler and Randle [12]; Kocks et al. [9]). In this chapter, a brief introduction of how to represent texture is presented.

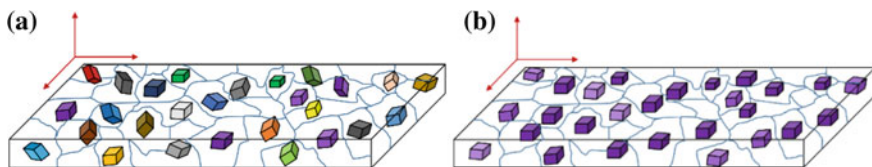


Fig. 2.4 Crystal orientations in a plate; **a** random orientation and **b** preferred orientation

2.2.1 Reference System

Reference system is an important parameter for representing crystal orientation. It may be sample reference system or crystal reference system. In sample reference system, the three mutually perpendicular axes of sample are taken as reference. But, in crystal reference system the three mutually perpendicular crystallographic axes of a unit cell are considered as reference and the same axes are considered for all the crystals within the sample, irrespective of their orientations. Generally for sample reference system, the axes were fixed, i.e., RD, TD, and ND; but for crystal reference system, the axes can be chosen arbitrarily. In Fig. 2.5a both the sample and crystal/unit cell have same orientation with respect to an external frame, and in Fig. 2.5b, the orientation gets changed but still both have same orientation. But in Fig. 2.5c the crystal has completely different orientation to that of the sample.

While representing orientation, it is necessary to transfer the sample reference system to crystal reference system or the vice versa.

2.2.2 Euler Angle

The Euler angles are the angles of rotation, which when performed in correct order, transforms the specimen coordinate system onto the crystal coordinate system. Bunge [13], Roe [14] and Williams [15] proposed different ways of transforming sample frame to the crystal frame. Out of these three ways, the one proposed by Bunge is commonly used [11]. The sequence of rotation given by Bunge is given below:

1. Rotation about the ND (normal direction) by an amount φ_1 , changing the TD (transverse direction) into TD' and the RD (rolling direction) into RD'
2. Rotation about the new RD axis, i.e., RD' by an amount Φ , converting TD' to TD'' and ND' to ND''
3. Rotation about the new ND, i.e., about ND'' by an amount φ_2

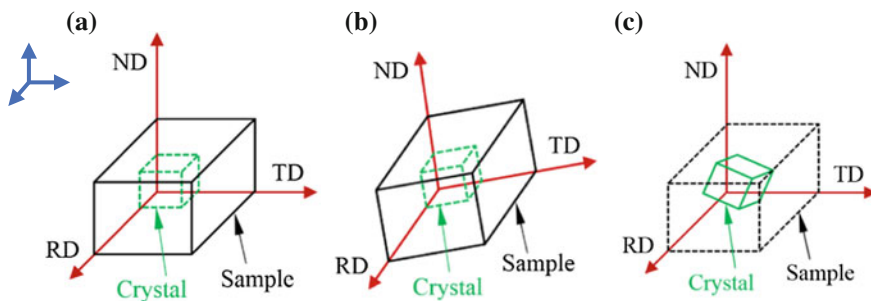
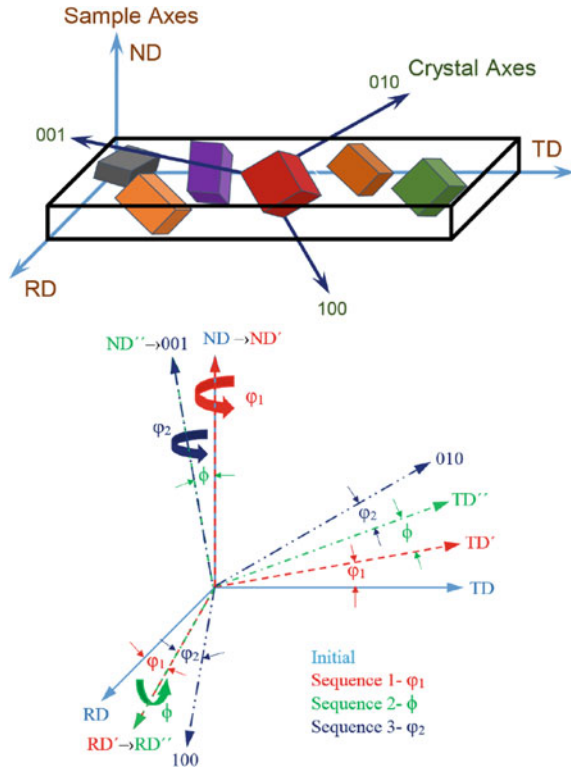


Fig. 2.5 Reference System

Fig. 2.6 Euler angles proposed by Bunge [13]



where ϕ_1 , Φ and ϕ_2 are the Euler angles. The sequence of rotation is represented graphically in Fig. 2.6 [16].

2.2.3 Representation of Texture

Graphically, texture can be represented by any of the following ways: pole figure showing the distribution of a specific crystallographic direction in the assembly of grains of the specimen in sample reference system; inverse pole figure (IPF) showing the frequency with which a particular crystallographic direction coincides with axes of the specimen; and orientation distribution function (ODF) which shows the full 3D representation of crystallographic texture calculated from a set of pole figures.

2.2.3.1 Pole Figure

Orientation of a plane can be represented by a line normal to it. If a sphere, termed as reference sphere, is drawn with the center on the plane, then the circle formed at the intersection of the plane and the sphere is called trace [17]. Now, if the line normal to

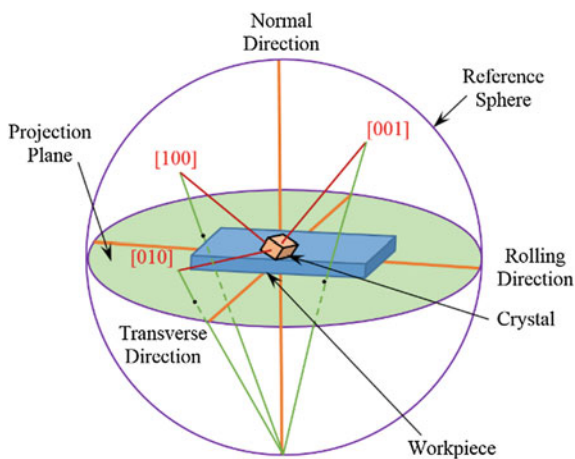
the plane is extended to the sphere, the intersection point will be the pole. The indices of these poles are same as that of the planes, to whom they are perpendicular. These formed poles, either on upper hemisphere or on lower hemisphere, are then mapped to a plane called as the projection plane. The formed circle with projected poles is called pole figure. Stereographic projection is the well-known mapping method used by metallurgists to map the hemisphere to a plane. Figure 2.7 shows the schematic diagram representing the formation of a pole figure. For material with high texture, poles are normally accumulated about a particular direction.

The projection of normal to the three mutually perpendicular planes viz. 100, 010, and 001, of a single unit cell, on the projection plane is represented in Fig. 2.7. Now, if we consider the same planes or poles for other grains, then they may be formed near to the same location as that of initial one or may be scattered on the projection plane depending on the orientation of the grains. If the poles are formed close to each other, forming cluster, they indicate a strong texture in the sample. But, if the poles are scattered in the projection plane, then it indicates random texture in the sample. Normally, pole figure is drawn for a single plane or pole, which indicates how the plane is oriented, with respect to the sample frame, in the considered scanned area of the sample. Pole figures can be represented by using the projected individual poles or by contour plot for overlap poles. In contour plot, the number near to contour line indicates the density of the pole with respect to that of a sample having random texture [11].

2.2.3.2 Inverse Pole Figure

Inverse pole figure (IPF) is the inverse or opposite of the pole figure. In pole figure, crystallographic orientations are represented with respect to an external, i.e., sample reference system but in IPF the sample directions (i.e., RD, TD, and ND) are represented with respect to the crystallographic axes. In other words, IPF represents

Fig. 2.7 Pole figure



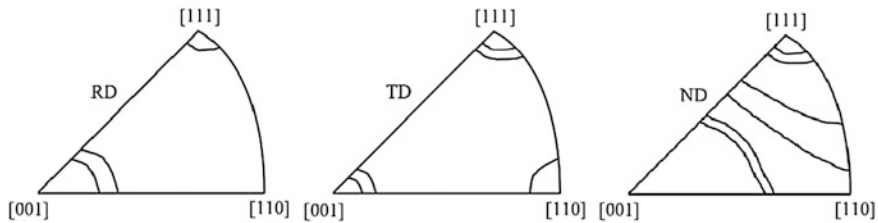


Fig. 2.8 Inverse pole figure

the frequency with which the sample axes coincide with the crystallographic axes. Stereographic projection has been made for crystallographic direction parallel to RD, TD, or ND, but due to the crystal symmetry a part of the projection is represented as IPF. Figure 2.8 shows a representation of IPF.

2.2.3.3 Orientation Distribution Function

To completely describe a polycrystalline structure, orientation, form, and position of each crystal is necessary, which is very complicated. So, relatively simplified statistical parameters are used to describe a polycrystalline structure. Orientation distribution function (ODF) is one of those statistical parameters, which is defined by only considering the orientation of the crystallographic axes with respect to the sample axes [13]. Mathematically,

$$\text{ODF} = f(g)dg = \frac{\Delta v(g)}{v}, \quad (2.4)$$

where, v = volume of whole sample, $\Delta v(g)$ = volume of all the crystallites having orientations in the range of $g + \Delta g$ and g is the orientation of the crystallite in terms of Euler angles, i.e., $g = g(\varphi_1, \Phi, \varphi_2)$. The texture details obtained from pole figure are in 2D as it is projecting the poles to a plane and hence has some limitations. Whereas, ODF can give a full 3D representation of the crystallographic texture of a polycrystalline material. Mathematical models, which take numerical data from several pole figures as input, are used to get a complete 3D ODF. Three-dimensional ODF is represented in a space having φ_1, Φ and φ_2 as the Cartesian coordinates. A point on this space gives a particular value of φ_1, Φ and φ_2 . If a number of crystals have same orientation, i.e., same value of φ_1, Φ and φ_2 then they will form a cluster in the 3D ODF, and hence represents the existence of a texture. Normally, ODF is represented by slicing the Euler space on any one of the three axes. If slicing is done on φ_1 axis, i.e., ODF is represented on constant φ_1 section, then it is called as sample orientation distribution (SOD). Whereas, if it is represented on constant φ_2 section, it is termed as crystal orientation distribution (COD).

As per Bunge, an orientation distribution function can be described by following series [5]:

$$f = (\varphi_1, \Phi, \varphi_2) = \sum_{l=0}^{\infty} \sum_{m=-1}^{+1} \sum_{n=-1}^{+1} C_1^{mn} P_1^{mn}(\Phi) \times \exp(im \varphi_2) \exp(in \varphi_1), \quad (2.5)$$

where C_1^{mn} is the series coefficients and $P_1^{mn}(\Phi)$ are certain generalizations of associated Legendre functions.

2.2.4 Ideal Orientations

Ideal orientations are the orientations of the grains or texture components, which are normally observed in rolled materials. Some of these components are named after the metal or alloys in which they were observed for the first time. Apart from the ideal orientations, there are some texture fibers, which are nothing but the lines joining the texture components having a range of orientations with a single degree of freedom about a fixed axis, has also been observed [9]. Followings are the list of ideal orientations for materials with different crystal structures presented in tabular forms (Tables 2.1, 2.2).

2.2.5 Prediction of Texture

Various mathematical models are used to predict the deformation mechanism and hence deformation texture during rolling. Basically these models consider the

Table 2.1 Ideal orientations in BCC materials [5]

Components	Miller indices $\{hkl\}\langle uvw \rangle$	Euler angles (°) ($\varphi_1, \Phi, \varphi_2$)
Cube (C)	$\{100\}\langle 001 \rangle$	45, 0, 45
Rotated cube	$\{001\}\langle 110 \rangle$	0, 0, 45
Goss (G)	$\{110\}\langle 001 \rangle$	90, 90, 45

Table 2.2 Ideal orientations in FCC materials [5, 9]

Components	Miller indices $\{hkl\}\langle uvw \rangle$	Euler angles (°) ($\varphi_1, \Phi, \varphi_2$)
Copper (Cu)	$\{112\}\langle 111 \rangle$	90, 35, 45
Brass (Bs)	$\{110\}\langle 112 \rangle$	35, 45, 0
Cube (C)	$\{100\}\langle 001 \rangle$	0, 0, 0
Goss (G)	$\{110\}\langle 001 \rangle$	0, 45, 0
S	$\{123\}\langle 634 \rangle$	59, 29, 63

behavior of the materials, which are normally polycrystalline, as a statistical function of the behavior of distinct grains. Some of the models are: Taylor model, Sachs' model, LAMEL, ALAMEL, GIA, CPFEM, viscoplastic self-consistent model and many more. The basics of these models start with deriving mathematical equation which transfers or relates the stresses and strains, the sample is subjected to, at the grain level. Now, these microlevel stresses and strains are linked to slip and twinning systems, by some constitutive equations, for the initiation of plastic deformation. The fundamental equation is shown below [11]

$$D^C = \dot{\epsilon} \sum_s \left| \frac{m^s : \sigma^C}{\tau^s} \right| m^s \operatorname{sgn}(m^s : \sigma^C) \quad (2.6)$$

where

D^C : Strain rate in a crystal

$\dot{\epsilon}$: Scaling factor

σ^C : Stress in a crystal

τ^s : Critical resolved shear stress (CRSS)

m^s : Schmid tensor

$$m^s = \left(\frac{1}{2} \right) \left(b_i^s n_j^s + b_j^s n_i^s \right) \quad (2.7)$$

s : slip and twinning systems

b : Slip direction

n : Normal to the slip plane

Slip in a system will occur when the resolved shear stress $m^s : \sigma^C$ approaches τ^s and the plane on which slip occurs, which were identified by simultaneously solving the equation for a single crystal as well as interaction between the crystals. Plastic deformation causes lattice rotation and can be calculated after inputting the activated slip system which is well known for different crystal structure materials. The obtained lattice rotations are used in deriving the deformation texture. These deformation models are also implemented to cross rolling to predict the deformation texture, by different authors, but the number of research papers available on this is not too high. Some of the works on the predicted deformation texture for cross rolling is given in Sect. 2.3.2.

2.3 Cross Rolling Texture: An Overview

2.3.1 Experimental Observation

Texture or preferred orientation, which affects material properties, contains information about the interrelation between processing parameters and material performance. It provides essential feedback for tuning the thermomechanical history to

get desired properties in the finished product [9]. This makes texture development an important field of research for researchers. Changing the deformation path by changing the rolling direction may be one way of tuning the thermomechanical processing route to get the required orientation, and hence required properties. Some of the available earlier articles on cross rolling are by, Custers and Riemersma [18], Merlin and Beck [19], Wassermann and Grewen [20], Yeung and Duggan [21], on materials with face centered cubic (FCC), body centered cubic (BCC), and hexagonal close packed (HCP) crystal structures. But it is in the last few decades, where there is a significant progress in the research on cross rolling, which is mainly due to the advancement in technology to detect and analyze textures in materials. Recently, some research works have been carried out using crystal plasticity finite element models to simulate the deformation mechanism during the process. Literatures are available where rolling has been done by placing the work-rolls at some angle in the rolling plane and termed as cross rolling. This type of rolling has not been discussed in the current chapter. Some of the research works, which are experimentally carried out on cross rolling, are discussed below.

2.3.1.1 Body Centered and Face Centered Cubic Materials

Due to the wide industrial application of BCC and FCC structure metals and alloys, a lot of research works has been carried out for texture evolution. Vanderschueren et al. [22] experimentally studied the effect of change in rolling direction on the magnetic properties of nonoriented 0.6 % Si steel. Nonoriented electrical steels, which are normally used in rotor and starter of comparatively smaller electrical machines, requires low core loss and high permeability to give an efficient performance to the machine. Hysteresis loss and eddy current loss are the two which mutually do the core loss. Eddy current loss is related to resistivity and can be controlled by the composition of the material but the hysteresis loss depends on the magnetic anisotropy, which depends on the orientation or texture of the material and can be modified during the processing of the material. The authors have studied the direction effect by changing the rolling direction to 90°(TD) during cold rolling and after which the sheets were subjected to annealing and decarburization. Cross-cold rolling changes the initial hot-rolling texture components and produces a strong $\{001\}\langle 110 \rangle$ component. The texture data were correlated to the magnetic properties, and found that, hysteresis loss was 80 % of the total loss and it was due to texture and grain size. Bocker et al. [2, 6] reported the texture development, through ODF, for two different materials namely Armco iron (BCC) and AlMn1 alloy (FCC) in two separate articles. The same rolling sequence consisting of a MSCR and TSCR was followed for both the materials. They concluded that for MSCR, the deformation path follows a tetragonal symmetry; whereas for TSCR, it is a broken path as the deformation path changes at 50 % of total reduction but both the parts of deformation has orthorhombic symmetry. For AlMn1, they found that, TSCR produces texture which has tube orientation extending between orientation A and B, whereas MSCR gives rise texture with ideal orientation C.

The high-temperature withstanding capacity of molybdenum (Mo) makes it an excellent refractory material and find its application in furnace, nuclear industry, etc. It is a well-known fact that rolling produces preferred orientation in the material in the rolling direction and molybdenum (BCC) is not an exception. Oertel et al. [23] investigated the influence of cross rolling as well as heat treatment on texture and formability of Mo sheet. The investigations were made at different stages (early stage and late stage) of the processing route and the rolling direction was changed in larger varieties, like 45° , 90° , and 135° . Texture produced in different sheets made by different rolling sequences are independent of cross-rolling steps and gives rise to an incomplete α -fiber with maximum strengths sited at the rotated cube component. However, the intensities of the texture for sheets with complex rolling sequences are much less as compared to others. Cross rolling done at the early stage, produces sheets with high mechanical anisotropy as compare to the sheets produced by processing where cross rolling is implemented at the later stage. This indicates the disappearance of effect of cross rolling, which is due to the subsequent rolling in one direction. Sheets produced by changing the rolling direction in complex manner give lower planar anisotropy (ΔR). The reported value shows the parameter Z, which is related to the earing formed during deep drawing, increases with the increase in ΔR value.

Aluminum alloys found a wide application due to its good strength, high ductility, high corrosion resistance, and low weight. But while doing sheet metal forming, like deep drawing of aluminum alloys, the chances of formation of earing is quite high due to its high plastic anisotropic properties. A good number of researchers have done cross rolling on various aluminum alloys to study this anisotropy parameter, as well as deformation texture. Liu et al. [24] studied the texture development in AA 3105 aluminum alloy (FCC), which has a strong β fiber rolling texture. They used a two-stage cross-cold-rolling process, where the rolling was done in original TD and reduced the 2 mm sheet to different thickness, maximum up to 90 %. The initial texture components present in the materials like B, S, and C get rotated and transform to B', S', and C', respectively. With increase in rolling reduction, intensities of components like B and S get increased, whereas there is no significant increase in the component C. They also made a quantitative analysis for texture by calculating the volume fraction of different texture components and correlated them with true rolling strain. In another paper, Liu et al. [25] reported the recrystallization texture of continuous cast AA 5005 aluminum alloy, where, the samples were annealed after rolled by pseudo-cross-cold-rolling process. Mondal et al. [26] makes a detailed analysis of cross rolling on AA 7010 aluminum alloys. They concluded that, cross rolling leads to the formation of β fiber in the aluminum alloy and with increasing number of cross rolling steps, the strength of the rotated-Bs component increases while that of rotated-Cu component reduces. In another study [27], made by same authors for a different kind of aluminum alloy, the authors found a strong rotated-Bs texture in the hot cross-rolled alloy.

Wronski et al. [10] studied the effect of cross rolling for pure copper (FCC) and low carbon ferritic steel (BCC), by increasing the strain level for the second pass, where it is rotated by 90° . Texture formation by cross rolling gets symmetrized with increase in strain value and becomes highest, when the amount of strain in both the

direction becomes equal. Symmetrization of the texture forms two more new axes of symmetry. With further increase in strain value, the symmetry of texture get reduced and start to form textures with characteristic same as that formed when rolled in one direction, i.e., the effect of cross rolling disappears. Due to the different slip system, the obtained rolling textures were different from each other. The ideal texture components which were observed for straight rolling of copper are S, C, B, and G, whereas for cross rolling, the B component becomes stable and the others are absent. Similarly for ferritic steel, straight rolling produces components like RW, A, Y, and Z, whereas in cross rolling, except component A all other components remain stable, but with different intensities. The authors also studied the plastic anisotropy parameter for cross-rolled plate. For copper, cross rolling makes the material more isotropic as the normal anisotropy approaches 1 and planar anisotropy reduces from 0.54 to 0.3 which is beneficial for deep drawing. But for ferritic steel, cross rolling causes increase in anisotropy which was due to the formation of α -fiber texture.

2.3.1.2 Hexagonal Close Packed Materials

A few literature is available on the study on texture development for HCP structure materials, as a function of rolling mode, as compared to BCC and FCC structure materials. Texture development in these materials depends on the c/a ratio; and commonly observed textures are R-type and T-type. Magnesium, which has a HCP structure and normally forms basal texture in rolling, is difficult to be deformed plastically as the resolve shear stress value is basically zero in the basal plane [26, 27]. It also has a high anisotropy as compared to aluminum. Al-Samman and Goststein [28], demonstrated for AZ31 magnesium alloy with initial basal texture, formation of basal texture in rolling was independent of the path of deformation (CR & UR), but cross rolling can reduce the strength of the developed basal texture. In cross rolling, due to continuous change in rolling direction, the samples obtained have lesser internal misorientation than that obtained in unidirectional rolling. They also concluded that, for high reduction per pass, cross rolling gives high surface quality and greater rollability, whereas for unidirectional rolling with the same reduction per pass surface cracks are observed. Li et al. [30] also observed same kind of results for ME20 magnesium alloy. The intensity ratio of the basal and non-basal textures reduced in cross rolling, and thus enhances the formability of the sheet. Cross rolling gives rise to sheets of finer microstructure but of lower yield strength, which is due to the weaker texture where basal poles get scattered from ND. Plastic anisotropy also got improved by CR. Xing-pin et al. [29] did experimental investigation on AZ31 magnesium alloy by rotating the plate by 90° after every five passes, with intermediate heating. For this rolling schedule, cross rolling gives symmetric but high intensity basal texture. Cross-rolling produces magnesium sheets with high and more uniform yield strength and percentage elongation; whereas for unidirectional rolling, the material shows high anisotropy with reasonably different percentage elongation, in all three principle directions. The difference in percentage elongation, for

unidirectional rolling, is basically due to the distribution of basal poles which are much closer to RD than TD. Xiong et al. [31] investigated the effect of cross rolling for Mg 0.6 wt% Zr sheet and compared with that of unidirectional. In both the modes of deformation, Schmid factor has higher value along RD but gradually reduces toward TD. This gives lower yield strength along RD. The other reported results are of similar kind to that of observed by other researchers for different Mg alloys.

Gurao et al. [32] studied texture evolution for metastable β titanium alloy using unidirectional and multistep cross rolling, with a constant true strain/pass. Along with different mode of rolling, they did recrystallization and aging of the rolled sample to study all types of texture evolution, viz. deformation texture, recrystallization texture, and transformation texture. Premkumar et al. [33] did experimental study on different sequences of rolling, including unidirectional rolling and different cross rolling, on multifunctional β titanium alloy (HCP) and reported the resulting texture as well as yield locus anisotropy. The developed textures were represented by two fiber textures; viz. α and γ . With the increase in rolling reduction, the intensities of γ fiber for all modes of rolling, i.e., two-step, multistep, and clock rolling, decrease. The intensity distribution is also not the same for all the cases. The authors conducted tensile as well as compression tests to get the yield loci of the rolled samples. Obtained anisotropy is minimum for clock rolling, whereas, it is maximum for multistep cross rolling. Moreover, the type of deformation texture components formed by rolling may remain the same but the intensities and distribution of these components get changed, in cross rolling, due to the rotation of the plate and these variations are functions of amount reduction per pass and the cross rolling sequences.

2.3.2 Prediction of Cross Rolling Texture

One of the earliest available researches on this field is by Wierzbowski in 1979 [34]. He predicted the texture of FCC and BCC materials during cross rolling as well as under compression, by using Sachs model and Taylor model. Both the models gave a close prediction to experimental results. He found that, due to cross rolling some new orientation, like $\{001\}\langle 100\rangle$ orientation, was introduced for FCC material, as this was not observed for simple rolling; and the predicted textures were highly symmetric. Yeung and Duggan [21] studied the texture development due to cross rolling in α brass. They used the program written by Dillamore [35] with a slip system of $\{111\}\langle 110\rangle$ for the FCC material, as used in Taylor-Bishop-Hill theory. The simulated result shows the stability of $\{110\}\langle 223\rangle$ component in cross rolling, whereas, the same component was unstable for straight rolling. Stability of the component was studied by plotting Euler angles for different rolling strains. Liu and Houthe [36] implemented full constraint and relaxed constraint Taylor-Bishop-Hill models to predict the deformation texture developed by cross-cold rolling, as well as by simple cold rolling, for molybdenum sheet. The considered slip systems were $\{110\}\langle 111\rangle$ and $\{112\}\langle 111\rangle$, for the BCC structure material. For cross rolling, in

order to get the input texture, the texture of previous pass was taken with respect to a new sample frame, obtained by rotating the sample reference frame about ND by 90° . In relaxed constraint model, they have considered different version of Taylor model, viz. the lath model, the Pancake model, and the three relaxations models [37] and found that Pancake model gave much more accurate result than the other models; whereas, for lower % reduction, the effect of cross rolling was not significant for full constrained model.

Suwas and Singh [38] used the relaxed constraint Taylor model to predict the texture obtained by a two-step cross rolling and unidirectional rolling for Cu alloys. The predicted results show instability of β fiber due to cross rolling. In case of cross rolling, texture intensity does not depend too much on % reduction per pass. This has been reported earlier by Al-samman and Gottestien [28]. They considered full constraint Taylor model with ratios of critical resolved shear stress as 1:38:50 (basal: prismatic: pyramidal) and simulated the rolling texture for both unidirectional and cross-rolling operations of magnesium alloy, with different reductions per pass. They compared results for both the modes of rolling, by plotting intensity of formed texture with respect to reduction per pass, and demonstrated that as compared to unidirectional rolling, cross rolling has low intensity texture and also does not depend on reduction per pass. The said model for texture prediction does not accommodate microstructure part like recrystallization, recovery, etc., due to which there is a difference between computed and experimental results as well. For cross rolling, the input texture was taken by changing the strain tensor of previous path; whereas for unidirectional rolling, it was taken without any change. Wronski et al. [10] predicted cross rolling as well as unidirectional rolling textures for low carbon steel and copper, by considering a deformation model with the interaction between grain and its surrounding as elasto-plastic. The plastic stress and strain at grain level were correlated to that of sample. Plastic deformation was initiated by slip, at planes where the values of shear stresses cross the critical resolved shear stress value. Slip systems considered were $\{111\}\langle 110 \rangle$ for copper and $\{110\}\langle 111 \rangle$ for steel. The model also considers hardening during deformation which is due to the interactions of slip systems. Stability of the texture components was also examined by the deformation model. Gurao et al. 2011 [4] used viscoplastic self-consistent formulation to study texture development by different modes of rolling for copper and nickel. A rate-dependent viscoplastic law, which correlates strain rate in grain to grain stress, was used.

2.4 Case Study

A case study for cross rolling on AISI 304 stainless steel is presented in this chapter. For better understanding, cross rolling is compared with the unidirectional rolling. The effect of change in direction is a function of percentage reduction per pass and the sequences in which the rolling is carried out. This case study is done for a three-pass rolling with equal amount of reduction in each pass.

2.4.1 Rolling

Samples were heated to the required temperature in the muffle furnace and the hot rolling was carried out on a 2-HI reverse rolling mill of capacity 75 ton. A total of 50 % reduction has been achieved in three passes. After rolling, the samples were left for air cooling. Experimental details and rolling schedule, used for the current study, is shown in Table 2.3 and Fig. 2.9, respectively. Figure 2.10 shows the 2-HI rolling mill and the samples obtained after rolling.

2.4.2 Tensile Test

2.4.2.1 Strength

Tensile specimens of 25 mm gauge length (ASTM E8 sub size specimen) were cut from the rolled sample in three different directions, as shown in Fig. 2.11a, and tested at room temperature in Universal Testing Machine (INSTRON 8862) with a cross-head velocity of 1 mm/min (Fig. 2.11b). Two samples from each direction were tested; one for determination of tensile properties and the other for determination of anisotropy parameter.

Table 2.3 Experimental details

Sample		Work-roll		Pass	
Material	304 SS	Speed	10 m/min	Number of pass	3
Initial thickness	12 mm	Diameter	320 mm	Reduction/Pass	2 mm
Initial temperature	1100 °C	Length	300 mm		

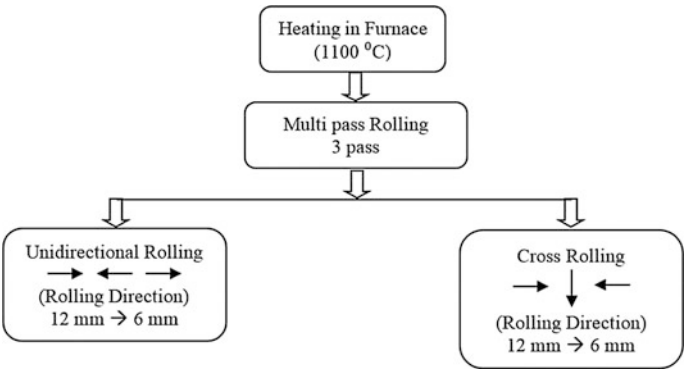


Fig. 2.9 Rolling schedule

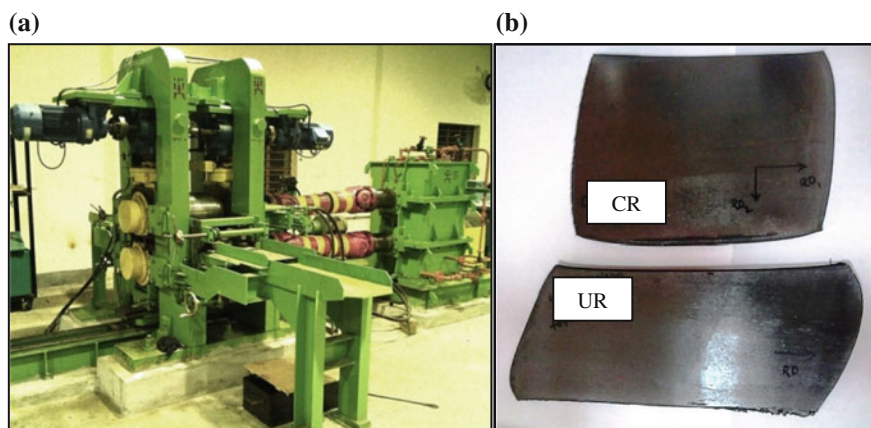


Fig. 2.10 a 2-HI Rolling mill and b Rolled samples

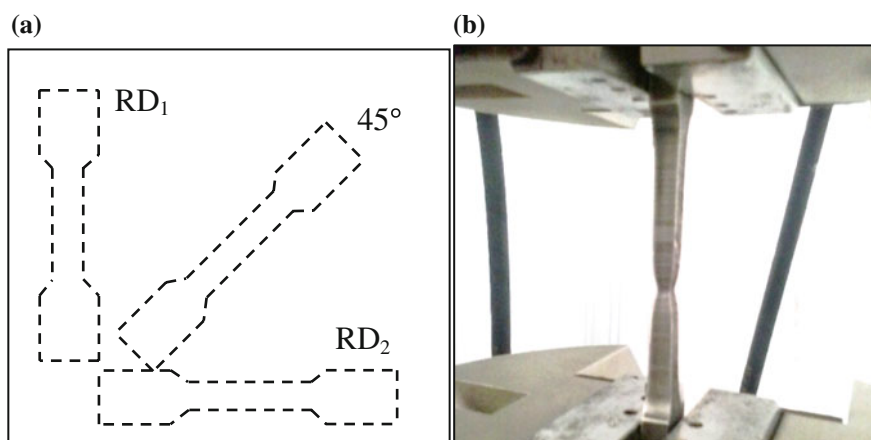
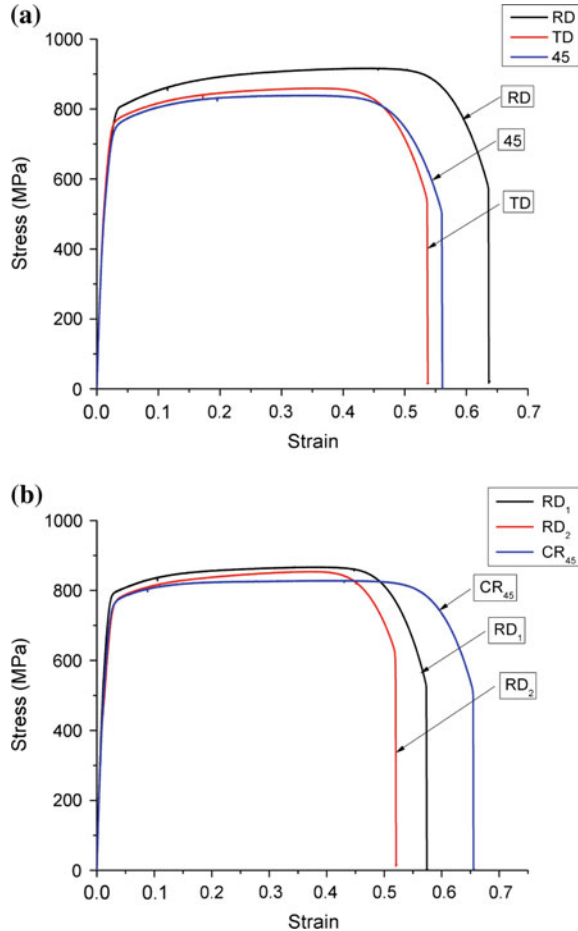


Fig. 2.11 a Tensile sample orientation and b Sample during testing on INSTRON

For Cross Rolling (CR), RD_1 = Rolling Direction (RD) of Unidirectional Rolling (UR), and RD_2 = Transverse Direction (TD) of Unidirectional Rolling.

Figure 2.12a, b show the Stress–Strain (engineering) plot for UR and CR. The results of the tensile tests are summarized in Tables 2.4, 2.5. By changing the rolling direction UTS reduces (in RD direction) from 916 MPa, as in unidirectional rolling, to 867 MPa. But it increases the % elongation along 45° direction from 56 to 65 %. In brief, it can be mentioned that cross rolling produces a plate with more isotropic properties in different directions as compared to unidirectional rolling.

Fig. 2.12 Stress–Strain (engineering) curve
a Unidirectional rolling and
b Cross rolling



2.4.2.2 Anisotropy

To find out plastic anisotropy parameter, uniaxial tensile tests were conducted on samples of 25 mm gauge length. Loading on the samples was stopped, as the elongation value reached to 20 %. Table 2.6 shows the values of average anisotropy parameter and planar anisotropy for CR and UR. Cross rolling increased the value of \bar{R} from 0.78 to 0.85, and also the absolute value of planar anisotropy decreased from 0.12 to 0.06. This result indicates that cross-rolling reduces plastic anisotropy of the rolled sample.

Table 2.4 Yield strength and ultimate tensile strength

Direction	Unidirectional rolling		Cross rolling	
	UTS (MPa)	YS (MPa)	UTS (MPa)	YS (MPa)
RD	916	427	867	502
45°	839	442	828	431
TD	860	518	854	432

Table 2.5 Percentage elongation

Direction	Unidirectional rolling		Cross rolling	
	TE (%)	UE (%)	TE (%)	UE (%)
RD	63	44	57	34
45°	56	32	65	43
TD	53	35	52	38

TE: Total Elongation, UE: Uniform Elongation

Table 2.6 Plastic anisotropy

Plastic anisotropy	Cross rolling	Unidirectional rolling
\bar{R}	0.85375	0.78625
ΔR	0.0695	-0.1275

2.5 Conclusion

Change in the direction of rolling during rolling is not a new process and it has been studied for many decades. However, it is only in the last two decades that extensive research work has been done in this area and thanks to the development of new technologies to detect and analyze the texture of a material very critically. Still, there are many areas which need to be explored further so that the application of cross-rolled material can be extended to a much wider field. An in-depth study of the correlation among microstructure, texture, and material properties is obviously required for successful commercial exploitation of the process. Moreover, the application of cross rolling to different alloys as well as composites can be studied in future.

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