The dependence of the strain path on the microstructure, texture and mechanical properties of cryogenic rolled Al-Cu alloy

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Abstract
An investigation was conducted on Al–4%Cu alloy sheets to study the role of deformation path on the strength properties, evolution of microstructure and crystallographic texture during cryogenic rolling. Samples were rolled to two distinct thickness strains (50% and 75%) by unidirectional and cross rolling (bidirectional) routes. The strength and hardness properties were found to be more efficient in the cross rolled samples at 50% reduction than their counterparts rolled unidirectionally. Dynamic recovery was observed at higher rolling reductions on cross rolling. Microscopic features observed by EBSD revealed the occurrence of significant grain refinement on the samples rolled with a change of strain path. Also, the alteration of the rolling route resulted in distinct deformation textures and microstructures. TEM studies pointed out the scattered diffusion of the disintegrated dislocation cores and the redistribution of the second phase particles on higher rolling reductions with the change of strain path. Furthermore, the texture results showed a threefold increase on the Goss/Brass ratio which indicated the good fracture toughness behaviour of the cross rolled samples at lower reductions.

1. Introduction
The lightness combined with high strength in the viewpoint of higher fuel efficiency stands behind the lot more attention of the precipitation hardenable (heat treatable) aluminium–copper alloy in the aerospace and automotive industries [1]. One way to upgrade the strength properties of the aluminium—copper alloys used in the structural parts is to cold roll the same to some extent to get the benefits of grain refinement as the rolling strain conditions both the microstructure and texture evolution [2]. At high strains, the ultrafine grain (UFG) regime plays a major role in the enrichment of mechanical properties of the aluminium alloys [3]. The desirable mechanical strength and hardness can be enhanced further by refining the grain structure using cryogenic rolling as described elsewhere [4, 5]. The cryogenic treatment has established the arrest of dynamic recovery during plastic deformation and resulted in the improvement of strength, hardness and wear properties. As the cryogenic rolling apply relatively lower strain than its counterparts, namely, high-pressure torsion, accumulative roll bonding and equal channel angular pressing, it can be a desirable industrial choice to produce UFG structures [6].

Conventionally, metals and alloys are rolled in a unidirectional way for several decades. Unidirectional rolling is a plane-strain dominated deformation process in which the width of the workpiece remains unchanged. In cross rolling, when the direction of the strain path is changed, the width of the workpiece is also increased. Hence, the major limitations associated with the cross rolling are the length of the rolls and the comparatively lesser dimensions of the sheet that can be deformed. However, cross rolling should be an approach to alleviate the directional dependency of the various mechanical properties in the rolled sheet metals [7]. As the direction of rolling is rotated by 90° in cross rolling, the direction of the resultant shear deformation is
also changed and the material is prone to significant changes on the microstructure and texture [8]. The effects of cross rolling have been studied on several face-centered cubic (fcc) metals like commercially pure Al, Cu, Ni and their alloys [9, 10]. Chino et al have claimed that the cross rolled magnesium alloy exhibited a well-refined microstructure with improved mechanical properties [11]. Wronski et al have reported that the cross rolling has significant effects on the texture, plastic anisotropy and residual stress of the rolled materials [12].

In general, the cross rolling technique is classified into two major categories. 1. TSCR (two-step (or) pseudo cross rolling), where the sample is rolled in a conventional (unidirectional) way for half of the total thickness to be reduced and the direction of rolling is rotated by 90° to roll in the transverse direction until the final thickness is reached [13]. 2 MSCR (multi-step (or) true cross-rolling), where the direction of rolling is changed after every rolling pass. Figure 1 illustrates the schematic drawing of a two-step cross rolling used for the present study. Although cross rolling has been investigated on various instances, the combined effects of the cross rolling and cryogenic temperature have still not been studied extensively. The study was particularly aimed to explore the effects of the change in strain path on the strength properties and microstructure of the rolled Al-4%Cu alloys with different thickness reductions at cryogenic temperature.

2. Experimental details

2.1. Material
The detailed chemical composition of the base material received in T6 condition is reported in table 1.

| Element | Cu   | Si   | Mn  | Mg  | Fe   | Pb   | Zn  | Ti  | V   | Cr  | Al   |
|---------|------|------|-----|-----|------|------|-----|-----|-----|-----|------|
| %       | 4.13 | 0.73 | 0.68| 0.54| 0.27 | 0.06 | 0.05| 0.03| 0.02| 0.02| balance |

Table 1. Elemental composition of the base material: Al-4% Cu alloy.

Figure 1. Sketch of the TSCR process (a) base material, (b) unidirectionally rolled to 50% reduction, (c) rolling direction is rotated by 90° and (d) final sample after rolled in transverse direction for the remaining 50% thickness reduction.

2.2. Experimental setup and procedure
The experimental study was carried out using a laboratory-scale Bonfiglioli® four high rolling mill (figure 2). The rolling speed was 8 rpm and the roll radius was 55 mm. The samples were rolled by two different strain paths (unidirectional and TSCR). The sheets of the base material with the initial thickness of 4.2 mm were cryogenically rolled to the final thicknesses of 2.1 mm and ~1.05 mm, corresponding to the thickness reductions of 50% and 75%, respectively. The reduction level between successive passes was set as 0.1 mm on all process routes of the rolling. The samples were submerged in a bath of liquid nitrogen (LN2) contained in a Dewar flask for 30 min to get rolled at cryogenic temperature (−195 °C). For the subsequent passes, the samples were immersed in liquid nitrogen for 5 min.

Table 2 presents the list of the samples rolled at different process routes. The nomenclature CT signifies the samples rolled at cryogenic temperature.

2.3. Mechanical testing and characterization
The Vickers microhardness and uniaxial tensile tests were conducted to assess the mechanical behaviour of the samples rolled by different rolling routes with various thickness levels. Measurement of the microhardness was carried out using a Wolpert Wilson® micro Vickers tester and the resistance to indentation by the plane-strain compression was investigated. Specimens for the hardness test were prepared by electric discharge machining, mechanical grinding, polishing and chemical etching. The hardness values were measured with a load of 0.1 kg applied on a pyramidal diamond indenter for a dwell time of 10 s. The stress-strain correlations of the rolled samples were measured by the tensile tests using an Instron 5582 universal testing machine. The dog bone
shaped tensile specimens with a thickness of 1 mm were sliced out for the stress-strain tests from the rolled sheets in the longitudinal direction of rolling. The gauge length and width were of 6 mm and 2 mm respectively [14]. The specimens were initially polished mechanically to remove the surface irregularities to ensure the accurate determination of the tensile properties. The tensile tests were carried out at ambient temperature with an initial strain rate of $1 \times 10^{-3}$ s$^{-1}$.

To distinguish the various microstructural features and texture properties of the differently rolled alloy samples, the orientation imaging microscopy was conducted using an Electron Back Scattered Diffraction (EBSD–FEI Quanta 3D FEG) detector attached with a Scanning Electron Microscope (SEM). The specimens for the EBSD analysis were prepared by mechanical grinding followed by electro-polishing. The polishing operation was carried out at 20 V for 15 s by a stabilized direct current power supply. A mixed solution of 90% ethanol and 10% perchloric acid was used to electro-polish the specimens. EBSD maps of the specimens were obtained by the automatic scans with a step size of 0.2 μm and the analysis was carried out with an accelerating voltage of 20 keV. The dislocation boundary characteristics of the specimens were captured in detail by the JEOL JEM 2100 high-resolution transmission electron microscope (HRTEM) with a Gatan Orious camera operated at an accelerating voltage of 200 KeV. Disks of 3 mm diameter and 0.1 mm thickness were dimpled from the center portion of the rolled sheets for the TEM analysis. The disks were finally processed by ion beam milling at argon atmosphere to get the electron transparent TEM specimens.

**Table 2.** Identification of samples used in the present experiment.

| Sample | Process condition |
|--------|-------------------|
| Base material | as received Al-4%Cu alloy |
| CT50S | straight/unidirectionally rolled to 50% thickness reduction |
| CT50C | cross rolled to 50% thickness reduction |
| CT75S | straight/unidirectionally rolled to 75% thickness reduction |
| CT75C | cross rolled to 75% thickness reduction |

**Figure 2.** The rolling mill used for the unidirectional and cross rolling experiments.
3. Results and discussion

3.1. Tensile properties
To quantify the effect of change in strain path on the mechanical behaviour of the investigated samples, the load-displacement parameters obtained from the uniaxial tensile test were converted in terms of engineering stress-strain values. In each condition, two specimens were tested. Figure 3 represents the strength and elongation of the samples rolled at different processing routes. The Yield Strength ($Y_S$) and the Ultimate Tensile Strength ($UTS$) of the base material were of 411 MPa and 484 MPa, respectively. As the cryogenic treatment arrests the dynamic recovery during deformation, an increase in the rolling strain, should lead to an enhancement in the $Y_S$ and $UTS$ of the liquid nitrogen treated samples. After a unidirectional reduction of 50% ($CT50S$), the exhibited $Y_S$ and $UTS$ values were of 467 MPa and 534 MPa, respectively. On the further increase of the rolling strain from 50% to 75% in the unidirectional way ($CT75S$), the accumulated deformation also increased the values of the $Y_S$ and $UTS$ to 494 MPa and 555 MPa, respectively. When the samples were subjected to the TSCR, the tensile properties were found to be enhanced enormously. On the change of strain path imposed with a thickness strain of 50% ($CT50C$), the $Y_S$ and $UTS$ values were found increased to 510 MPa and 583 MPa, respectively. The values of the strength parameters obtained by the change in strain path ($CT50C$) were found higher than the values obtained by unidirectional rolling at 50% and 75% reductions. On the other hand, the cross rolled samples at 75% rolling reductions ($CT75C$) resulted in the $Y_S$ and $UTS$ of 503 MPa and 568 MPa, respectively, which were slightly lower than the strength properties of the $CT50C$. The elongation was found slightly increased with the increasing thickness reduction from 50% to 75% on unidirectional rolling. The change of strain path caused the decrease in elongation on both thickness reductions compared to the unidirectional rolling. The elongation was at its least on the cross rolled sample of 50% reduction ($CT50C$). Obviously, the elongation was compromised on the increase in strength of the cross rolled samples.

Based on the statistical analysis of the stress–strain results, it can be ascertained that the tensile properties increase continuously with increasing strain on unidirectional rolling. Compared to the straight rolled samples, the cross rolled ones exhibited higher mechanical strength (both $Y_S$ and $UTS$) on both lower (50%) and higher (75%) reductions and the deviation of the $UTS$ between the unidirectional and cross rolled samples was high at lower reductions. However, the $CT75C$ contradicted slightly with the results of cross rolling of the previous reduction ($CT50C$) on both $Y_S$ and $UTS$ values. Nevertheless, the strength values of the $CT75C$ were higher than the corresponding values of the base material, $CT50S$ and $CT75S$, but lesser than the $CT50C$ alone.

3.2. Microhardness
The Vickers microhardness ($Hv$), represents the resistance to local plastic deformation by indentation. In general, the cryogenic treatment results in an increase of the hardness. The hardness profiles of the unidirectional and cross rolled samples rolled at different thickness levels are shown in figure 4. The initial hardness of the base material was at 120 $Hv$. The histogram shows that the hardness values of the unidirectionally rolled samples increase with the increasing rolling reduction ($CT50S$ and $CT75S$). On the other hand, a slight decline of the hardness was found on the cross rolled route with higher reduction ($CT75C$) compared to the lower reduction ($CT50C$). Yet, the $Hv$ of the $CT75C$ was higher than the base material, $CT50S$ and $CT75S$. The cross rolled samples exhibited significantly higher hardness compared to the hardness of the base material.
unidirectionally rolled samples. The highest value on the micro-hardness was recorded by CT50C (168 Hv). The hardness results were seemed to be in correlation with the results of the ultimate tensile strengths of the rolled samples. The results of the slight decrease in the mechanical properties at higher strains during cross rolling could be ascribed to the beginning of dynamic softening due to the dynamic recovery by the increased deformation of the alloy. The softening or decline in strength could be attributed to many reasons including the thermomechanical induced recovery at higher deformation levels. The reduction in strength after reaching a peak is coinciding with the results of the works demonstrated by Gavgali et al [15].

### 3.3. Microstructure

#### 3.3.1. EBSD analysis

The backscattered diffraction analysis was carried out to probe the average grain size and distribution of the textural components in various process routes of the rolled Al-4%Cu alloy. Figure 5 shows the microstructure of the base material as well as the other rolled conditions.

Figures 5(a) and (b) illustrate the presence of coarse grains and orientation of the same, respectively, in the base material before rolling. Also, figure 5(a) represents the distribution of the second phase particles in black coloured spots mostly along the grain boundaries in the base material. The bimodal grain size distribution of the various processed conditions is illustrated in figures 5(c)–(f). Figure 5(c) shows a typical deformation-induced banded structure (appear in straight lines along the rolling direction) obtained by the unidirectional rolling at a lower reduction (CT50S). The same can be seen diminished by the effect of cross rolling with diffusion of grains in the transverse direction as shown in figure 5(d) (CT50C). The deformation bands usually arise at severe strains in the aluminium alloys during unidirectional rolling. The severe strains would have been caused by the earlier levels of deformation of the base material. Annihilation of the deformation bands during the change of strain path always leads to the evolution of better strength properties. The bulk structures on figure 5(e) represents the accumulation of elongated grains mainly along the rolling direction during the higher rolling reductions (CT75S) and figure 5(f) shows the fragmentation of the same into very fine equiaxed grains. From the IPF image of the CT75C, it is clear that the grains became progressively smaller on cross rolling. In general, the grains with the high aspect ratio usually get fragmented by the shear deformation of the rotated grains on the progressive step of cross rolling. The more homogeneous microstructure obtained by the uniform spread of fine refined grains on the rolled as well as the transverse directions exhibits the effect of change in deformation path on higher thickness reductions. The orientation imaging micrographs revealed that the grain refinement is enormous in cross-rolling compared to unidirectional rolling with comparatively more uniform grain size.

#### 3.3.2. Grain size distribution

To quantitatively probe the evolution of microstructure resulted by the different strain path conditions, the EBSD grain size analysis was carried out. The volume fractions of the various grain size ranges obtained by the unidirectional and bidirectional rolling are shown in table 3. Initially, the base material was found to be fully composed of coarse grains. The fine grains started to evolve with the unidirectional rolling of the samples (CT50S). The table depicts that the volume fraction of the coarse grains (>5 μm) present in the base material is considerably reduced (from 99.82% to 45.93%) at the initial stages of the cross rolling (CT50C). The observed
drop in the fine grain size (<1 μm) from 11.88% to 4.6% and the corresponding increase in the other ranges (>1 μm) in CT75S could be due to the evolution of elongated grains at excessive strains in unidirectional rolling. Generally, the large grains on the surface elongate in the direction of rolling due to tension at high strains. The elongation of grains with increased aspect ratio at higher rolling reductions in commercially pure aluminium sheets has previously been reported by Rahimi et al [16]. When the unidirectionally rolled ones (CT75S) were cross rolled (CT75C), the elongated grains were broken down into fine equiaxed grains and this was believed to be the reason behind the drastic increase in the volume fraction of the grain size of <1 μm (from 4.6% to 36.93%). This indicates a more homogeneous distribution of the fine grains in the cross rolled samples at higher reductions (CT75C). The significant grain refinement attained by the cross rolling can be a good explanation for the increase in UTS of the cross rolled samples than their counterparts rolled in the unidirectional way as observed by the tensile tests.

Figure 5. EBSD (a) image quality map, (b) inverse pole figure (IPF) map of the base material; IPF maps of the differently rolled Al-4% Cu alloy samples: (c) CT50S, (d) CT50C, (e) CT75S and (f) CT75C.
3.3.3. TEM analysis

The observed TEM micrographs (figure 6), illustrate the effect of change in strain path on the dislocations. Generally, the cryogenic rolling restricts the dynamic recovery and the dislocation cores are usually prevented from disengaging in unidirectional rolling. Moreover, as the width of the samples is constrained on the plane-strain deformation, intact clusters of the strong dislocation entanglements obviously evolve in the unidirectionally rolled specimens. This is believed to be one of the reasons behind the increase in the strength properties with increasing strain levels on the unidirectional rolling. Figure 6(a) depicts the strongly bundled dislocation cores in the unidirectionally rolled Al-4%Cu alloy specimens at higher reductions (CT75S). On the cross rolled route, the dislocations are found disintegrated in orthogonal directions as shown in figure 6(b). Fan et al have reported that the change in the rolling direction could enable the slip systems from several directions to eliminate the traces of the deformation substructure developed on the previous stages of strains [17].

From the TEM micrographs (figures 6(a) and (b)), it is evident that the dislocations walls and cores bundled by the previous stage of the unidirectional rolling are partially destructed and heterogeneously distributed irrespective of the rolling direction which is supposed to be due to the change in direction of the shear deformation. The annihilation of the dislocations observed on the cross rolled samples of the Al-4%Cu alloys is in correlation with the results of the dislocation structures developed during cross rolling by suwas et al [13].

The energy dispersive spectroscopy (EDS) analysis indicates the presence of fine precipitates of $\theta$-Al$_2$Cu and intermetallics of AlCuMg (figures 6(c) and (d)). Generally, at an initial stage of deformation, the particles of the second phase resist the movement of dislocations in precipitation-hardenable alloys. Figure 6(e) represents the accumulated dislocations structure of the CT75S retained intact by the intermetallic particles on the unidirectional rolling. When a change of strain path is imposed, the change in the direction of shear deformation tends to reassign the deformation substructures developed during the previous stages of deformation. At higher strains, the ability of the precipitates to retain the dislocation structures would be reduced which could eventually lead to the beginning of softening. The dislocations interact, annihilate and getting rearranged when the second phase particles are overpowered by the severe levels of strain. It is evident from the figures 6(f) and (g) that the dislocations are diffused along with the disbursed particles which could cause the reduction in strength at higher rolling reductions on the change of strain path.

3.4. Texture

The crystallographic texture which is an inherent characteristic of the aluminium alloys has a significant influence on their physical and mechanical properties. Table 4 illustrates variations of the volume fractions of the high angled grain boundaries (HAGB), texture intensity and the Goss/Brass ratio as a function of strain path of the rolled Al-4%Cu alloy. These properties closely associated with the evolution of texture during deformation.

From the table 4, it is inferred that there is a twofold increase (from 2.4% to 4.8%) on the fraction of HAGB levels at higher thickness reductions in cross rolling (CT75S and CT75C). As a result, the softening effect could be ascribed on higher rolling strains with the change of strain path. Notably, the grain refinement is the predominant factor on the evolution of mechanical properties. Hence, the effect of softening could not be of a significant level as the levels of the grain refinement were found enormous on the cross rolled samples. This is in agreement with the slight reduction of the strength properties in terms of UTS and hardness at higher reductions of cross rolling. Table 4 indicates that there is only a slight increase in the texture intensity when the samples are cross rolled. As the change in deformation path changes the formation of substructure on the previous path of plastic deformation, this causes the change in texture intensity. The threefold increase in the Goss/Brass ratio by cross rolling exhibits good fracture toughness at 50% reduction [18, 19]. On higher reduction levels, the Goss/Brass ratio decreased due to the higher volume fractions of the brass component. However, at higher reductions

| Table 3. Statistical results of the grain size distribution affected by the change in strain path of the rolled Al-4%Cu alloy samples. |
|-----------------------------------------------|
| Volume fraction (%) of grain sizes           |
| <1 $\mu$m | 1 $\mu$m–5 $\mu$m | > 5 $\mu$m |
| Base material                  | 0.01  | 0.13  | 99.82 |
| CT30S                         | 11.88 | 26.52 | 61.55 |
| CT50C                         | 28.8  | 25.17 | 45.93 |
| CT75S                         | 4.6   | 29.06 | 66.31 |
| CT75C                         | 36.93 | 47.54 | 15.43 |
Figure 6. TEM images of the (a) entangled dislocation cores at CT75S, (b) diffused dislocation of the CT75C, (c) intermetallics of the Al-4%Cu alloy; (d) EDS images of the Al₄Cu and AlMgSi intermetallics; (e) dislocations retained by the intermetallics at CT75S; (f) and (g) bright and dark field images of the CT75C, respectively, with the diffused dislocation structures along the distributed precipitates.

Table 4. Evolution of crystallographic properties of the rolled Al-4%Cu samples by different process routes.

| Condition | HAGB(%) | Texture intensity | Goss/Brass ratio |
|-----------|---------|------------------|-----------------|
| CT50S     | 2       | 1.903            | 0.33            |
| CT50C     | 3.1     | 2.161            | 0.94            |
| CT75S     | 2.4     | 2.044            | 0.16            |
| CT75C     | 4.8     | 2.179            | 0.15            |
either by unidirectional or cross rolling methods, the Goss/Brass ratio is almost the same which indicates that there is no major change on the fracture toughness properties.

The evolution of the typical rolling and recrystallization texture components of the rolled Al-4%Cu alloy samples at cryogenic temperature is shown in figure 7. In general, the Brass \{110\} \langle 112 \rangle, Copper \{112\} \langle 111 \rangle and S \{123\} \langle 634 \rangle are termed as rolling textures and the Cube \{100\} \langle 001 \rangle and Goss \{110\} \langle 001 \rangle are known as recrystallization textures. The base material was found to have the higher volumes of the Copper, Cube and Goss textures. On 50% reduction in the unidirectional rolling, the Copper, Cube and Goss textures were found reduced whereas the volume fraction of the brass texture was found increased. On the subsequent reduction of 75%, the unidirectional rolling increased the volume fractions of the Cube, Brass and S components while the Cu component was found reduced. When the material was cross rolled at lower reductions, the volume fraction of the copper remained the same as it was on the unidirectional rolled condition. The Cube and Goss were found increased with a corresponding reduction of Brass texture. The formation of cube texture is a common phenomenon during the recrystallization of high stacking fault energy materials. The notable increase of the recrystallization components (Cube and Goss) with a declining primary deformation component (Brass), exhibits the effect of dynamic recrystallization which could also contribute reasons for the grain size variations during the cross rolling process (CT50C). The absence of the notable changes on the volume fractions of the Cube and Goss on both process routes ruled out any further activity of dynamic recrystallization at higher rolling reductions (CT75S and CT75C) [20]. Meanwhile, the Brass component stands apart as the dominant component at higher reductions on both processing routes followed by a strong increase in the volume of S component. This could be one of the reasons behind the appreciable strength properties of the cross rolled samples with higher rolling reductions.

The representative components of the orientation distribution function (ODF) plots of the rolled samples calculated from the \(\{111\}\), \(\{200\}\) and \(\{220\}\) planes are shown in figure 8. A typical rolling texture, with high intensities of Cube and Goss, was found on the base material. The CT50S represents the diminishing of the Cube and Goss on the unidirectional rolling. The CT50C represents a uniform concentration of all recrystallization and deformation components. The samples rolled at 75% reductions represent qualitatively similar ODF on both CT75S and CT75C, with the presence of typical \(\theta\) and \(\gamma\) fibres. Also, the absence of the \(\beta\) fibres was noticed on both rolling reductions. The observations from the ODF plots are coinciding with the observed changes in the volume fractions of the texture components at lower and higher rolling reductions.

4. Conclusions

To this end, the effects of change in deformation path on the mechanical behaviour and microstructure of the Al-4%Cu alloy sheets rolled at cryogenic temperature with two distinct rolling strains were evaluated. Combined the quantitatively analysed results of the tensile and hardness values and characterization of microstructural aspects produced by the unidirectional rolling and cross rolling routes, the results were concluded as follows:

1. Cryogenic rolling imparted appreciable enhancement on the UTS and hardness of the samples on both rolling routes. The experimentally measured mechanical properties were found to be strongly affected by
the change in strain path. Results from the tensile and hardness perspectives indicated that the material attained its maximum strength by the deformation-induced grain refinement at 50% reduction level by the change of strain path. Also, the yield strength was found enhanced by cross rolling with a little reduction in elongation. While the higher strains imparted better tensile properties and hardness by the unidirectional rolling, the cross rolled samples exhibited a slight reduction of the same which could be ascribed to the effect of dynamic softening due to dynamic recovery. The drastic increase of the HAGB fraction with the increasing rolling strain and change in strain path indicates the beginning of dynamic softening on the cross rolled alloys at higher reductions.

2. The cryogenic treatment and the strain path strongly influenced the microstructure of the deformed materials. The increase in strength properties corresponded well with the additional grain refinement by the rolling deformation on both process routes. Cross rolling was found to enhance the microstructure with better grain refinement than the unidirectional rolling on both reduction levels. Cross rolling resulted in a more homogeneous and refined microstructure at higher reductions. Though the TEM studies revealed the slightly disintegrated and destabilized dislocation cores by the change in strain path, the effective grain refinement is found to be the principal dominating factor in enhancing the strength properties by cross rolling. Unfortunately, at higher rolling strains on cross rolling, the distribution of the strengthening precipitates could not accumulate dislocation cores further, which could be ascribed as the reason for the slight reduction in strength of the CT75C compared to CT50C.

3. The threefold increase in the Goss/Brass ratio made it evident that the samples attained higher fracture toughness by cross rolling at 50% rolling reduction. The significant increase in Cube and Goss texture components by cross rolling indicated the occurrence of dynamic recrystallization at 50% thickness reduction. However, at higher reduction levels with the change in strain path, there was no significant change on the volume fractions of the Cube and Goss which ruled out any further tendencies of recrystallization.
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