# FUTURISTIC TRENDS IN CRYOGENIC ROLLING

**Abstract**

The market is experiencing a massive increase in demand for lightweight vehicle components. The majority of these parts are produced via metal-forming procedures, which result in lightweight, sturdy, and rigid parts. The majority of rolling processes are employed to improve the material's ductility and strength. During the deformation, a further cross-rolling step is introduced to alter the rolling surface. This essay has reviewed the sheet aluminum alloy's mechanical characteristics. The essay concentrates on the existing context, recent developments, and predicted directions for the future. This article compares the effectiveness of several rolling procedures, including room temperature rolling and cryogenic rolling, on a variety of materials in the literature.

**Keywords:** Aluminium alloys, cold rolling, cryorolling, microstructure

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## I. INTRODUCTION

Lightweight materials are essential to the aerospace and automotive industries because they increase fuel efficiency and lower pollutants. Because they have a higher strength to weight ratio than steel, aluminum alloys must now be used as lightweight structural materials. Huge interest in these materials has also been sparked by the growing demand for complicated parts with little material waste and maximum energy savings. Precipitation (age) hardening at high temperatures is primarily responsible for giving heat-treatable Al alloys their strength[1]. Due to their qualities including high fatigue strength and good corrosion resistance, these alloys are widely employed in the automotive, aerospace, and marine industries. Al alloys that cannot be heat-treated are typically strengthened at room temperature by strain hardening. Despite the common strengthening techniques, aluminum alloys typically have a lower tensile strength that is just 200–300 MPa. Various thermo-mechanical mechanisms that result in different microstructural evolution and property alteration can be used to further improve strength.[2]

Strength and toughness are both increased when metallic materials' grains are refined to very small sizes on the order of a few hundred nanometers.[3] Smaller grains have a wider grain boundary network, which makes it more challenging for dislocations to move about. As a result, the yield stress—the amount of stress necessary for plastic deformation—increases. Additionally, lowering grain size to the nanoscale range can have an impact on the mechanical, chemical, and physical properties of materials.[4]

Applications in engineering use aluminum alloys with a variety of mechanical characteristics. Al alloys are widely employed in the aircraft sector because of their decreased weight and high corrosion resistance. The usage of aluminum alloys in vehicle production is on the rise in the automotive sector. The lesser strength and formability of aluminum alloys is one of its drawbacks, though. The development of aluminum alloys' mechanical characteristics has drawn the attention of material scientists. Serious plastic deformation procedures can increase the strength of ductile materials. In order to create Ultra Fine Grain Structures (UFGS), which have stronger strength at the expense of ductility, parent materials must undergo very high strains throughout these standard metal forming procedures (Naka & Yoshida, 1999). Some of these include Cryogenic rolling (CYR), Accumulative roll-Bonding (ARB), High Pressure Torsion (HPT), and Equal Channel Angular Pressing (ECAP).[5]

One method for producing nanostructured bulk materials from their bulk counterparts at cryogenic temperatures—roughly -196° C for liquid nitrogen—is cryogenic rolling, also known as cryorolling[6].Most of these techniques call for sizable plastic deformations (strains substantially greater than unity). The prevention of the dynamic recovery during cryorolling preserves the deformation in the strain-hardened metals[7]. A two-high rolling mill is used in the schematic diagram of the standard cold rolling and cryogenic rolling operations in Figure 1. The sheets are rolled at room temperature through a number of passes in conventional cold rolling (CCR) to get the desired final thickness.[8]

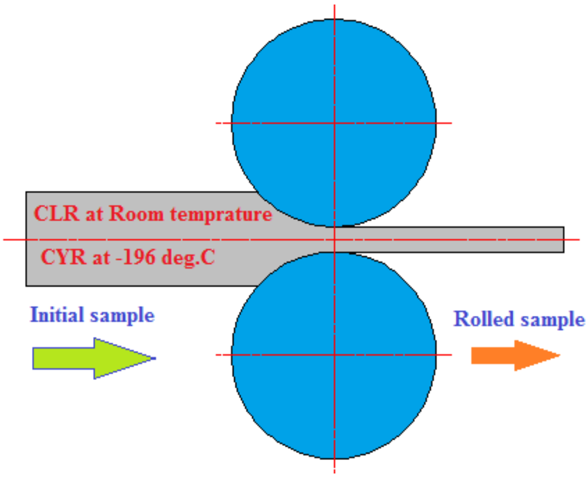


**Figure 1:** A schematic showing conventional cold rolling and cryogenic rolling.[8]

Low temperature annealing of cryorolled aluminum alloy sheets (to minimize considerable loss of strength) could result in sheets with an excellent balance of strength and formability. This is intended to broaden the range of applications for aluminum alloys in the automotive and other industries.

Aluminum alloys reinforced by cold or cryorolling lose ductility, rendering the material unsuitable for forming purposes. As a result, the cold rolled (CLR) and cryorolled (CYR) sheets were given an appropriate heat treatment to improve ductility without compromising too much strength. To achieve the necessary mix of strength and ductility, a partial annealing (recovery annealing) at 150-300° C (below the recrystallization temperature) for 30 minutes was performed.[8]

## II. IMPORTANCE OF ALUMINUM ALLOYS

Nowadays, when environmental preservation and energy conservation are critical, there is a greater interest in weight reduction in all types of transportation vehicles than ever before. There has been a growing trend toward the usage of light metals and their alloys, such as aluminum alloys, which offer significant weight reduction potential in the automotive, marine, and other industries[9] [10]. Because the density of aluminum alloys is roughly one-third that of steel, several of the alloys have a good strength-to-weight ratio. Work hardening and heat treatment can improve the mechanical characteristics of Al alloys.[11] Aluminum alloys are resistant to corrosion in marine environments, retain hardness at low temperatures, are non-toxic, and can be recycled with just approximately 5% of the energy required to make Al from its ore.[12] [13]

Vehicle weight reduction is one of the most important ways to reduce fuel consumption. Custom component design and material selection are the two fundamental techniques, and they are inextricably linked. In terms of materials, there has been a tendency toward using light metals and their alloys instead of traditional materials such as steel. Aluminum, magnesium, and their alloys are the most promising materials, while little research has been done on the use of nonmetallic materials. Significant attempts have been made to replace conventional steel grades with aluminum alloys in the manufacture of auto body parts due to their promising weight savings, lower fuel consumption, pollution

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reduction, and other benefits such as strong corrosion resistance. Because of their acceptable mechanical properties, Al-Mg type alloy sheets are a cost-effective promising material for sheet metal forming applications.

## III. LIMITATIONS OF ALUMINUM ALLOYS FOR SHEET METAL FORMING

Though aluminum alloy sheets have some advantages over steel, as mentioned in the preceding section, they also have several significant restrictions that limit their usage for sophisticated sheet forming applications. Some of these constraints are as follows:

- Aluminum alloys have lesser strength and ductility than conventional steel grades, which are widely employed in the aerospace, shipbuilding, and automobile industries.
- Aluminum alloys have substantially worse formability than low carbon steel grades such as Extra Deep Drawing (EDD) steels and Interstitial Free (IF) steels. In deep drawing, the LDR of aluminum alloys is typically 1.6-1.8, but EDD/IF steel sheets can obtain LDRs as high as 2.1-2.3. Multi-stage deep drawing is utilized to obtain massive LDR, which increases the number of forming processes and incurs additional tooling costs.
- Aluminum panels have lower dent resistance, energy absorption, and crash resistance than steel panels.
- Aluminum alloys have a higher susceptibility for wrinkling and cracking.

## IV. TECHNIQUES FOR ENHANCING STRENGTH OF ALUMINUM ALLOYS

Due to the limits of current methods for producing aluminum alloy sheets, innovative approaches such as Severe Plastic Deformation (SPD) processes are being explored to manufacture aluminum alloys with high strength. Severe plastic deformation (SPD) procedures can produce high strength ultrafine grain (UFG) structured materials. Many SPD procedures, such as equal channel angular pressing (ECAP), cryogenic rolling, accumulative roll-bonding (ARB), high-pressure torsion (HPT), and others, have been developed.[14]

1. **Cryogenic Rolling of Aluminum Alloys:** Cryogenic rolling, often known as cryorolling, is the rolling of metals at cryogenic temperatures using a liquid nitrogen bath. This is one of the probable methods for creating nanostructured materials in sheet form from bulk materials. Rolling pure metals and alloys at cryogenic temperatures suppresses dynamic recovery, and the density of accumulated dislocations increases with the number of cryorolling passes, resulting in ultrafine-grained structures with high angle grain boundaries, as reported in the majority of the literature.[15] [16] As a result, stronger and harder ultra-fine grain structured sheet materials can be generated than with traditional cold rolling. The process enables the creation of ultrafinely structured, stronger metal and alloy sheets. Despite the fact that ductility diminishes with cryorolling, recovery annealing can be used to some extent to adjust the ductility of metals and alloys.[17]

   The literature has noted that cryorolling has shown to be a successful method for boosting the strength of certain aluminum alloys. After cryorolling, the necessary balance of ductility and strength can be obtained with the right heat treatment. However, the majority of these investigations noted the improvement of mechanical characteristics and microstructural development in numerous aluminum alloys. In the case of cryo-rolled aluminum alloys, formability—a crucial component of Al alloy sheets for forming—has not been researched. As low formability of cryorolled aluminum alloys is anticipated, cryorolled sheets can be made more formable by using atypical forming methods like hydroforming.[18] [19] [20]

2. **Microstructural Changes during Cryorolling:** By suppressing dynamic recovery, the drop in deformation temperature lessens the annihilation of dislocations. Several authors have reported this. Figure.2 shows the mechanism of grain refining during cryorolling.

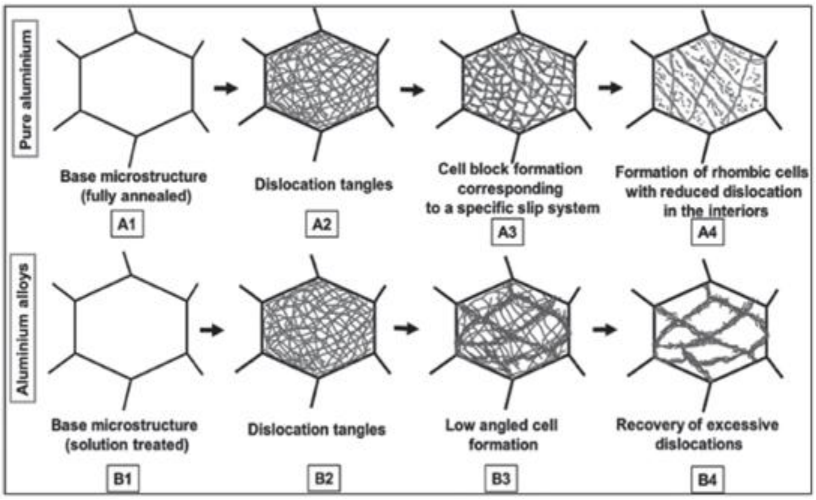


**Figure 2:** Development of sub-grains during cryorolling of pure Al and Al alloys

Many scientists investigated how cryorolling affected the microstructure of various materials and discovered that deformation at liquid nitrogen temperature can result in the production of ultrafine-grained materials[21]. By causing a thermal (work) hardening, the deformation at very low temperatures slows dynamic recovery and increases dislocation density. The structural characteristics of cryorolled materials are quite complex, and they include non-equilibrium grain boundaries, twin boundaries (in the case of low stacking fault energy materials), high internal stress, high lattice distortion, and changes in the local phase composition, in addition to having a high density of extrinsic dislocations. Applied total strain, strain rate, and liquid nitrogen immersion period are some of the external variables that affect the cryorolling process. Work to raise the temperature to that of liquid nitrogen[22]. For instance, Changela et al.[23] recently calculated the amount of time needed for samples to warm up to the liquid nitrogen temperature before to cryorolling.

The time needed for the three mm thick sheet samples used in their research to attain the liquid nitrogen temperature was determined using the lumped capacitance approach for varying immersion times.

When face-centered cubic (FCC) materials are deformed at low temperatures, stacking fault energy has a significant impact on the development of substructure features[24]. Recently, Dhal et al [25] examined the stacking fault energy of pure aluminum and aluminum alloys (AA 5083 and AA 2014) under cryorolling. Pure aluminum has a high SFE (166 mJ/m2) and is predicted to recover from cryorolling more quickly than alloys with lower SFE like AA 5083 (33 mJ/m2) and AA 2014 (98 mJ/m2).

Al alloys with alloying elements have lower SFE and hence slower recovery kinetics. The authors of this work also covered the numerous dislocation accumulation and restoration mechanisms for grain refinement in cryorolling of pure aluminum and aluminum alloys. The dynamic recovery process for pure aluminum and aluminum alloys during cryorolling is depicted step-by-step in Figure.2 [25]. Different defects (dislocations, vacancies, etc.) are produced during the early stage of cryorolling at low plastic strains as a result of the dissolution of atomic bonds and fill gaps both within and outside of the grains. As more deformation occurs, dislocations become interconnected, resulting in a tangled microstructure, as seen in Figure.2 (A2 and B2). Dislocation annihilation and multiplication both occur simultaneously with increasing plastic strain.

Pure Al has rapid dislocation contacts followed by polyslip deformation due to the high stacking fault energy and lack of solute atoms, which ultimately causes considerable cell development inside the parent grains. Each cell block is made up of a low energy architecture of disordered dislocations. The rate of strain hardening is substantially higher when Al alloys (A3 and A4 in Figure.2) are cryorolled, and the tangled microstructure results in a comparatively orderly structure during cell formation. Dense dislocations make up the cell borders, and when dislocations within the cells are eliminated, fine sub-grains with a little higher misorientation arise [25].

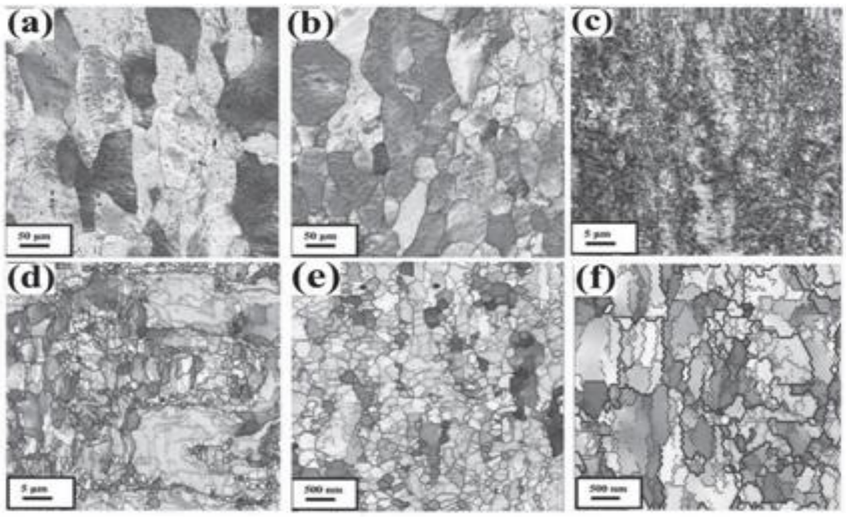


**Figure 3:** EBSD micrographs of AA 6063 alloy in cryorolled (CYR) and cold-rolled conditions at different strains: (a) CYR 0.4, (b) CR 0.4, (c) CYR 2.3, (d) CR 2.3, (e) CYR 3.8, and (f) CR 3.8

Figure.3 from Panigrahi and Jayaganthan [26] illustrates the microstructural evolution of AA 6063 alloy samples subjected to cold rolling and cryogenic rolling under three distinct true strain levels: 0.4, 2.3, and 3.8. According to Figures 5.3(a) and (b), the grains in both samples have undergone a 0.4 strain elongation along the rolling direction. At a strain of 2.3, sub-grain fragmentation and elongation were seen along the rolling direction (Figure.3(c) and (d)). The majority of the dislocations inside the elongated

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grains in the cryorolled sample were converted into equiaxed sub-grains at a total true strain of about 3.8 (Figure.3 (e)). However, at comparable strain, this change was not seen in the cold-rolled samples (Figure.3 (f)).

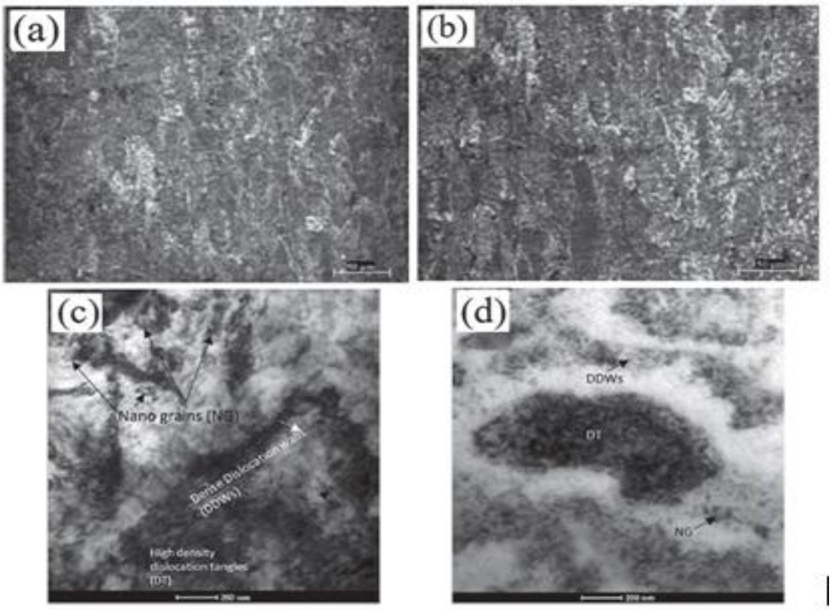


**Figure 4:** Optical and TEM microstructures of AA 5083 alloys in cryorolled (a) and (c), and cold rolled (b) and (d) conditions[27]

The microstructure evolution of cryorolled and cold rolled samples was studied by Feyissa et al. [27], who found that optical microscopy was unable to distinguish grain boundaries in either sample clearly and that grain size could not be determined from the optical microstructures (Figure.4 (a) and (b)). Figure.4 (c) and (d) illustrate how TEM analysis was used to examine the microstructure evolution of cold rolled and cryorolled samples and quantify the grain size. The average grain size of the cryorolled sample was determined to be 200 nm, and it displayed highly dense dislocations with cellular structure (Figure.4(c)). These findings are in line with those of Singh et al.[28]. The absence of adiabatic heating during cryorolling, which inhibited dynamic recovery, was the main cause of the high density of dislocations in cryorolled materials. Due to the existence of several sub-grains that were absent from the cold rolled samples, higher grain refinement was attained in the cryorolled samples (Figure.4 (d)).

The key elements affecting the cryorolled microstructure are the dislocation structure and local misorientation. The misorientation between adjacent grains or sub-grains is represented by the local misorientation. One tool for analyzing dislocation structures and local misorientation is EBSD paired with kernel average misorientation (KAM). For cryorolled AA 5083 and AA 6061 alloys, Changela et al.[29] applied KAM analysis to determine local misorientation and KAM distributions. The KAM maps and distributions of the solutionized and cryorolled AA 5083 and AA 6061 samples are displayed in Figure.5[29]. Figure.5 (b) and (d) show that the KAM value in CYR 5083 is nearly three times that in solutionized state, whereas Figure.5 (f) and (h) show that it is nearly twice that in 6061. larger KAM value equates to larger dislocation density, claim Zhong et al.[30].

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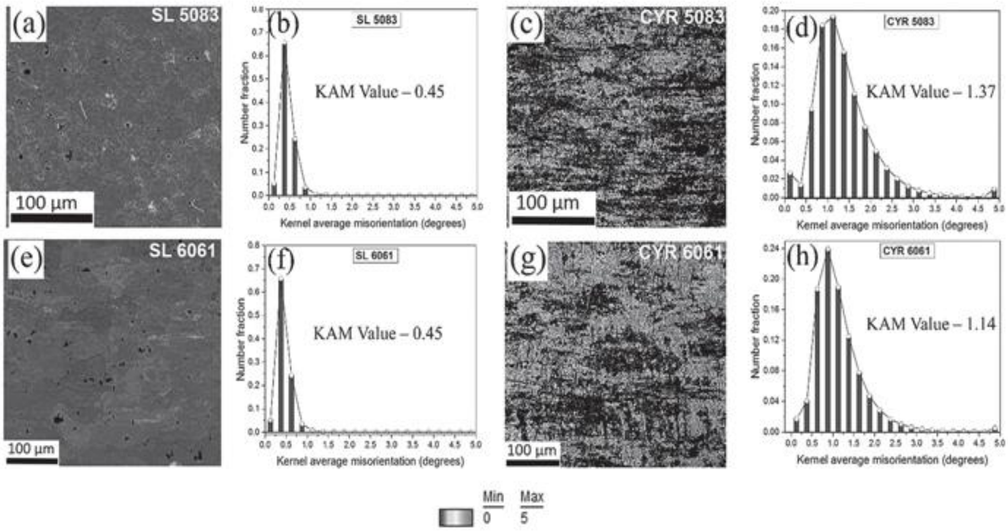


**Figure 5:** KAM maps and distributions of (a) and (b) SL 5083, (c) and (d) CYR 5083, (e) and (f) SL 6061, and (g) and (h) CYR 6061

Additionally, when compared to solutionized samples, the KAM peak in cryorolled samples migrated towards higher angles, indicating significant strain fields near dislocations. AA 7075 alloy's microstructure was studied by Jayaganthan et al.[31] utilizing electron backscattered diffraction (EBSD) and transmission electron microscopy (TEM).

The misorientation distribution obtained from EBSD is shown in Figure.6 (a) and (b). When compared to the cryorolled sample, the solutionized sample exhibits a greater fraction of high angle grain boundaries (HAGBs). The cryorolled sample's TEM image (Figure.6(c)) with a 90% thickness reduction reveals elongated grains in the submicron range of 300–400 nm. The nanometer-sized grain contains a significant number of dislocations. While a significant portion of unrecrystallized grains are present in the room temperature rolled sample, Panigrahi and Jayaganthan[32] found a combination of unrecrystallized and equiaxed recrystallized grains in cryorolled AA 7075 alloy at a higher true strain of 3.4.

Figure.6 (d) depicts the TEM picture of the cryorolled AA 5083 alloy at 90% thickness reduction and the associated SAED pattern. The diffused rings in the SAED pattern show that there are many low angle grain boundaries in the alloy CYR AA 5083. Along with dislocation tangles (shown by squares) and small dislocation cells (marked by arrows), large numbers of sub-grains (indicated by oval shape) are also seen.

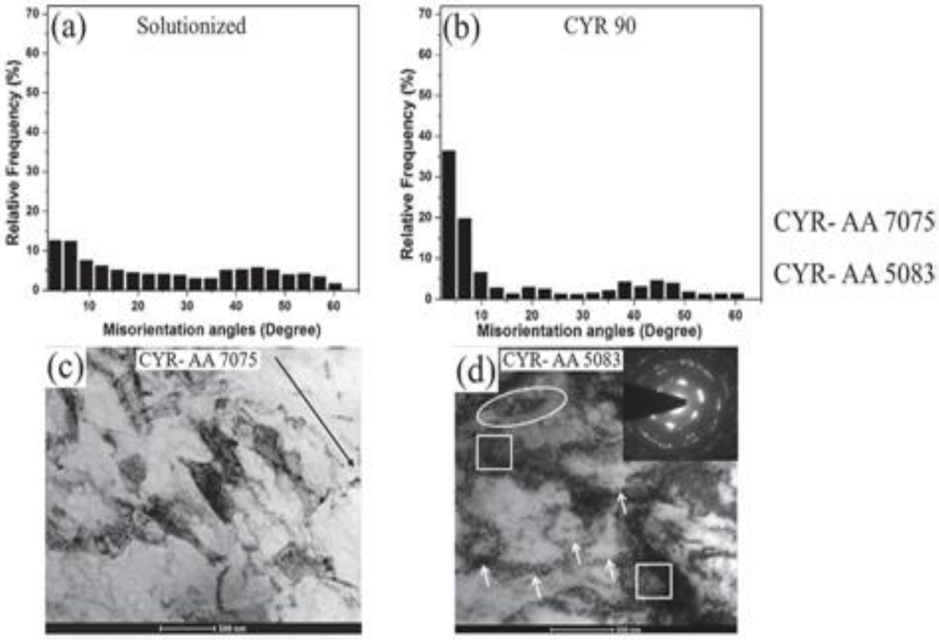


**Figure 6:** Misorientation distribution of AA 7075 alloy for the condition of (a) solutionized and (b) Cryorolled with 90% thickness reduction, and (c) TEM microstructure of cryorolled Al 7075 alloy sample at 90% of thickness reduction [46]. (d) TEM image of cryorolled AA 5083 alloy at 90% of thickness reduction.

## V. EFFECT OF HEAT TREATMENT AND POST PROCESSING ON CRYOROLLED SHEETS

As previously indicated, as-cryorolled sheets have low strain hardening capacity and weak ductility at room temperature, which restricts their industrial applicability. For cryorolled material to be sufficiently ductile for sheet metal forming applications without considerably losing strength, it is vital to evaluate the post-heat treatment conditions. After cryorolling, heat treatment or post processing demonstrated to be effective ways to improve mechanical properties with controlled microstructure.

Heavy cold wrought metals' structural characteristics can be quantitatively determined, as Liu et al. [33] shown. These quantitative metrics can be used to model microstructure that has been significantly distorted and then annealed. In severely deformed (cryorolled) and annealed sheets, the mechanism of substructure development and grain refinement is quite complex.

Grain lengthening initially occurs in the rolling direction at low plastic strain, associated with an increase in dislocation density. The production of disordered cellular structures is caused by the dislocation density, which keeps rising as a result of the suppression of dynamic recovery linked to cross slip and dislocation climb. Dhal et al.[34] conducted a thorough microstructural analysis and comparison of pure aluminum and aluminum alloys (AA 5083 and AA 2014) during cryorolling and post-annealing treatment. They noticed that the Cryorolling of Aluminum Alloy Sheets was the primary cause of the difference in recovery, recrystallization, and grain development.

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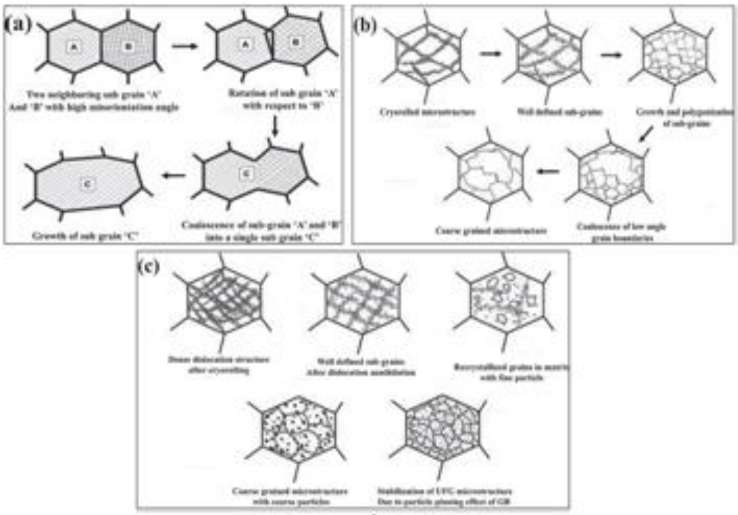

**Figure7:** Variation in microstructure during annealing of (a) pure Al, (b) AA 5083, and (c) AA 2024

These alloys differ from one another in terms of strengthening mechanisms and stacking fault energy. Figure.7 depicts the microstructure evolution of pure Al, AA 5083, and AA 2024 during annealing. It was emphasized that after cryorolled samples were annealed, there was a striking difference between the microstructure of aluminum alloys and pure aluminum. The quick recovery and sub-grain expansion due to cell block structure are the proposed mechanisms in pure Al. According to Figure.7 (a), the formation of rhombic grain structure, the existence of high angle grain boundaries in cryorolled samples, and the low concentration of dislocations all contributed to the reduced grain boundary migration in the case of pure Al. The annealed microstructure of Al alloys, in contrast, exhibits a high rate of static recovery during the annealing treatment, faster recrystallization kinetics, and rapid transformation of low angle grain boundaries into stable high angle grain boundaries via grain boundary migration.

## VI. SUMMARY

The results of numerous researchers' investigations on how cryorolling and post-processing treatments affect the microstructure, mechanical characteristics, and formability of various aluminum alloys are reviewed in detail here. Overall, cryorolling is a successful SPD approach to produce UFG structure in sheets of aluminum alloy with higher mechanical qualities as compared to traditional cold rolled conditions. The methods by which UFG structure was created in cryorolled samples were disclosed by microstructural evolution during the cryorolling process.

Cryorolling Al alloys has been found to improve strength and hardness more than cold rolling due to the effective suppression of dynamic recovery that results in increased dislocation density. However, due to the sheets' low ductility in their as-cryorolled condition, post-cryorolling procedures including warm rolling and low temperature annealing have been tried in an effort to create sheets with the best possible balance of ductility and strength. After a brief annealing treatment at 300$^{o}$C for 6 min on a CR sample with a 90% thickness reduction, a uniform ultrafine grained structure with an average grain size of 300 nm was produced. The average misorienation of CR 90% + SA, as determined by the KAM analysis, was 0.8 degrees, falling between ST and CR 35% thickness reduction. It was determined that the combined effects of static recovery and recrystallization were what caused the production of ultrafine grained structure following short annealing treatment.

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