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Analyze the effect of Cryorolling on Mechanical Properties and Microstructure of AA8011

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In this study, cryorolled annealed and cold rolled annealed sheets of the AA8011 alloy were fabricated. The microstructure and mechanical characteristics of both sheets were compared. One of the crucial severe deformation processes to create sheets with great strength is cryorolling. This aluminium alloy was cryorolled in several passes to get a required final thickness of 1 mm from three-millimeter-thick sheets. According to research on the impact of annealing temperature and duration on hardness, a quick annealing at 200°C for 45 minutes following cryorolling process would produce a excellent balance of strength as well as ductility. Microstructure analysis revealed that the bimodal grain structure of the cryorolled and brief annealed samples is what gives them greater mechanical performance than cold rolled sheets.

Keywords: aluminium alloys, cold rolling, cryorolling, microstructure, mechanical properties.

1. Introduction

A growing number of industries, including construction, packaging, transportation, electronics, mechanical, and electrical manufacturing, aerospace, and petrochemical, are using pure aluminum and aluminum alloys because of the alloy's low density, superior flexibility and strength, and ease of surface processing. [1]. Additionally, they are simple to process for items like sorts, pipes, foil, bars, and so on. Thus, after iron and steel, pure aluminum and its alloys are used as the second most prevalent metal worldwide. [2]. One of the three new roll-cast aluminum alloys is from the 8000 class. Li and Sn make up the bulk of the constituent elements in aluminum alloys. It is frequently employed in the production of packaging, satellites, radiators, and anti-theft covers [3].

Gopi et al., 2012 [4]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. Most of these techniques call for significant plastic deformations (strains substantially greater than unity) [5].The prevention of the dynamic recovery during cryorolling preserves the deformation in the strain-hardened metals. In Figure 1 a diagram shown is two-high rolling mill which is used for cold rolling and cryogenic operations. The sheets are rolled at room temperature through a number of passes in conventional cold rolling (CCR) to get the desired final thickness.

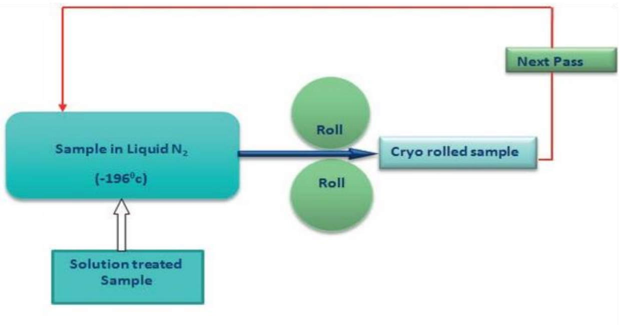


Figure 1: A schematic showing conventional rolling and cryogenic rolling.

Cryorolled aluminum alloy sheets could be annealed at low temperatures (to prevent considerable loss of strength) to produce sheets that have an excellent balance of strength and formability. This is anticipated to broaden the spectrum of uses for aluminum alloys in the auto industry and other sectors. Considering the above fact, this work examined the impact of cryorolling and annealing (after cryorolling) of the AA8011 alloy.

One of the tested methods for producing extremely fine-grained aluminium alloys with better strength and hardness in comparison to standard cold rolled sheet is cryorolling, a process of severe plastic deformation when sheets are rolled at -196°C in liquid nitrogen [6].Various conflicting reports exist on the qualities attained through cold rolling and cryorolling. The drop in temperature of deformation lessens the annihilation of dislocations by suppressing dynamic recovery. Several authors have reported this [7–9] [10].

2. METHODOLOGY

2.1 Material selection

AA8011 alloy sheets in the H116 condition were purchased in 3mm thickness. Table.1 displays the alloy's chemical composition after spectroscopic analysis in weight%.

Table 1: Composition of alloying elements in weight% of AA8011

AA8011	Aluminum (Al)	Chromium (Cr)	Copper (Cu)	Iron (Fe)	Magnesium (Mg)	Manganese (Mn)	Silicon (Si)	Titanium (Ti)	Zinc (Zn)	Nickel (Ni)
	98.58	0.002	0.020	0.66	0.012	0.061	0.63	0.020	00	0.003

Table 1 lists their chemical composition. Samples of these sheets with dimensions 200mm x 200mm were under go cryorolling process and cold rolling process using a 4 high rolling mill with a roller diameter of 200 mm. Speed of working roller is 50rpm. The thickness was reduction take place upto a final thickness of 1mm. It was accomplished in several passes, with a 15-20% reduction in each pass. The gap between roller was adjusted after completion of each pass by using the digital display of the roll gap. Figure.2 depicts the experimental setup and the rolling mill used for cold rolling and cryorolling process. To create a stable microstructure, rolled sheets were annealed at a low temperature.

(a) Experimental setup used for cold rolling cryorolling process

(b) cryorolling process

Figure 2: (a) Experimental setup used for cold rolling cryorolling process; (b) cryorolling process

In Cold rolling operation, we required 4 no of pass to reduce thickness of 3 mm 8011 al alloy sheet to the 1mm Thick. In each pass, we get approximately 25% reduction in thickness.

In cryorolling initially we dipped 3mm thick 8011 Al alloy sheet into the liquid nitrogen for a long enough period of time to reach the necessary cryogenic temperature (-196^{0}C). Amount of temperature was determined using digital temperature measurement gun and the necessary dipping time been determined to be 40–45 minutes. In cryorolling we required 6 no of passes to reduce thickness of 3mm 8011 Al alloy sheet to 1mm thick and during each pass we dipped our specimen in to liquid nitrogen for 10-15min. In each pass, we get approximately 15-17% reduction in thickness.

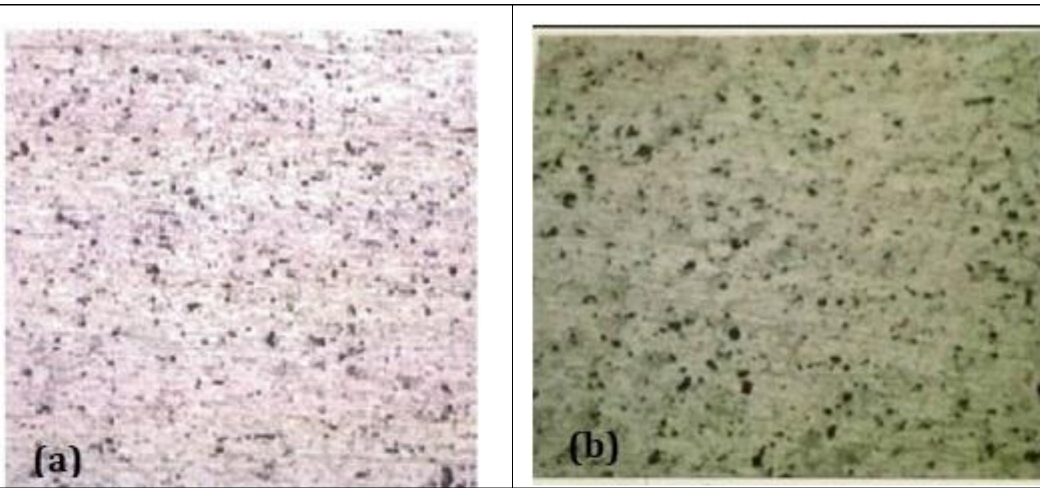
2.2 Cryorolling and Heat treatment

Since achieving ultra-fine grain structure necessitates high thickness reductions, a 3 mm thick sheet sample measuring 200mm x 200mm was rolled using a 4 high rolling mill at 80% reduction under cryogenic conditions to produce final sheets that were 1mm thick. To examine the increase in strength and hardness, the initial samples were also cold rolled at room temperature.

The reduction in ductility in aluminum alloys reinforced by cold or cryorolling renders the material unsuitable for forming purposes. As a result, the cold rolled (CLR) and cryorolled (CYR) sheets received an appropriate heat treatment to increase ductility without significantly reducing strength. To obtain the necessary balance of strength and ductility, a partial annealing (recovery annealing) was performed in between the temperature range of 200°C and 250°C (below the recrystallization temperature) for 40 min.

3 Material Characterizations

3.1 Microstructure



(a) as fully annealed 200°C cold rolled	(b) as fully annealed 200°C cryorolled

Figure 3: (a) Optical micrographs of AA8011 alloys in different conditions

Magnesium is added to aluminum to boost strength while maintaining ductility in the alloy. Better weld-ability and corrosion resistance are also outcomes of this. Since strength declines with lower magnesium levels, the high manganese concentration in AA8011 promotes strength. Iron is the contaminant that occurs most frequently in aluminum. Fe quickly dissolves in all molten stages during the creation of aluminum alloys because it is highly soluble in molten aluminum. Silicon increases the molten alloy's fluidity and corrosion resistance. Lithium serves as the primary alloying component in AA8011. It has a reduced density and can be added to aluminum in large enough amounts to achieve both a low density and higher rigidity.

Using an optical microscope, microstructural analyses of cold- and cryo-rolled sheets that had been annealed at 200°C for 45 minutes were performed. The optical micrographs are displayed in Figure.3. The microstructural characteristics of the samples that were cold rolled and those that were cryorolled show significant variances. A short annealing time has produced a grain structure with interiors free of dislocations. The dislocation density has been greatly decreased by recovery annealing. Dislocation density is important for reinforcing the material. The ultrafine recovered grains and extremely fine re-crystallized grains used in the cryorolled sample resulted in the bimodal grain structure shown by the arrows in Figures 3a and 3b. It is expected that the re-crystallized grains will increase the ductility by accommodating dislocations during deformation. After annealing, the proportion of low angle grain boundaries has reduced but grain boundary misorientation has increased. There was no evidence of re-crystallized grains in the cold rolled sample (Figure.3(a)), merely regained grain structure with a lesser degree of grain fineness. This is explained by lower dislocation density and stored energy before annealing.

3.2 Surface Roughness Testing

After thickness reduction of up to 1 mm, cold rolled and cryorolled samples were subjected to Surface Roughness assessment in accordance with ASTM D7127:2017. Surface roughness values were recorded using Surface roughness testing machine PS1(DMSPL/07/11).

Table 2: Surface Roughness observed of AA8011 alloys in different conditions

Conditions	Observed Value in Ra (μm)	Average Ra(In μm)
Cold rolled + annealed	1.162, 0.892, 0,933, 1.014, 0.792	0.959
Cryorolled + annealed	0.381, 0.861, 0.564, 0.246, 0.491	0.509

3.3 Hardness

Vicker's microhardness testing apparatus was used to conduct hardness tests on the cold rolled and cryorolled samples in compliance with ASTM E18-22 standard, with an applied force of 100 g with a dwell period of 15 s. Three different locations were used to record the hardness values. To determine the ideal annealing conditions, hardness has been determined for both cold-rolled and cryorolled samples as a function of annealing time and temperature after a 3 mm to 1 mm decrease.

Table 3: Hardness values of cold rolled annealed and Cryorolled annealed AA8011 alloy

Conditions	Hardness in HV1			Average
Cold Rolled+ Annealed	49.2	55.2	55.8	53.40
Cryo Rolled+ Annealed	61.0	64.1	59.0	61.36

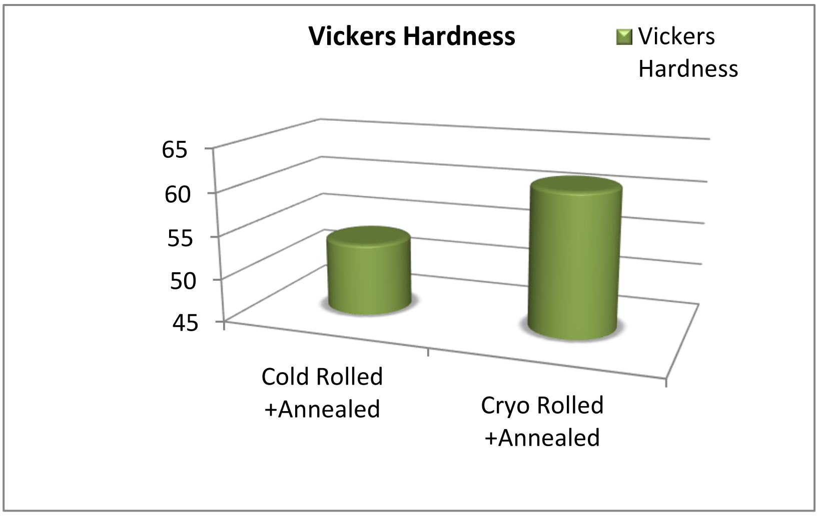


Figure 4: Variation of hardness of AA8011 alloys for cold rolled and cryorolled conditions

The rolled condition's hardness values are also shown for comparison. Cryorolled material has 15% higher hardness ratings than cold rolled sheets after a 3 to 1 mm drop. The higher hardness of cryorolled sheets is attributed to a higher dislocation density [11]. Rolling pure metals and alloys at cryogenic temperatures increases the density of accumulated dislocations with the number of passes and inhibits dynamic recovery. [12]. With increasing annealing temperature, the hardness reduced, with a larger rate of decline occurring beyond 200°C.

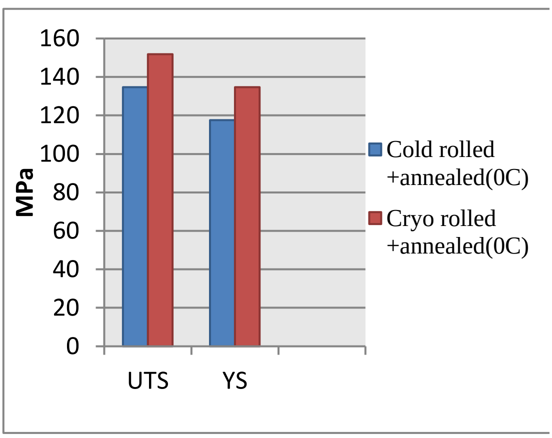
3.4 Tensile properties

Cold rolled and cryorolled sheets for Tensile test of were evaluated at room temperature on an Instron machine with a fixed crosshead speed of 2.5 mm/min. According to ASTM E8/E8M-22 regulations, laser cutting was used to create the specimens. In order to create engineering stress-engineering strain curves, load elongation data from tensile testing on cryorolled and cold rolled specimens had to be obtained. After tensile testing the data of YS, UTS, and percentage elongation, were computed. The rolling direction, both normal to and inside the sheet plane, affects the characteristics of sheet metals. This characteristic, called anisotropy, is brought about by the crystalline texture of the rolled sheet metals.

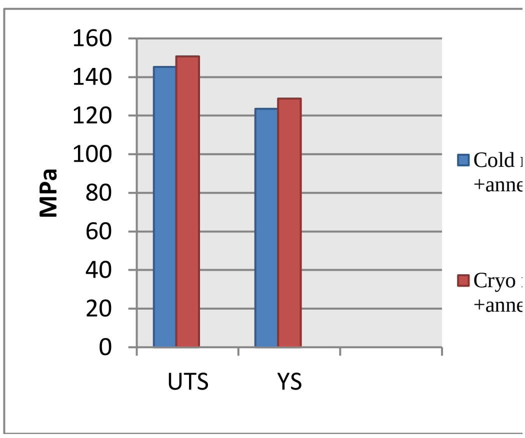
When the sheet is rolled out, there are a lot of dislocations in it. Dislocation density is observed to increase even further when processing temperatures are decreased to cryogenic levels, as this suppresses dynamic recovery. Table 4 illustrates that, in comparison to cold rolling, this resulted in enhanced strength and hardness in all three testing orientations (0 degree, 45 degree, and 90 degree to rolling direction).

Table 4: Tensile characteristics of AA8011 alloy samples that were cryorolled and cold rolled

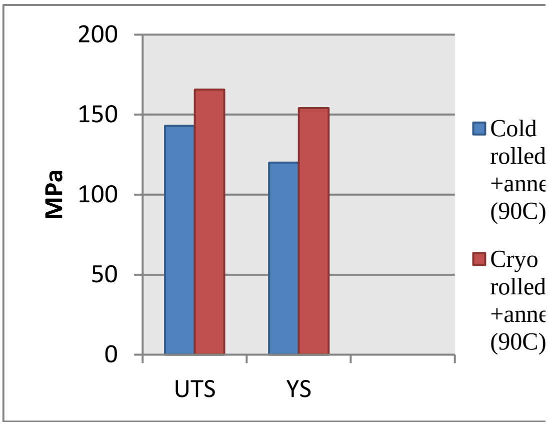
Conditions	Orientation of rolling direction	YS (N/mm^2)	UTS (N/mm^2)	Total Elongation (%)
Raw Material	--	94.268	98.175	1.20
Cold Rolled+ Annealed	0°	117.507	134.613	2.84
	45°	123.472	145.234	3.44
	90°	120.114	143.131	3.06
Cryo Rolled+ Annealed	0°	134.648	151.761	3.72
	45°	128.857	150.722	3.94
	90°	154.161	165.762	3.98



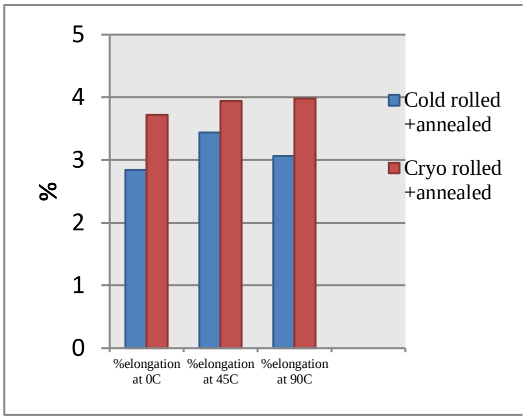
(a) Comparison of UTS and YS for cold rolled and cryorolled sheet at 0°C of rolling direction



(b) Comparison of UTS and YS for cold rolled and cryorolled sheet at 45°C of rolling direction



(c) Comparison of UTS and YS for cold rolled and cryorolled sheet at 90ºC of rolling direction



(d) Comparison of %Elongation for cold rolled and cryorolled sheet at 0ºC , 45ºC and 90ºC of rolling direction

Figure 5: Comparison of % elongation, YS and UTS of the cold and cryorolled samples at 0ºC, 45ºC and 90ºC of rolling direction.

4. Result and Discussion

4.1 Chemical composition and microstructure

Comparing AA8011 to other grades of aluminum sheet metal, Mg concentration is low while Mn, Si, and Fe concentrations are high. The grain has a discontinuous grain boundary and is extended in the rolling direction. Due to the presence of the element Fe, the microstructure has numerous corrosion pits. The hazardous impurity element Fe in AA8011 affects corrosion resistance. After six rolling passes, the result is AA8011.The grain is longer in the rolling direction compared to the roll cast state. Furthermore, as distortion increases, there is no recrystallization and the fiber microstructure is excellent. The microstructure of AA8011 has a lot of dislocations after deep cryogenic rolling. The combined effects of dislocation accumulation and tangling lead to improve the tensile and yield strengths, which results in hardening of work.

4.2 Surface Roughness

Surface roughness of both cold rolled and cryorolled 1mm 8011 aluminium alloys can be measured at six different points. For cold rolled 1mm 8011 aluminium alloys we get 1.162, 0.892, 0.933, 1.014, 0.792 µm roughness value at different points and 0.959 µm the final average value. For cryorolled 1mm 8011 aluminium alloys we get 0.381, 0.861, 0.564, 0.246, 0.491 µm roughness value at different points and 0.509 µm the final average value.

4.3 Hardness

To increase the work hardenability of the rolled material annealing process carried out at appropriate temperature with fine microstructure. It has been discovered that an annealing temperature of 200°C is appropriate for severely rolled Al 8011 alloys with ultrafine-grained structures[13]. As the percentage of deformation rises, Fig. 4 shows the effect of cryorolling on the hardness of the Al 8011 alloy. After applying the real stain of 0.35 (70% decrease) at cryorolling temperature, the hardness value of the Al 8011 alloy rose from 53 HV to 61 HV (almost 15%). The enhancement in hardness is attributed to the high dislocation density generated in the samples during rolling at liquid nitrogen temperature and the effective cross slip or climb of dislocations linked to dynamic recovery.

4.4 Tensile Properties

Figures 5 depict how the percentage elongation, YS, and UTS vary with rolling direction for cryorolled and cold rolled samples. Table 3 provides a summary of the findings. Cryorolled sheets have revealed somewhat increased YS and UTS in both rolled and annealed regimes. It is evident that better strength and approximately equal ductility are generated using cryorolling, which is then quickly annealing at a low temperature. Cryorolled sheets are more durable than cold rolled sheets as a result. The previously mentioned bimodal microstructure in cryorolled samples can be used to explain why compare to cold rolled the cryorolled samples have higher strength while maintaining almost identical ductility.

Figure 5(a) shows the Comparison of UTS and YS for cold rolled and cryorolled sheet at 0^o with respect to rolling direction. At 0^o cold rolled annealed sheet have YS 117.507(MPa) and UTS 134.613(MPa) while cryo rolled annealed sheet have YS 134.648(MPa) and UTS 151.761(MPa). From this values of YS and UTS for both cold rolled and cryorolled annealed sheet we can say that there is a nearly 15% increase in YS and 13%increase in UTS for cryorolled annealed sheet as compared to cold rolled annealed sheet. Figure 5(b) shows the Comparison of UTS and YS for cold rolled and cryorolled sheet at 45^o with respect to rolling direction. At 45^o cold rolled annealed sheet have YS 123.472(MPa) and UTS 145.234(MPa) while cryo rolled annealed sheet have YS 128.857(MPa) and UTS 150.722(MPa). From this values of YS and UTS for both cold rolled and cryorolled annealed sheet we can say that there is a nearly 4% increase in YS and 4% increase in UTS for cryorolled annealed sheet as compared to cold rolled annealed sheet. Figure 5(c) shows the Comparison of UTS and YS for cold rolled and cryorolled sheet at 90^o with respect to rolling direction. At 90^o cold rolled annealed sheet have YS 120.114(MPa) and UTS 143.131(MPa) while cryo rolled annealed sheet have YS 154.161(MPa) and UTS 165.762(MPa). From this values of YS and UTS for both cold rolled and cryorolled annealed sheet we can say that there is a nearly 28% increase in YS and 16% increase in UTS for cryorolled annealed sheet as compared to cold rolled annealed sheet.

Figure 5(d) shows the Comparison of %Elongation for cold rolled and cryorolled sheet at 0^oC, 45^oC and 90^oC with respect to rolling direction. At 0^o cold rolled annealed sheet have elongation 2.84% while cryo rolled annealed sheet have elongation 3.72%. From this values of elongation for both cold rolled and cryorolled annealed sheet we can say that there is a nearly 30% increase in elongation for cryorolled annealed sheet as compared to cold rolled annealed sheet. At 45^o cold rolled annealed sheet have elongation 3.44% while cryo rolled annealed sheet have elongation 3.94%. From this values of elongation for both cold rolled and cryorolled annealed sheet we can say that there is a nearly 15% increase in elongation for cryorolled annealed sheet as compared to cold rolled annealed sheet. At 90^o cold rolled annealed sheet have elongation 3.06% while cryo rolled annealed sheet have elongation 3.98%. From this values of elongation for both cryorolled cold and cold rolled annealed sheet we can say that there is a nearly 30% increase in elongation for cryorolled annealed sheet as compared to cold rolled annealed sheet.

5. Conclusion

The impact of cryorolling and cold rolling on the mechanical properties and on microstructure of AA8011 was examined in the current experiment, and the following findings were reached.

- One method for creating Al alloy AA 8011 sheets with an ultrafine-grained structure is cryorolling. Dynamic recovery is prevented, and increased dislocation density with time contributes to enhanced mechanical qualities. CLR's AA8011alloy sheets are more durable and strong than after a 3mm to 1mm reduction, CLR alloys.

- In comparison to cold rolled annealed sheets, cryorolled AA 8011 alloy sheets with a thickness reduction of 3 to 1 mm and annealing at a 200ºC for 45 minutes give higher strength without losing ductility, leading to sheets with good damage tolerance ability and greater toughness.

- Improved hardness values were the result of strain hardening brought on by rolling reductions. When compared to CLR samples, CLR's AA8011alloy samples showed higher hardness values, most likely as a result of the grain boundary areas' second-phase reinforcement.

- When compared to cold rolling, cryorolling is reported to significantly improve yield strength and ultimate tensile strength due to the high density of dislocations.

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Data availability: All data incorporated in manuscript.

Declarations: Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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