Effects of thermo-mechanical treatments on mechanical properties of seamless rolled rings in 5083 aluminium alloy for wind turbine application

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This paper presents the studies on various thermo-mechanical treatments (TMT's) carried out on seamless rolled rings in 5083 Aluminium alloy for wind mill applications and its effects on tensile properties of the material. The thermo-mechanical treatments includes hot forging & hot rolling, intermediate soft annealing to restore the ductility & formability and final cold straining. Cold straining/ work hardening is accomplished by rolling the rings at room temperature (cold rolling). Extensive trials were carried out with different combinations of the above thermo-mechanical processes, as well as with different percentages of cold rolling/ strain hardening operation. The tensile properties achieved in each of these experiments were evaluated against the required specifications. The optimum degree of cold straining to meet both strength and elongation requirements in H116 temper condition had been established from these trials. Grain size determination according to ASTM E112 and exfoliation corrosion tests (ASSET test) according to ASTM G66 had been evaluated on the rings with the optimum mechanical properties and compared against the stipulated requirements by Customer. The soundness of the rings had also been evaluated by non destructive surface and volumetric examinations, viz. liquid penetrant test as per ASTM E165 and ultrasonic flaw detection as per ASTM B594 respectively and ensured absence of significant indications in the rings.

KEYWORDS: SEAMLESS RING ROLLING, 5083 ALUMINIUM ALLOY, THERMO-MECHANICAL TREATMENTS, TENSILE TEST, EXFOLIATION TEST, NONDESTRUCTIVE EXAMINATIONS

INTRODUCTION

Aluminium alloy 5083 consisting of 4.5% Magnesium, 0.5% Manganese and 0.1% Chromium is a non heat treatable alloy, in-contrast to Aluminium alloys like 2xxx type of Al-Cu alloys (or) 7xxx type of Al-Zn alloys, which are subjected to solution treatment and precipitation hardening heat treatments for higher mechanical and physical properties.

5083 wrought alloy is used either in annealed condition ("O" temper) for higher ductility & corrosion resistance requirements (or) in strain hardened condition ("H" tempers) for superior mechanical strength. The strain hardended wrought alloys are manufactured in different temper conditions, with varying degrees or percentages of strain hardening viz. H111, H112 & H116. Due to low density, superior corrosion resistance, excellent weldability and higher strengths, this alloy is widely used in marine applications and industrial chemical

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environments. They are used in bearings and in the end section of blades of wind turbines, where high quality and mechanical stability is required.

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Extensive trials were carried out with different combinations of the above thermo-mechanical processes, as well as with different percentages of cold rolling/ strain hardening operation. The tensile properties achieved in each of these experiments were evaluated against the required specifications. The optimum degree of cold straining to meet both strength and elongation requirements in H116 temper condition had been established from these trials. Grain size determination, exfoliation corrosion tests (ASSET test) and non-destructive examinations (Ultrasonic flaw detection and Liquid Penetrant test) had been carried out on the rings with the optimum mechanical properties and evaluated against Customer specifications.

RAW MATERIAL BILLETS

Direct chill cast, homogenised and scalped billets of diameter 360mm were used as raw material for this product. The chemical composition of 5083 Aluminium alloy billet was maintained as reported in the below table, which conforms to ASTM B247 material specification.

Tab.1 - Chemical Composition of DC Billets.

Chemical Composition of DC Billet										
Spec	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Ca	Na
Min.	-	-	-	0.50	4.10	0.08	-	-	-	-
Max.	0.15	0.20	0.05	0.70	4.50	0.12	0.05	0.05	0.0010	0.0005
Heat No: 17										
Launder Anal	0.097	0.138	0.019	0.575	4.22	0.106	0.009	0.039	0.0003	<0.0005
Product-Top	0.089	0.134	0.017	0.564	4.13	0.104	0.008	0.038	0.0001	<0.0005
Product-Bot	0.096	0.134	0.022	0.561	4.11	0.107	0.012	0.036	0.0002	<0.0005
Heat No: 18										
Launder Anal	0.088	0.157	0.016	0.597	4.26	0.109	0.007	0.040	0.0003	<0.0005
Product-Top	0.079	0.150	0.014	0.580	4.15	0.110	0.006	0.037	0.0003	<0.0005
Product-Bot	0.088	0.141	0.016	0.570	4.13	0.105	0.009	0.036	0.0005	<0.0005

Note: Other impurities: Each <0.05% and Total <0.15%.
H2 content: Start-0.049, End-0.052 ml /100 gms of liquid Aluminium (Spec: Max.0.15 ml/ 100 gms of Al.)

The raw material billet processing includes primary melting in gas fired melting & holding furnace, followed by proprietary liquid Aluminium refining technique, degassed and inclusions filtered using special ceramic filters (40 ppi), casting by patented direct chill cast technology and homogenized by gas fired travelling furnace. Chemical analysis was performed in the launder, at different stages of casting and finally on the product from top & bottom of billets.

The cast billets were subjected to homogenization treatment and scalped by rough turning on OD to remove surface imperfections, chilled zone and to facilitate ultrasonic testing. All the billets were subjected to macrostructure & microstructure examination (grain size between 80-140 microns from surface to center), 100% ultrasonic examination for flaw detection according to AMS 2630, Quality Class A (Pointed – 2.0mm FBH & Grouped/Multiple/Linear indications – 1.2mm FBH)

OPEN DIE FORGING AND SEAMLESS RING ROLLING

In order to develop and establish the production cycle for the rings meeting all product quality requirements, it was decided to perform trials internally before proceeding with the production of Customer order. Six trials were carried out with different combinations of thermo-mechanical treatments, which includes hot forging & rolling, intermediate annealing and final cold rolling, as tabulated below.

Tab.2 - List of trials with different combinations of thermo-mechanical treatments

Trials	Hot Rolled Size *(Note a)*			Intermediate Annealing *(Note a)*	Cold Rolled Size			% Cold Straining	Test condition	
	OD	ID	HT		OD	ID	HT		Test 1	Test 2
Trial 1	875	695	520	☑	995	845	480	18.4%	*HR+AN*	*HR+AN+CR*
Trial 2	924	760	520	☑				10.4%	*HR+AN*	*HR+AN+CR*
Trial 3	800	605	520	☒				23%	*HR*	*Note b)*
Trial 4	800	605	480	☑				23%	-	*HR+AN+CR*
Trial 5	924	760	520	☒				9.3%	*HR*	*HR+CR*
Trial 6	924	760	480	☑				9.3%	-	*HR+AN+CR*

Legends: HR-Hot rolled, AN-Annealed, CR-Cold rolled.

Note:

a) Test ring of 25mm thick was cut from the height of hot rolled (HR) / hot rolled (HR)+annealed (AN) rings, prior to cold rolling, to perform tensile tests in test condition no.1

b) Test condition planned in cold rolled condition was not done in trial 3, due to heavy surface peel off and damage of the ring during cold rolling without intermediate annealing operation (i.e. due to severe work hardening/ cold straining; Refer Fig.2)

Hot forging process includes heating of billets to 460-510o C in electrical furnace and pancaking by open die forging technology using 3500 Tons hydraulic press. The pancakes are subsequently hot rolled at 460-510o C in 630T/315T radial-axial seamless ring rolling mill. Soaking time 30-45 Mins/Inch of effective thickness was maintained for first heat and for 15-30 Mins/inch for subsequent heats. Finish temperature was maintained ~ 310-350o C in both hot forging and hot rolling processes.

Intermediate annealing involves loading the hot rolled rings into the furnace set at 330-350 o C and soak for 2-4 minutes/mm of effective thickness, followed by furnace cooling to room temperature. Cold rolling involves rolling of rings in the seamless rolling mill at room temperature (No heating of rings to high temperatures).

Upsetting operations were performed with concave dies, except final upsetting with round disc, before punching/ piercing operation. Drawing operations were performed with V dies for better working in the center of the billets. Reduction ratio for all upsetting (height ratio) and for all drawing (diameter ratio) operations were maintained above 2:1. Saddling and hot rolling were maintained between 1.4-1.5%. The total reduction ratio of more than 100: 1 was maintained in all the trials.

Fig.1 - Cold rolling of ring in rolling mill.

Fig.2 - Cold rolled ring (trial 3) showing heavy surface peel off and ring damage!

MECHANICAL TESTS

Integral test prolongation on height of the ring (70mm thick) was provided on every heat, heat treatment batch and size basis for testing as shown below.

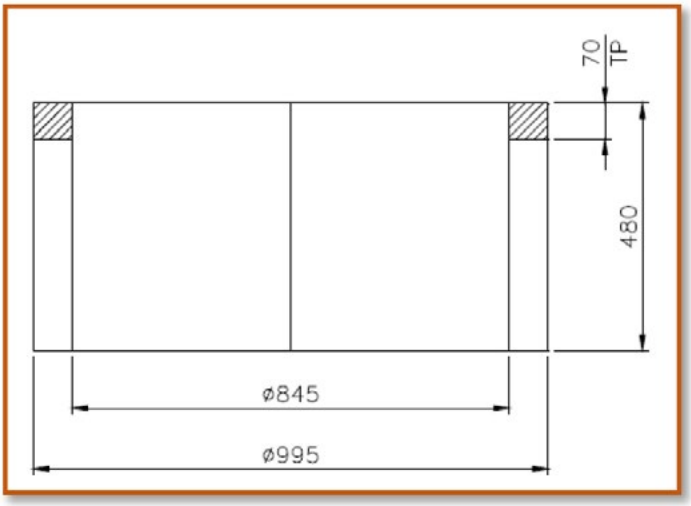

Fig.3 - Integral Test Prolongation on the ring.

TENSILE TEST AT ROOM TEMPERATURE

The tensile tests were carried out at room temperature, according to ASTM B557 standard, which includes 0.2% offset yield strength (YS), ultimate tensile strength (UTS) and % elongation test values. These specimens were taken in longitudinal (tangential) & transverse (axial/ radial) directions from test prolongation of the rings.

The summary of tensile test results for different combinations of TMT's are tabulated below.

Tab.3 - Summary of RT tensile test results for different TMT combinations.

Trials	TMT combination	Test Condition	Degree	Tangential			Axial			Radial		
				UTS (MPa)	0.2% YS (MPa)	EL (%)	UTS (MPa)	0.2% YS (MPa)	EL (%)	UTS (MPa)	0.2% YS (MPa)	EL (%)
			Spec	≥290	≥ 200	≥ 10	≥290	≥ 180	≥ 10	NS	NS	NS
Trial 1	HR + AN + CR (18.4%)	HR+AN	0°	287	123	30.0	-	-	-	280	122	29.2
			120°	285	119	30.9	-	-	-	264	118	28.0
			240°	286	119	29.7	-	-	-	258	118	27.4
		HR+AN+CR	0°	317	235	13.1	306	215	13.6	290	200	16.0
			120°	322	245	13.8	298	218	14.8	303	210	14.7
			240°	319	235	15.2	299	207	15.2	307	214	15.1
Trial 2	HR + AN + CR (10.4%)	HR+AN	0°	286	126	30.0	-	-	-	260	125	24.2
			120°	274	118	28.7	-	-	-	264	120	25.6
			240°	280	122	29.9	-	-	-	262	124	25.6
		HR+AN+CR	0°	330	245	17.1	310	212	15.8	310	235	16.4
			120°	315	220	18.0	301	206	16.5	281	200	17.2
			240°	333	254	16.0	299	206	15.5	286	207	18.0
Trial 3	HR + CR (23%)	HR	0°	293	142	23.2	-	-	-	275	127	25.8
			120°	284	130	24.6	-	-	-	286	138	24.8
			240°	280	131	25.2	-	-	-	277	128	24.7
Trial 4	HR + AN + CR (23%)	HR+AN+CR	0°	341	284	13.6	329	263	8.6	325	261	6.5
			120°	332	275	13.2	334	268	9.2	329	252	9.6
			240°	346	290	10.4	319	257	8.8	326	258	8.8
Trial 5	HR + CR (9.3%)	HR	0°	289	132	24.3	-	-	-	282	131	23.1
			120°	287	135	24.0	-	-	-	275	127	24.9
			240°	286	136	25.6	-	-	-	279	134	24.4
		HR+CR	0°	308	209	15.8	298	207	16.8	289	196	13.7
			120°	317	227	14.8	294	199	15.1	291	200	13.4
			240°	310	216	16.0	302	210	16.4	292	193	15.2
Trial 6	HR + AN + CR (9.3%)	HR+AN+CR	0°	322	251	13.6	311	232	13.3	285	204	13.0
			120°	321	234	14.2	320	247	12.6	294	215	15.0
			240°	320	240	13.8	301	222	13.8	295	215	13.6

Both UTS and YS test values are lower and below the minimum specification limits in hot rolled (HR) and hot rolled+annealed conditions (HR+AN) (which are highlighted in red color cells). However, % elongation values are much higher than other TMT's, thereby improves ductility and facilitates subsequent cold rolling process for strain/ work hardening.

Higher extent of cold working/ straining after annealing (Trial 4; 23% Strain) has given higher strengths (UTS & YS) compared to the rings produced with lower extent of cold rolling (Trials 1, 2 & 6). However, the elongation values were lower than the other trials and below the minimum specification limit for H116 temper condition.

Hence, it is concluded that cold rolled rings with intermediate annealing (HR+AN+CR) and cold straining between 10-15% (trial 2/ trial 6) would produce the optimum test results meeting both strength (UTS & YS) and elongation requirements in H116 temper condition, as required by our Customer specifications. Subsequent to the trials, our Customer order was executed with production of rings to the above cycle and all the inspection and test results were fully in compliance to the intended specifications.

METALLOGRAPHY

GRAIN SIZE DETERMINATION

Grain size determination according to ASTM E112 by optical light microscopy had been carried out on the production rings with the optimum tensile properties. Grain size ASTM No.5 and ASTM No.4 observed in tangential and axial directions respectively (Acceptance criteria; ASTM No. 4 or finer)

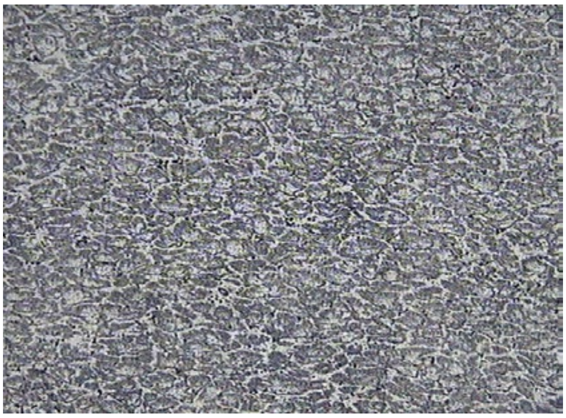

Fig.4 - Grain size ASTM No.5 in Tangential Specimens.

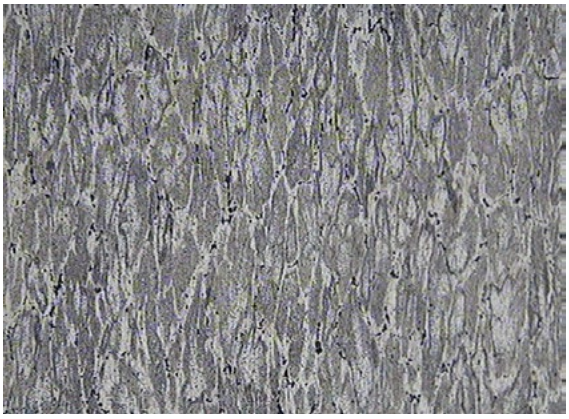

Fig.5 - Grain size ASTM No.4 in Axial Specimens.

CORROSION TESTS

EXFOLIATION TEST

Visual Assessment of Exfoliation Corrosion Susceptibility of Aluminium Alloys (ASSET test) according to ASTM G66 had been carried out on the production rings with the optimum mechanical properties. The test specimen of size (mm): 40 W x 9 T x 100 L with test solution quantity 1000ml with volume to surface area of 65 ml/in2 was used. Prior to immersion in test solution, the specimens were degreased with acetone and then etched in 5% NaOH at 80°C for 1 minute followed by rinsing in water. Desmut for 30 seconds in conc.HNO_3 at room temperature followed by rinse with distilled water & air dry. Finally, the specimens were immersed in a solution containing ammonium chloride (NH_4Cl - 53.5 gms), ammonium nitrate (NH_4NO_3 -20 gms), ammonium tartrate ($(NH_4)_2C_4H_2O$) – 1.8 gms) and hydrogen peroxide (H_2O_2 – 10ml of 30% stock solution) with pH value of 5.2-5.4, for 24 hours at 65°C. The susceptibility to exfoliation is determined by visual examination using performance ratings established by reference to standard photographs.

Pitting Rating; Classification – N (no appreciable attack) both in specimen side A and B was observed as against acceptance criteria; Classification – N (no appreciable attack) or PA (pitting A degree). Pitting of degrees PB, PC and Exfoliation of degress EA, EB, EC and ED are not acceptable (Refer below Figures)

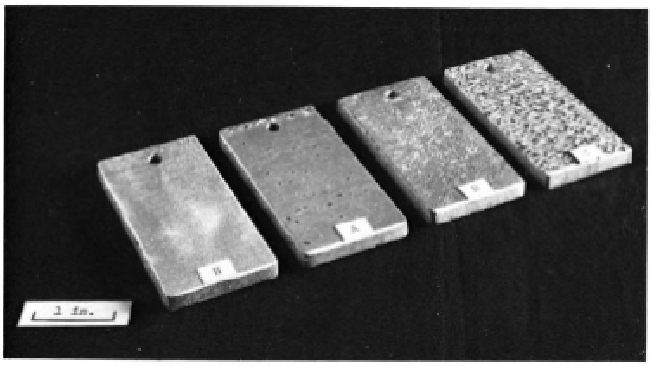

Fig.6 - ASSET Tested Exfoliation Resistant Specimens (N—No appreciable attack; A, B, C—Three Degrees of Pitting and Pit-Blistering)

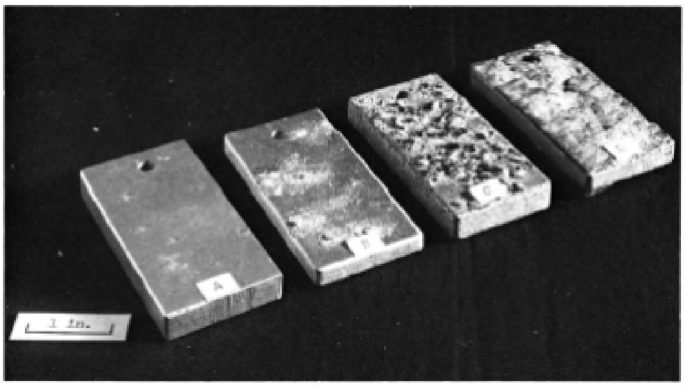

Fig.7 - ASSET Tested Exfoliation Susceptible Specimens (A, B, C, D—Four Degrees of Exfoliation)

NON-DESTRUCTIVE EXAMINATIONS

Post heat treatment, the rings were rough machined to OD 970 x ID 870 x HT 380mm and evaluated for absence of defects, by non-destructive surface and volumetric examinations viz. liquid penetrant test and ultrasonic flaw detection respectively, according to Customer specification requirements.

ULTRASONIC FLAW DETECTION (UT)

UT was performed on all the rings, according to ASTM B594 standard specification. Pulse-echo direct contact method was carried out using B4S (24mm dia, 4MHz) normal beam and MSEB4 (10mm dia, 4MHz) dual crystal probes with scanning in two mutually perpendicular directions (i.e. radial and axial scanning on rings).
DGS method using 1.5mm ERS reference curve was used. Level-2 qualified and certified personnel to SNT-TC-1A standard had been deployed on this examination. No recordable indications above DGS curve detected in any of the forgings (Acceptance criteria; Max.5 indications with size between 1.5mm to 2.5mm ERS allowed with minimum distance between 2 indications > 20mm. No indications beyond 2.5mm ERS is acceptable). Hence the above NDE examination on all rings complies to the stipulated Customer specification.

LIQUID PENETRANT TEST (PT)

PT was also performed on all the forgings, according to ASTM E165 standard specification with acceptance criteria of no linear indications permissible beyond 1.5mm. Solvent removable penetrant and Non-flourescent technique was used. Level-2 qualified and certified personnel to NAS-410 standard had been deployed on this examination. No significant PT indications detected in the forgings and hence the above examination also comply to the stipulated specification by Customer.

CONCLUSION

Cold rolling/ cold straining without intermediate annealing operation, after initial hot rolling, has shown heavy peel off / surface tearing of Aluminium layers during cold rolling process and eventually resulted in surface cracks/ defects. Hence, intermediate annealing operation between hot rolling & cold rolling is required to improve the formability during cold rolling, thereby guarantees the sound quality of the cold rolled rings.
From the above trials conducted, it is concluded that cold rolling rings with intermediate annealing and cold straining between 10-15% would produce the optimum test results meeting both strength (UTS & YS) and elongation requirements from our Customer in H116 temper condition. All the qualification checks carried out on the production rings including Chemical Analysis, Mechanical Properties, Metallography & Ultrasonic Examination conform to the applicable Customer Specifications and drawing.

REFERENCES

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[5] ASTM G66- Standard Test Method for Visual Assessment of Exfoliation Corrosion Susceptibility of 5XXX Series Aluminum Alloys (ASSET Test)
[6] ASTM B594-Practice for Ultrasonic Inspection of Aluminum Alloy Wrought Products for Aerospace Applications
[7] ASTM E165- Standard Practice for Liquid Penetrant Examination
[8] ASTM E1251- Test Method for Optical Emission Spectrometric Analysis of Aluminum and Aluminum Alloys by the Argon Atmosphere, Point-to-Plane, Unipolar Self-Initiating Capacitor Discharge
[9] AS1990- Aluminium Alloy Tempers

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