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Yield Locus of Solution Treated and Aged Aluminium Alloy AA2014 Forge Plate

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***Abstract*— Aluminium alloys have been the important materials for the automobile and aero space structural parts. In this paper the study on the deformation behaviour of a forged aluminium alloy AA 2014 and the effect of artificial ageing, is reported. The data obtained from uniaxial tensile test and knoop hardness test is analysed. The study revealed that the alloy exhibits moderate values of in-plane anisotropy and anisotropic index in the plane perpendicular to the forging direction. The aged alloy plate exhibits higher values of yield strength, ultimate tensile strength compared to the solution treated plate. There is variation in work hardening exponent with the direction of forging. It is highest in T direction and lowest in L direction in case of solution treated specimen and it is highest in L direction and lowest in L+45° direction for peak aged .Yield locus is obtained from knoop hardness test results. The yield locus generated shows that the alloy under study exhibits in-plane anisotropy.**

Keywords—Aluminium alloy AA2014; in-plane anisotropy; yield locus; knoop hardness number; work hardenening exponent.

I. INTRODUCTION

Aluminium and its alloys have become important materials for automobile, military, space, and several commercial applications due to their better mechanical properties, low density, higher specific strength and specific modulus apart from adequate fracture and fatigue resistance. A few attempts have been made earlier to study deformation behaviour of aluminium alloys for sheet metal applications. Also studies were made to reveal the basic formability characteristics and different methods to characterize the forming behavior and forming limits of automotive aluminium sheet [1, 2]. Extensive studies were conducted in correlating the variation of mechanical properties in different test directions i.e. in-plane anisotropy, texture and yield locus in thin sheet components of Nimonic-263 Alloy, Hastalloy C-276 and Alloy-90 [3, 4]. The studies on mechanical properties anisotropy correlated with hardness of forged alloy AA 2014 are lacking. The present work aims at studying the in- plane anisotropy and plane stress yield locus of forged alloy AA 2014 in solution treated and peak aged conditions. Yield locus of the material based on Knoop Hardness Number (KHN) in a polycrystalline material, Wheeler and Ireland proposed a method [5], which is followed in present work.

II. EXPERIMENTAL

The material selected for investigation is aluminium alloy AA 2014 which is Al-Cu-Mg-Si alloy. The forged AA 2014 block in the present investigation was obtained from Mishra Dhatu Nigam (MIDHANI), Hyderabad, India. The Table I shows the nominal composition of the alloy forging, which is found to be well within the specified range of the standard composition of aluminium alloy AA 2014.

The Copper is one of the most important alloying elements for aluminium, because of its strengthening effect and good solubility. Many commercial aluminium alloys contain copper as the major addition or among the principle alloying element. For production of more complex alloys, the binary aluminium – copper alloys are used as master alloys. In these alloys the relatively high silicon content increases the response to hardening on artificial ageing, hence higher strengths are achieved [6]. This alloy is particularly well suited for parts and structures requiring high strength to weight ratio and are generally used to make aircraft wheels, aircraft wing skins, truck and structural parts and those parts requiring good strength at temperatures up to 150 °C. This alloy has good machinability but has limited weldability. Required number of plates of size 170 mm x105 mm x 4 mm for testing are prepared with EDM wire cut machine subsequently they were solutionised and aged. Different orientations of specimens for tensile test are prepared from forged block as shown in Fig. 1

All the plates were solutionised at 502±5 °C for 55 min and quenched in hot water of 64 °C in order to avoid distortion and warpage

TABLE I. CHEMICAL COMPOSITION OF SOLUTIONISED ALUMINIUM ALLOY AA 2014

Element	**Cu**	**Si**	**Mn**	**Mg**	**Fe**	**Al**
Weight, %	4.4	0.8	0.8	0.4	-	Remainder

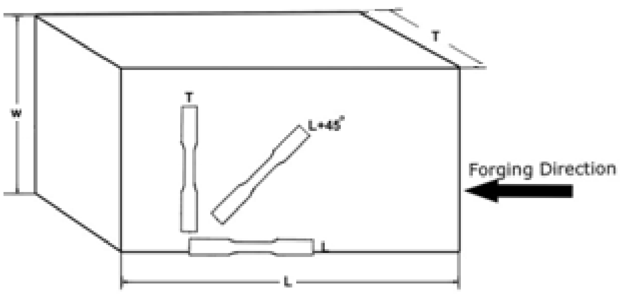

Fig.1. Orientation of tensile specimens cut from forged block.

The plates were aged at 177±3 °C in the furnace for 10 h and were designated as peak aged heat-treated condition. The specimens were prepared by metallographic grinding followed by fine polishing using alumina paste followed by etching for optical microscopy. Kellers reagent is used for etching aluminium alloy samples, it consisting of HF 1 ml, HNO_3 3 ml, HCl 3 ml, H_2O 93 ml. Tensile tests were conducted at room temperature on INSTRON 5500R-4507-250 kN universal testing machine at a crosshead speed of 1 mm per min. The specimens prepared are as per ASTM recommended standard E-8 shown in Fig. 2. Two specimens were tested in each sample direction and average values of 0.2% of yield strength (σ_{YS}), ultimate tensile strength (σ_{UTS}), percentage elongation were determined. The strain was recorded with an axial extensometer.

Knoop hardness test was conducted with 100 g load. The flow surface of the material is formed from six KHN values obtained from the indentations taken along two mutually perpendicular directions of each of the three orthogonal planes of material's principal axes (X,Y and Z directions and ND,TD and RD planes) defined in Fig. 3 along six orientations of indenter (a to f) six KHN values are obtained.

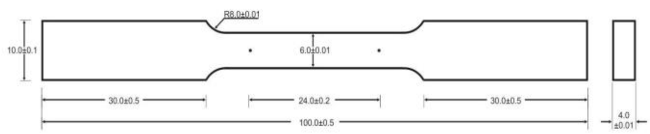

Fig.2. Schematic diagram of tensile specimen (All dimensions are in mm)

III. RESULTS AND DISCUSSION

A. *Microstructure*

Microstructural evaluation has revealed that the alloy under investigation contains fine insoluble dispersoids. These dispersoids are $(Mn\ Fe)_3\ Si\ Al_{12}$, $Cu_2Mn_3Al_{20}$ and Mn_3SiAl_{12} and soluble ternary phase particles are distributed throughout the matrix in the structure.

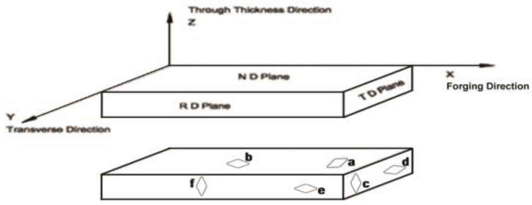

Fig.3. Three orthogonal planes of forged plate and orientations of knoop indentation used for micro hardness test

The fine grain structure in elongated shape in the direction of forging, which is result of forging in hot condition also helps in the improved mechanical properties. Fully recrystallized microstructure with equiaxed grains in all three planes were observed in microstructure of this alloy. This can be attributed to complete recrystallization during solution treatment. The main reason for variation in mechanical properties anisotropy of Al and Ni based alloy is the alloy composition and texture resulted due to thermo mechanical processing of materials. The Fig. 4 shows the optical micrographs revealing the microstructure of the alloy in solution treated as well as aged condition following tensile deformation to fracture.

B. *Tensile Properties*

The anisotropy in tensile properties of aluminium alloy AA 2014 plate in solution treated condition is given in the Table II. It shows that work hardening exponent is highest in T direction and lowest in L direction. Similarly work hardening exponent is highest in L direction and lowest in L+45° direction for peak aged (ST+450 K/10 h) treated condition (Table III). Figure 5a, b show engineering stress-engineering strain diagrams up to breaking stress of aluminium alloy AA 2014 in solution treated condition and peak aged condition (ST+450 K/10 h) respectively.

The ultimate tensile strength (σ_{UTS}) is maximum in T direction and minimum in L+ 45° directions in solution treated condition. Similarly the yield strength (σ_{YS}) and ultimate tensile strength (σ_{UTS}) are minimum in L+45° direction and significantly higher in both L and T directions in peak aged condition (see data in Table III). The higher degree of uniform elongation is associated with low nucleation and high growth of micro-voids.

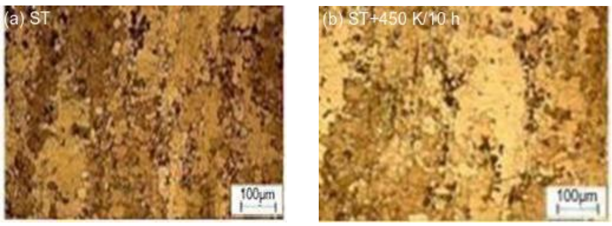

Fig.4. Optical micrographs showing microstructure of aluminium alloy AA 2014 alloy specimens after tensile deformation to fracture (a) solution treated condition, (b) peak aged condition (ST+450 K/10 h)

TABLE II. ANISOTROPY IN TENSILE PROPERTIES OF ALUMINIUM ALLOY AA 2014 PLATE IN SOLUTION TREATED CONDITION. (TESTS WERE CONDUCTED AT ROOM TEMP AT AN INITIAL STRAIN RATE OF 10^{-4} S^{-1})

S.No.	Property	Specimen orientation with respect to the forging direction, Deg		
		L	L+45°	T
1	0.2 % Y.S, MPa	277.1	276.3	281.8
2	UTS, MPa	399.6	398.7	408.7
3	Total Elongation, % (25 mm gauge length)	19.6	20.7	18.4
4	Work Hardening exponent n	0.13614	0.13704	0.18217
5	σ_{UTS} / σ_Y	1.442	1.443	1.450

TABLE III. ANISOTROPY IN TENSILE PROPERTIES OF ALUMINIUM ALLOY AA 2014 PLATE IN PEAK AGED (ST+450 K/10 H) TREATED CONDITION. (TESTS WERE CONDUCTED AT ROOM TEMP AT AN INITIAL STRAIN RATE OF 10^{-4} S^{-1})

S.No.	Property	Specimen orientation with respect to the forging direction, Deg		
		L	*L+45°*	*T*
1	0.2 % Y.S, MPa	450.1	422.0	447.2
2	UTS, MPa	496.4	472.8	492.3
3	Total Elongation, % (25 mm gauge length)	11.04	5.32	8.92
4	Work Hardening exponent n	0.05678	0.04751	0.05013
5	σ_{UTS} / σ_Y	1.1026	1.1181	1.1169

Consequently, elongation is maximum along the L sample direction for peak aged specimen and along L+45° sample direction for solution treated condition. The low ductility and work hardening exponent n values of tensile samples along L and L+45° directions also support the formulation of Mc Clintock [7]. The anisotropy of metals and alloys can be determined by percentage in-plane anisotropy (A_{IP}) [8, 9] and anisotropy index (δ) [10].

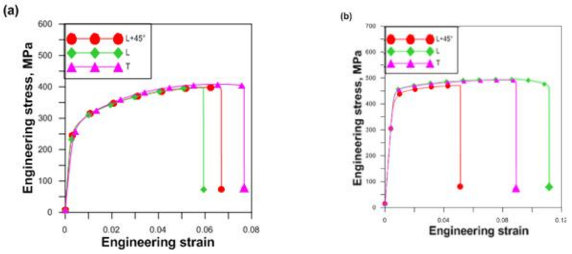

Fig. 5. Engineering stress-engineering strain diagram up to breaking stress of aluminium alloy AA 2014 in (a) solution treated condition and (b) peak aged condition (ST+450 K/10 h)

$$A_{IP} = \frac{2(\sigma_{YS})_{L+45^\circ} - [(\sigma_{YS})_L + (\sigma_{YS})_T]}{2(\sigma_{YS})_{L+45^\circ}} \quad (1)$$

TABLE IV. IN-PLANE ANISOTROPY AND ANISOTROPIC INDEX OF ALUMINIUM ALLOY AA 2014

S.No.	Condition	In plane Anisotropy A_{IP} Pct	Anisotropic Index δ
1	ST	-1.14	3.158
2	ST+450 K/10 h	-6.31	10.620

$$\delta = \frac{(Pct.El.)_L - (Pct.El.)_T}{(Pct.El.)_L + (Pct.El.)_T} \quad (2)$$

Yield strength anisotropy is associated with A_{IP} and δ is related to elongation anisotropy. For isotropic materials values of A_{IP} and δ are zero. Both A_{IP} and δ for current alloy in the two heat treatment conditions are given in Table IV.

The data in testing shows that the alloy exhibit moderate values of A_{IP} and δ in both heat treatment condition and also both A_{IP} and δ are moderately higher in artificial ageing (peak aged condition) as compared with that of solution treated condition.

C. Determination of yield locus

The value of anisotropy shall be determined by a method proposed by Hill [11] by using the values of knoop hardness numbers. Extensive studies and validation were made on this for different materials. FCC materials and alloys can yield and deform plastically by dislocation motion and twinning. An assumption was made that yield surface of specimen be symmetric about origin in stress space, the magnitudes of tensile and compressive yield stresses are equal. But in actual practice the yield stress of a material will be different in tension and compression due to presence of texture. Wheeler and Ireland [5] proposed a method of graphical representation of yield strength of material using anisotropy of KHN in poly crystalline materials. The yield strengths determined from KHN are five to six times higher than experimental values obtained by tensile test. This method is used only to the extent that it is a measure of relative resistance to the indentation [3, 12].

The graphical representation of KHN based plastic flow is an octahedral plane defined by the sum of s_1, s_2 and s_3 is a constant, where the values of s_1, s_2 and s_3 are the deviatoric stresses defined as per (3) below:

$$s_1 = \sigma_1 - \sigma \;,\; s_2 = \sigma_2 - \sigma \text{ and } s_3 = \sigma_3 - \sigma \quad (3)$$

Where σ_1, σ_2 and σ_3 are the principal stresses and σ is the hydrostatic stress given by

$$\sigma = \frac{1}{3}(\sigma_1 + \sigma_2 + \sigma_3) \quad (4)$$

The ratio of 1 to 7 of minor to major diagonal in knoop indentation is selected because it produces flow surfaces similar in shape with surfaces determined by standard method [5]. It is believed that this value originates in the usual ratio of minor to major diagonal in knoop indentation, which is about 1:7.

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This has been considered for two reasons: (i) When $d\varepsilon_w / d\varepsilon_i = \alpha$ the deformation under a knoop indenter approaches plain strain and (ii) Shape of the locus where plane strain represented is not overly sensitive either to the exact value of $d\varepsilon_w / d\varepsilon_i$ or to the degree of anisotropy, within a rather wide range of both variables. Hence, the values α_i for different orientations (a – f) will be different (Fig. 3) and are given by

$$\alpha_a = \sigma_y / \sigma_x = (2+\delta)/(2\delta+1) \tag{5}$$

And

$$\alpha_b = 1/\alpha_a \, , \alpha_c = (1-\delta)/(2+\delta) \, ,$$
$$\alpha_d = (\delta-1)/(1+2\delta) \, , \ \alpha_e = 1/\alpha_d \, , \ \alpha_f = 1/\alpha_c \tag{6}$$

Wheeler and Ireland plotting method is used for the insertion of the loading path with locus line. It can be established that the KHN is proportional to the shearing stress on the octahedral plane. Hence, for plane stress condition,

$$KHN \approx (\sigma_x^{\,2} - \sigma_x\sigma_y + \sigma_y^{\,2})^{1/2} \tag{7}$$

Or

$$\sigma_i \approx KHN / (1-\alpha_i + \alpha_i^{\,2})^{1/2} \tag{8}$$

Where σ_i represents the stress in one of the orientation or a – f, which enables the construction of yield locus. The presence of anisotropy can be proved by a best fit ellipse. Yield strength in tension along longitudinal (σ_X) and yield strength in

compression along transverse (σ_Y) axes different. Hence the material under study exhibits moderate anisotropy. In literature the yield locus plots are calibrated with data obtained from tensile test in longitudinal and transverse directions [9]. For biaxial plane stress condition (σ_2=0) the von Mises' yield criterion can be expressed mathematically as

$$\sigma_1^{\,2} + \sigma_3^{\,2} - \sigma_1\sigma_3 = \sigma_0^{\,2} \tag{9}$$

This is an equation of ellipse whose semi major axis is $\sqrt{2}\,\sigma_0$ and minor semi axis is $\sqrt{\frac{2}{3}}\,\sigma_0$. The plot with the values obtained by σ_i of the (8) is called yield locus.

The main interpretation of the von Mises' criterion is that it represents a critical value of the distortional energy stored in the isotropic material while the Tresca criterion is that of a critical value of the maximum shear stress in the isotropic material. Generally, the Tresca form was considered to be the more fundamental of the two, but the Mises' form was seen as mathematically convenient. Both are usually stated side by side with little or no preference [7].

TABLE V. YIELD LOCUS DATA OF ALUMINIUM ALLOY AA 2014 ALLOY PLATE IN SOLUTION TREATED CONDITION IN DIFFERENT ORIENTATIONS

S. No.	Indentation orientation	$\alpha = \sigma_y/\sigma_x$ with δ = 7	$\sqrt{(1-\alpha+\alpha^2)}$	KHN at 100 g Load	Stress in MPa σ_x	Stress in MPa σ_x
1	a	0.60	0.872	154.1	1733.6	1040.2
2	b	1.67	1.454	151.8	1024.2	1710.4
3	c	0.67	1.454	153.1	-1032.1	692.0
4	d	0.40	0.872	150.2	-1689.2	-675.7
5	e	2.50	2.180	152.7	-686.9	-1717.2
6	f	1.50	2.180	147.1	661.9	-992.8

The yield locus for maximum shear stress criterion (Tresca) falls inside the critical value of the distortional energy stored (von Mises') yield ellipse . These two yield criterion predict the same yield stress for conditions of uniaxial stress and balanced by axial stress (σ_1= σ_2). The yield stress predicted by von Mises' criterion is 15.5% greater than the yield stress predicted by Tresca criterion. The two criteria are specified below in principal stress space and are one-parameter forms, specified by either the unaxial tensile strength, T, or the shear strength, S.

A best fit ellipse drawn from all the six yield stresses of σ_a to σ_f provides the yield locus and the yield locus thus established for the present alloy in the two heat treated conditions are shown in Fig. 6a, b.

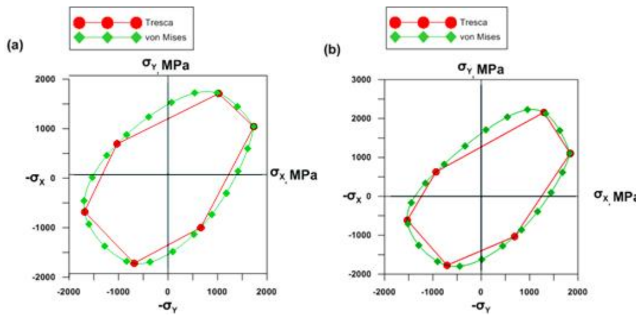

Fig.6. Yield locus plot of aluminium alloy AA 2014 (a) solution treated (b) peak aged condition (ST+450 K/10 h)

From the yield locus plots, the intersection points on the X (longitudinal or forging direction) and Y (transverse direction) provide the σ_X and σ_Y values, respectively for the tension and compression loading. The values of σ_X and σ_Y in solution treated and peak aged conditions of alloy under study, are given in Tables V and VI and they show similar anisotropy trends with the experimentally determined yield and ultimate tensile strength values obtained from tensile testing (see the data in Table II and III).

TABLE VI. YIELD LOCUS DATA OF ALUMINIUM ALLOY AA 2014 ALLOY PLATE IN PEAK AGED (ST+450 K/10 H AGED) IN DIFFERENT ORIENTATIONS

S. No.	Indentation orientation	$\alpha = \sigma_y / \sigma_x$ with δ = 7	$\sqrt{(1-\alpha+\alpha^2)}$	KHN at 100 g Load	Stress in MPa σ_x	Stress in MPa σ_x
1	a	0.60	0.872	163.4	1838.2	1102.9
2	b	1.67	1.454	150.9	1292.4	2158.3
3	c	0.67	1.454	138.9	-937.1	627.9
4	d	0.40	0.872	136.1	-1530.6	-612.2
5	e	2.50	2.180	157.6	-709.2	-1773.0
6	f	1.50	2.180	152.95	688.3	-1032.4

The main reason for variation in mechanical properties along three directions in aluminium base wrought products is mechanical texturing of grain boundaries or second phases. In addition, crystallographic texture was identified as the main cause for anisotropy in mechanical properties of Al-Li alloys [8]. In aged samples of Al-Mg-Si alloy to predict yield strength anisotropy, it was proposed that the concept of effective Taylor factor that accounts for anisotropic contribution from precipitates and crystallographic texture of matrix [13].

Theory of plasticity for indentation of a plastic rigid material is satisfactory only when the ratio of elastic modulus to yield stress is very high. Otherwise the hardness measurement reflects mainly the elastic contribution of material [8] .For the alloy under investigation has the ratio of elastic modulus to yield stress for solution treated is 157.8 and that for peak aged (ST+450 K/10 h) is 224.4

Contribution of the present work is to understand directionality in the properties of aluminium alloy AA2014 which may be utilized to get improved formability. This help to enhance the service performance of components made of this material in a particular orientation.

CONCLUSIONS

1. The alloy under investigation exhibits moderate values of in-plane anisotropy A_{IP} and anisotropic index δ for which is attributed the presence of anisotropy. Percentage in-plane anisotropy (A_{IP}) and anisotropic index (δ) are highest in peak aged (ST+450 K/10 h) condition and moderate in solution treated condition.
2. Yield locus has been generated from the calculated yield stress values using equations and from the experimentally determined KHN values in the six orientations shows the alloy in forged condition exhibits moderate degree of in-plane anisotropy.
3. Work hardening exponent is highest in T direction and lowest in L direction in case of solution treated specimen and it is highest in L direction and lowest in L+45° direction for peak aged (ST+450 K/10 h).
4. For the alloy in present study has the ratios of elastic modulus to yield stress for solution treated is 157.8 and that for peak aged (ST+450 K/10 h) is 224.4.
5. The present work contributed studying the in- plane anisotropy and plane stress yield locus of forged alloy AA 2014 in solution treated and peak aged conditions. Yield locus of the material is obtained based on Knoop Hardness Number (KHN) in a polycrystalline material.
6. Future work can be done to study the fine distribution of precipitates within the aluminium matrix and the respective morphologies of solution treated and peak aged alloy by conducting the TEM, SEM, XRD and texture analysis.

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