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Constitutive Flow Stress Model of Maraging steels in Cold Flow Formed and Aged conditions

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Abstract

There is an increasing demand to predict the flow stress levels of materials to know its response under load at various service conditions. Constitutive models are the mathematical expressions of behaviour of materials under deformation. Flow stress data was used for study of constitutive models to know the behaviour of maraging steels under under cold flow forming and aged conditions. Maraging steel of grade C 250 was subjected to Cold flow forming. Reduction of material was carried out in three passes to produce tubes of wall thickness 5.0 mm, 3.0 mm and 2.3 mm with an amount of reductions 58 %, 75% and 81% respectively. This study presents the constitutive flow curves for flow formed and flow formed plus aged specimens show best fit with Voce's constitutive model.

Keywords: *18% Maraging steels, Cold flow forming, Aging, Tensile flow curves, True stress, True plastic strain, Constitutive equations, Voce's constitutive equations.*

1. INTRODUCTION

Maraging steel of grade C 250 was chosen for present study. This grade of materials is considered as most suitable material for rocket motor propulsion casings of missiles due to its excellent combination of strength and toughness. The rocket motor propulsion casings are manufactured by cold flow forming of extruded and annealed tube of Maraging steel. A varying percentage of reduction is given during different stages of cold flow forming. During each stage of flow forming the material get strain hardened to certain extent at the respective cold reduction stage. The different extent of work hardening at different stages of flow forming results in varying plastic flow characteristics which is given by constitutive equations. The reason for different constitutive equations for varying plastic flow behaviour of materials has been explained by several authors [2-6]. These authors have explained various models of constitutive equations for varying extent of plastic flow are due to associated microstructure or phase content, their morphology and distribution in the matrix. A very little work has been carried out for finding out constitutive equations as function of degree of cold deformation particularly in the field of flow forming of Maraging steels [7]. In the present study an attempt has been made to establish the empirical or semi empirical constitutive equations during cold flow forming of extruded Maraging steel after varying extent of their cold reduction. The strength parameters and plastic flow characteristics are evaluated and validated from the uniaxial tensile test data.

2. EXPERIMENTAL WORK

The present work entitled "Constitutive Flow stress Models of Maraging steels of Grade C 250 in Cold Flow Formed and Aged conditions" is to study the plastic flow behaviour of material under flow formed and flow formed plus aged conditions. Material obtained from double vacuum treatment i.e. VIM (Vacuum Induction Melting) & VAR(Vacuum Arc Remelting) was extruded to a tube of Maraging steel grade C 250 having size Outside Diameter(OD) -375 mm , Inside Diameter (ID)-340 mm with a length of 570 mm. This extruded tube was double homogenized at 950°C / 2 Hrs / Water quenching followed by solution annealing at 820°C / 3 Hrs /Air cooling(AC). Chemical composition of starting material was evaluated using optical emission spectroscope (OES, Make:Spectrolab M 10) for all important elements except carbon and sulphur. The carbon and sulphur contents were analysed by using Leco CS600 analyser. The extruded tube with initial thickness of 12.0 mm has been taken as starting material (Preform) for flow forming to different extent of cold reduction. In present study a technique of reverse flow forming was employed to produce the Maraging steel tube of required wall thicknesses considered for present experiment. The cold flow forming was carried out on a three roller CNC (Computer Numerical Control) flow forming machine of Make: ILK WANG TECH IK TF60-225 CNC. The flow-forming machine used in this present work is shown in Fig.1.

Figure1: Flow forming machine

Specifications of flow forming machine are given in Table 1. Initially starting material called as preform of wall thickness 12.0 mm is fastened to the CNC controlled mandrel on which rollers are surrounded radially at an angle of 120°. In flow forming, axial and radial forces are simultaneously exerted on the the perform interior and exterior surfaces with simultaneous rotation and reduce wall thickness and increase the length of starting material without change in internal diameter. The reduction of material was carried out in three passes to produce tubes of wall thickness 5.0mm, 3.0 mm and 2.3 mm with an amount of reductions 58 %, 75% and 81% respectively as shown in Table.2 without any thermal treatment in between passes. Flow formed tubes of sizes 5.0 mm , 3.0 mm and 2.3 mm were subjected to aging treatment at 485° C / 6Hrs /AC. Tensile test samples were selected from variable sizes of flow formed and flow formed plus aged tubes.

Table 1: Specifications of flow forming machine

Minimum forming diameter	60 mm
Maximum forming diameter	700 mm
Mandrel RPM	0-750
Radial forces of each roller	500 KN
Axial force of the saddle	600 KN
Spindle power	225 KW

Table 2: Percentage of reduction at each stage of cold flow forming

Pass No	Initial Size (mm)	Final Size (mm)	Reduction (%)
1	12.0	5.0	58.33
2	5.0	3.0	75.0
3	3.0	2.3	80.83

2.1 Tensile Test

Room temperature tensile testing of flow formed and flow form plus aged tubes were carried out by extracting flat specimens from 3.0 and 5.0 mm thick flow form tubes in axial direction as per standard ASTM E 8 M as shown in Fig.2. Gauge Length (G)50.0mm Width (W) 12.5 mm The tensile test was carried out on servo-hydraulic Instron 8500 universal testing machine. An extensometer of Instron make having gauge length of 25 mm and calibration class of 0.5 was used to measure average linear strain with accuracy of 1x10^{-4}. The crosshead speed maintained during test was 0.5 mm / min so as to maintain the strain rate of 0.0088 mm/mm/min which is within the range specified in ASTM standard. Flow data obtained from tensile test was evaluated to determine the true stress and true plastic strain values to know the constitutive models.

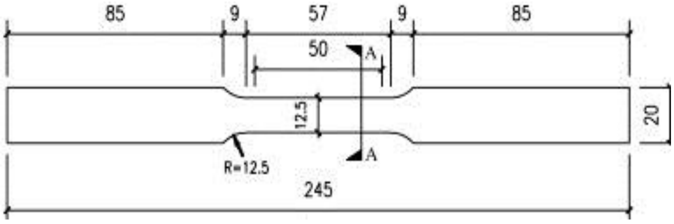

Figure 2: Flat tensile specimen drawing (in mm) **[**ASTM E 8]

3. RESULTS AND DISCUSSION

The analyzed chemical composition of starting material is given in Table.3. The chemical composition of each element is given in weight percent and lie well within the range of specification of Maraging steel grade C 250 (AMS 6512).

3.1Tensile Test Parameters

As shown in Fig .3 (a-b) The engineering stress –strain and true stress-strain curves of flow formed and flow formed plus aged material in axial direction show that the stress continuously increases up to UTS.

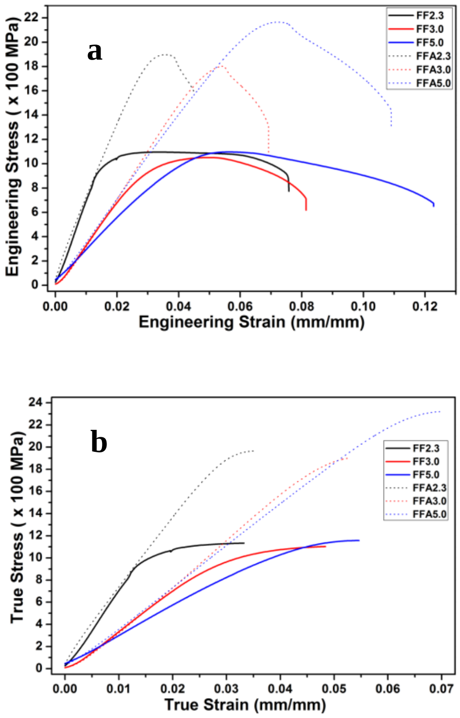

Figure 3 (a) Engineering stress - strain and (b) True stress - strain curves for flow formed and flow formed plus aged specimens in axial direction of flow formed and aged Maraging steel tubes.

Table 3: Chemical composition of extruded and solution annealed Maraging steel

Elements Wt %	**Specified values in**	**Obtained values**
C	0.03 Max	0.005
Si	0.1 Max	0.005
Mn	0.1 Max	0.01
Ti	0.3 to 0.5	0.44
S	0.01 Max	0.002
P	0.01 Max	0.005
Ni	17.0 to 19.0	18.09
Al	0.05 to 0.15	0.11
Cr	0.5 Max	0.01
Co	7.0 to 8.5	8.04
Mo	4.6 to 5.2	4.89
Fe	Balance	Balance

True stress and true plastic strain curves for flow formed and flow formed plus aged specimens were given in Fig. 4 (a-b). A number of models, such as Hollomon, Ludwik, Ludwigson etc., have been attempted to best fit the experimental flow curves data. It has been observed that any of the above models do not satisfied the condition of best fit that is value of co-efficient of determination (R2) is 0.99 or better. Finally, an important characteristic has been noticed that the true stress-true plastic strain curves are approaching to saturation of true stress in high strain regime. Based on this observation the tensile data have been attempted to fit to Voce's relationship because this type of exponential behaviour has been modelled using Voce's [5, 7] relation. This is given as

$$\boldsymbol{\sigma = \sigma_S - (\sigma_S - \sigma_0)\,\exp(-K_V \varepsilon)} \qquad \text{(Eq-1)}$$

Where σ_S is the saturation stress roughly correspond to ultimate tensile strength (UTS). The σ_0 is the initial stress corresponds to some approximation of initial dislocation density while K_v is a constant called as Voce constant which defines shape of the exponential curves. Flow curve parameters of all the flow formed and flow formed plus aged specimens in axial direction is fitted with the equation (Eq-1) and corresponding values of flow parameters (σ_S, σ_0 and K_v) are given in Table-4. The co-efficient of determination (R^2) values lie in the range 0.993-0.999 and 0.995-0.999, for flow formed and flow formed plus aged specimens, respectively which reflect an adequate fit of flow curves data. The values of σ_S obtained by Voce's relation display close resemblance with UTS values of flow formed and flow formed plus aged specimens (Table 4 and 5).

Table 4. Tensile test parameters of flow formed and flow formed plus aged materials

Condition of Material	**Sample Identification**	**Tensile Test Parameters**		
		0.2% Proof stress in MPa	**Ultimate tensile stress in MPa**	**% Elongation at gauge length 50 mm**
Flow formed to 5.0 mm	FF5.0	877	1097	12
Flow formed to 3.0 mm	FF3.0	876	1050	8
Flow formed to 2.3 mm	FF2.3	1022	1096	7.5
Flow formed and aged 5.0 mm	FFA5.0	1906	2164	11
Flow formed and aged 3.0 mm	FFA3.0	1691	1802	7
Flow formed and aged 2.3 mm	FFA2.3	1890	1897	4.5

Table 5 Voce's fitted flow curve parameters of flow formed and flow formed plus aged Maraging steel tubes.

Condition	**Specimen Identification**	**σ_S (MPa)**	**σ_0 (MPa)**	**$-K_V$ (MPa)**	**(R^2)***
Flow formed	FF5.0	1165	631	303	0.996
	FF3.0	1096	565	297	0.993
	FF2.3	1135	885	249	0.999
Flow formed and aged	FFA5.0	2346	1911	358	0.995
	FFA3.0	1967	499	463	0.996
	FFA2.3	1970	1761	886	0.999

* The error has been calculated by considering co-efficient of determination (R^2) between experimental and Voce fit true stress versus true plastic strain curves.

The numerical values of K_v increase for flow formed and flow formed plus aged specimens from FF5.0 to FF2.3. On the other hand, the value of σ_S and σ_0 decrease and increase from specimens FF5.0 to FF3.0 and FF3.0 to FF2.3 for flow formed and flow formed plus aged materials. It can be observed that the average values of σ_S is significantly lower for flow formed specimens as compared to that of flow formed and aged specimens.

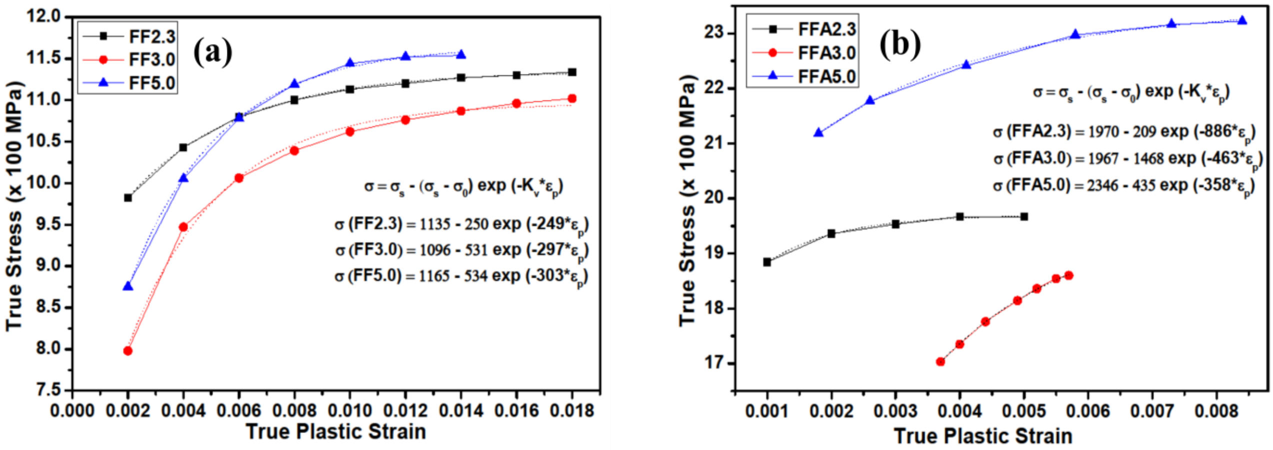

Figure 4: Experimental and best fit true stress – plastic strain curves for (a) flow formed and (b) flow formed plus aged specimens of Maraging steel tubes

4. CONCLUSIONS

Following conclusions are made based on the results obtained from present work:

- The flow curves of flow formed and flow formed plus aged specimens show best fit with Voce's model of constitutive model.
- The values of σ_S obtained by Voce`s constitutive model display close resemblance with ultimate tensile strength (UTS) values of flow formed and flow formed plus aged.
- The numerical values of Kv will increase for flow formed flow formed and flow formed plus aged specimens.

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