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Modelling of Reversed Austenite Formation and its Effect on Performance of Stainless Steel Components

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Abstract

The kinetics of reversed austenite formation in 301 stainless steel and its effect on the deformation of an automobile front bumper beam are studied by using modelling approaches at different length scales. The diffusion-controlled reversed austenite formation is studied by using the JMAK model, based on the experimental data. The model can be used to predict the volume fraction of reversed austenite in a temperature range of 650 – 750 °C. A 3D elastoplastic phase-field model is used to study the diffusionless shear-type reversed austenite formation in 301 steel at 760 °C. The phase-field simulations show that reversion initiates at martensite lath boundaries and proceeds inwards of laths due to the high driving force at such high temperature. The effect of reversed austenite (RA) and martensite on the deformation of a bumper beam subjected to front and side impacts is studied by using finite element (FE) analysis. The FE simulations show that the presence of reversed austenite and martensite increased the critical speed at which the beam yielded and

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failed. RA fraction also affects the performance of the bumper beam.

Keywords: Reversed austenite, JMAK model, Phase-field model,
Microstructure, Finite element analysis, Stainless steels

1. Introduction

Steels are widely used in the automotive industry. The main reason for its use is the range of yield strengths that the different grades of steel provide and their ability to absorb energy during impact. Steel, however, is not lightweight and therefore in recent years, there has been an increase in the research into the possible use of stainless steel components in the automotive industry [1]. This growing interest is due to stainless steel being lightweight, which aids in fuel reduction and exhaust emissions that are important factors considered in the environmental and government regulations [2].

Austenitic stainless steels are mainly used for applications where it is important to have good corrosion resistance along with good aesthetic properties. Due to their low yield strength, austenitic stainless steels are not considered to be suitable for structural purposes [3]. As a result, there has been a lot of research conducted into heat treatments that could be used to improve the mechanical properties, e.g. high strength, good ductility and good corrosion resistance, of stainless steels that would allow them to be used in more applications, such as the automotive industry.

The formation of martensite can impart significant strength to steels. The yield strength of steels can also be significantly increased by grain refinement, due to Hall-Petch effect. Reversion annealing process, i.e. heat treatment to revert martensite to austenite, has proved to be successful in reducing the

grain size and thereby in improving the mechanical properties of steels [4–10]. The improved strength of reversion annealed steel is also due to the high dislocation density of reversed austenite, inherited from martensite [11–13]. Reversed austenite has also been reported to improve corrosion resistance of stainless steel [14].

Earlier studies showed that reversion can take place at the austenite-martensite interfaces or inside the martensite laths [12, 15]. The reversed austenite can grow by a diffusionless shear mechanism or by a diffusional mechanism, depending on the composition [12]. The reversion of martensite has been reported to occur by diffusional mechanism in Fe-18Cr-8.5Ni steel [16], Fe-18Cr-9Ni steel at 650 °C [13], 301 type steels up to the temperature of 750 °C [17] and in 301LN steel [18]. Reversion by shear mechanism has been reported to occur in Fe-16Cr-10Ni steel [13], 301 steels at 800 °C and possibly at 850 °C [17] as well as between 700–800 °C [9]. Thus it is essential to study both mechanisms in order to predict the transformation kinetics.

The Johnson-Mehl-Avrami-Kolmogorov (JMAK) model has been used to study austenite formation during intercritical as well as reversion annealing [19–21] and can be used to study the reversion kinetics of the diffusional phase transformation. The phase-field method [22, 23] has been successfully used to study the microstructure evolution during martensitic transformations [24–29] and reverse transformation of martensite to austenite [30–32]. The effect of phase fractions on the mechanical properties and performance of the components can be studied by using macroscale finite element analysis.

In the present work, modelling approaches at different length scales are used to study the reversion kinetics in 301 stainless steel as well as its ef-

fect on the macroscopic mechanical performance of a stainless steel component. JMAK model, based on the experimental data, is used to study the diffusion-controlled reversed austenite formation in 301 stainless steel. A 3D elastoplastic phase-field model is used to study the diffusionless shear-type reversed austenite formation in Fe-17Cr-7Ni steel. The effect of reversed austenite and martensite on the macroscopic behaviour of a stainless steel front bumper beam of an automobile is studied by subjecting it to different loading conditions using the finite element analysis.

2. Modelling, results and discussion

2.1. JMAK model

The diffusion-controlled reversed austenite formation process is a nucleation and growth process. Johnson and Mehl derived an equation to study the nucleation and growth process of phases during phase transformations. The JMAK (Johnson-Mehl-Avrami-Kolmogorov) equation, can be applied to predict the fraction of reversed austenite formed during the heat treatment [20].

The JMAK equation expresses the volume fraction of reversed austenite transformed (V) in terms of the rate of nucleation (N) and the rate of growth of the nuclei (G). The rate of nucleation is defined as the number of nuclei per unit volume of reversed austenite formed per second in the parent phase, i.e. martensite, and the rate of growth is the radial growth [33].

The JMAK equation in its simplest form is [20]:

$$V_a = 1 - \exp(-kt^n) \quad (1)$$

where V_a is volume fraction of reversed austenite formed, k is constant related to the reversion temperature, t is time (seconds) and n is constant that depends on nucleation and growth mechanisms of the phase transformation. Considering that there are only two phases, i.e. martensite and austenite, present in the microstructure, the martensite volume fraction (V_m) can be calculated using:

$$V_m = 1 - V_a = \exp(-kt^n) \quad (2)$$

In order to model the effect of annealing temperature and time on the reversed austenite formation, experimental data of the volume fraction of martensite reverted to austenite in 301 steels annealed at 650 °C, 700 °C and 750 °C was obtained from Ref. [6]. From the experimental data (Fig. 1a), $\ln(-\ln(V_m))$ and $\ln(t)$ are calculated and then plotted (Fig. 1b). A line of best fit was applied to the straight line section of the graph. The equation of the line of best fit is:

$$\ln(-\ln(V_m)) = n\ln(t) + \ln(k) \quad (3)$$

where n is gradient of the line of best fit and $\ln(k)$ is y-intercept, which are the required constants in JMAK equations (Eqs. (1) and (2)). Fig. 1b shows the plot for 650 °C. Similar analysis is performed for all the temperatures and the predicted values of k and n are shown in Table 1. Table 2 shows the established relationships to determine the constants k and n in different temperature ranges.

The calculated values of the constants (k and n) in Table 1 are used in JMAK equation and the volume fraction of martensite reverted to austenite is estimated. Fig. 2 shows the predicted volume fractions of reversed austenite

(a)

(b)

Figure 1: (a) Experimental data of martensite volume fraction during annealing at different temperatures. (b) Plot showing $\ln(-\ln(V_m))$ and $\ln(\text{time})$ for 650 °C to estimate constants k and n in the JMAK equation.

at different temperatures compared to the experimental data. The predicted phase fractions are in agreement with the experimental data (Fig. 2). Fig. 2 shows that there is a change in the transformation rate between the annealing temperatures of 700 °C and 750 °C. It is believed that this change in rate of

Table 1: JMAK model constants, k and n , at different temperatures.

Temperature (°C)	Steel	k	n
650	301	0.0393	0.4248
700	301	0.0826	0.3459
750	301	0.0275	0.8464

Table 2: Variation of JMAK model constants, k and n , with temperature.

Temperature	k	n
650 °C – 700 °C	$k = 0.0009(T) - 0.5456$	$n = -0.0016(T) + 1.4505$
700 °C – 750 °C	$k = -0.0011(T) + 0.8539$	$n = 0.01(T) - 6.6611$

transformation can be explained by a change in transformation mechanism, as supported by numerous studies. Johannsen et al. [17] studied the reversed austenite formation in 301 stainless steel annealed between 600–900 °C. They found that between 600–750 °C the stainless steel underwent a diffusional reversion mechanism from martensite to reversed austenite [17]. Diffusional reversion occurs by nucleation and growth of ultra-fine grains of austenite at martensite boundaries [34]. Another study by Lee et al. [15] confirmed the diffusional reversion mechanism in this transformation temperature range as they found reversed austenite, with a film-like structure and with a thickness of 1 μm , had formed along the martensite lath boundaries.

It was reported that by 800 °C the reversed austenite was formed by a shear reversion mechanism [17]. The shear reversion process involves the transformation of the strain-induced martensite, formed by cold rolling, into reversed austenite laths which have a high dislocation density [35]. The

(a)

(b)

(c)

Figure 2: Comparison of experimental data [6] with JMAK model for martensite volume fraction during annealing at $T =$ (a) 650 °C, (b) 670 °C, (c) 700 °C and 750 °C.

microstructure obtained at higher transformation temperatures, such as 750-1000 °C, is believed to consist of granular reversed austenite structure which existed inside the martensite laths as well as the film-like reversed austenite at the lath boundaries [15]. Another important feature that is noticeable in Fig. 2 is that the rate of transformation is significantly high in the initial stages of the annealing process. This can be attributed to the rapid grain growth which occurs due to the large amount of grain boundaries and therefore there is a large driving force for grain growth to occur [34].

2.2. Phase-field model

The diffusionless shear-type reversion mechanism and the microstructure evolution is studied by using the phase-field approach. The phase-field equation governing the microstructure evolution is given by [24, 25]:

$$\frac{\partial \eta_p}{\partial t} = - \sum_{q=1}^{q=v} L_{pq} \frac{\delta G}{\delta \eta_q} \quad (4)$$

where η_q is the phase field variable that tracks the evolution of martensite, v is the total number of martensite variants and L_{pq} is a matrix of kinetic parameters. In the present work three phase-field variables (η_1, η_2, η_3) that correspond to the three Bain variants, which form the basis for the Kurdjumov-Sachs (K-S) orientation relationship (OR) are considered [36].

The Gibbs energy of a system undergoing athermal martensitic transformation can be expressed as:

$$G = \int_V (G_v^{chem} + G_v^{grad} + G_v^{el}) dV \quad (5)$$

where G_v^{chem} corresponds to the chemical part of the Gibbs energy density, G_v^{grad} is the gradient energy term, G_v^{el} is the elastic strain energy density.

G_v^{chem} is expressed as a Landau-type polynomial [24, 25]:

$$G_v^{chem}(\eta_1, \eta_2, \eta_3) = \frac{1}{V_m} \left[\frac{1}{2} A (\eta_1^2 + \eta_2^2 + \eta_3^2) - \frac{1}{3} B (\eta_1^3 + \eta_2^3 + \eta_3^3) + \frac{1}{4} C (\eta_1^2 + \eta_2^2 + \eta_3^2)^2 \right] \quad (6)$$

where V_m is the molar volume and the coefficients A, B, C are expressed in terms of Gibbs energy barrier and the driving force [25].

G_v^{grad} is expressed as [24, 25]:

$$G_v^{grad} = \frac{1}{2} \sum_{p=1}^{p=3} \beta_{ij}(p) \frac{\partial \eta_p}{\partial r_i} \frac{\partial \eta_p}{\partial r_j} \quad (7)$$

where $\mathbf{r}(\mathbf{x}, \mathbf{y}, \mathbf{z})$ is the position vector expressed in Cartesian coordinates. β_{ij} is the gradient coefficient matrix expressed in terms of the interfacial energy, molar volume and the Gibbs energy barrier.

G_v^{el} can be expressed as:

$$\begin{aligned} G_v^{el} &= \int_{\epsilon_{ij}^0(\mathbf{r})}^{\epsilon_{ij}(\mathbf{r})} \sigma_{ij}(\mathbf{r}) d\epsilon_{ij}(\mathbf{r}) \\ &= \int_{\epsilon_{ij}^0(\mathbf{r})}^{\epsilon_{ij}(\mathbf{r})} c_{ijkl} \left(\epsilon_{kl}(\mathbf{r}) - \epsilon_{kl}^0(\mathbf{r}) - \epsilon_{kl}^{pl}(\mathbf{r}) \right) d\epsilon_{ij}(\mathbf{r}) \end{aligned} \quad (8)$$

where $\sigma_{ij}(\mathbf{r})$ is the internal stress generated in the material due to martensite formation, c_{ijkl} is the tensor of elastic constants and $\epsilon_{kl}^{pl}(\mathbf{r})$ is the plastic strain. $\epsilon_{ij}(\mathbf{r})$ is the total strain, calculated by solving the mechanical equilibrium condition $\frac{\partial \sigma_{ij}(\mathbf{r})}{\partial r_j} = 0$. $\epsilon_{ij}^0(\mathbf{r}) = \sum_{p=1}^{p=3} \eta_p(\mathbf{r}) \epsilon_{ij}^{00}(p)$ is the stress-free

transformation strain. Bain strain tensors ($\epsilon_{ij}^{00}(p)$) of different variants are:

$$\begin{aligned}\epsilon_{ij}^{00}(1) &= \begin{bmatrix} \epsilon_3 & 0 & 0 \\ 0 & \epsilon_1 & 0 \\ 0 & 0 & \epsilon_1 \end{bmatrix}, \quad \epsilon_{ij}^{00}(2) = \begin{bmatrix} \epsilon_1 & 0 & 0 \\ 0 & \epsilon_3 & 0 \\ 0 & 0 & \epsilon_1 \end{bmatrix}, \\ \epsilon_{ij}^{00}(3) &= \begin{bmatrix} \epsilon_1 & 0 & 0 \\ 0 & \epsilon_1 & 0 \\ 0 & 0 & \epsilon_3 \end{bmatrix}\end{aligned}\tag{9}$$

where ϵ_3 and ϵ_1 are compressive and tensile transformation strains, respectively.

The material undergoes plastic deformation when the internal stress exceeds the yield limit. The evolution of plastic strain $\epsilon_{ij}^{pl}(\mathbf{r})$ is governed by [25, 26]:

$$\frac{\partial \epsilon_{ij}^{pl}(\mathbf{r})}{\partial t} = -k_{ijkl} \frac{\delta G_v^{shear}}{\delta \epsilon_{kl}^{pl}(\mathbf{r})}\tag{10}$$

where k_{ijkl} is the plastic kinetic coefficient. G_v^{shear} is the shear energy density expressed as $G_v^{shear} = c_{ijkl} \left(\frac{1}{2} e_{ij}(\mathbf{r}) e_{kl}(\mathbf{r}) + \frac{1}{2} e_{ij}^0(\mathbf{r}) e_{kl}^0(\mathbf{r}) - e_{ij}(\mathbf{r}) e_{kl}^0(\mathbf{r}) \right)$, where $e_{ij}(\mathbf{r})$ is the deviatoric actual strain tensor and $e_{ij}^0(\mathbf{r})$ is the deviatoric stress-free transformation strain tensor [25]. Linear isotropic strain hardening is considered by using the following expression [37]:

$$\sigma_y = \sigma_y^0 + H \epsilon^{pl}(\mathbf{r})\tag{11}$$

where σ_y is yield stress of the material that depends on plastic strain, σ_y^0 is initial yield stress, H is hardening modulus and $\epsilon^{pl}(\mathbf{r})$ is von Mises equivalent plastic strain.

The following input simulation data corresponding to stainless steels with a composition of Fe-17 wt %Cr-7 wt %Ni are acquired from different sources,

such as CALPHAD, ab initio calculations and experiments [27, 30]: $A = 1188$ J/mol, $B = 3564$ J/mol, $C = 2376$ J/mol, $\beta = 0.1061 \times 10^{-10}$ J/m; Bain strains are $\epsilon_1 = 0.1316$, $\epsilon_3 = -0.1998$; elastic constants of austenite are $C_{11} = 209$ GPa, $C_{12} = 133$ GPa and $C_{44} = 121$ GPa; elastic constants of martensite are $C_{11} = 248$ GPa, $C_{12} = 110$ GPa and $C_{44} = 120$ GPa; σ_y^0 (austenite) = 500 MPa, σ_y^0 (martensite) = 800 MPa, $H = 738$ MPa, $k = 0.2$ $GPa^{-1}s^{-1}$, driving force = -3600 and +200 J/mol at $T = -10$ °C and 760 °C, respectively.

A single crystal of austenite of 1 μm grain size is subjected to quenching at -10 °C and subsequent isothermal annealing at 760 °C. Ref. [9] reported that shear-type reversion occurs in the range of 700 – 800 °C, whereas Ref. [17] reported that shear-type reversion occurs at 800 °C and diffusional reversion occurs up to 750 °C in 301 stainless steels. In order to consider a temperature that is in agreement with both these experimental data as well as to study an annealing temperature that has not been studied before by the phase-field approach, 760 °C is considered as the annealing temperature to study the shear-type reversion mechanism in the present work. A pre-existing martensite embryo is considered in the center of the grain. Dirichlet (clamped) boundary conditions are considered. Simulations are performed on a 50 x 50 x 50 mesh by using FemLego software [38]. Due to the lack of available experimental data on the kinetics of lath martensite, L_{pq} in Eq. (4) is considered to be unity and the microstructure evolution is discussed in terms of dimensionless time, t^* .

A lath-type martensitic microstructure is obtained during quenching (Fig. 3), in agreement with the microstructure observed in 301-type stainless steels

[39, 40]. The simulation is started with one martensite variant and as it grows further, other martensite variants are formed due to autocatalysis such that the strain energy is minimized (Fig. 3) [25]. The volume fractions of martensite obtained during the athermal martensitic transformation as well as during the reversion annealing are shown in Fig. 3d. It shows that by annealing the steel at 760 °C, large amount of martensite (23 %) can be reverted to austenite. The volume fraction of martensite that reverts to austenite increases with the holding time, Figs. 3d and 4.

Figure 3: Martensitic microstructure evolution during quenching. Snapshots taken at (a) $t^*=5$, (b) $t^*=15$ (c) $t^*=80$. (d) Change in martensite volume fraction during quenching and reversion annealing. t^* is dimensionless time. Red, blue and green colors in the simulated microstructure represent the martensite variants in different orientations.

The top view of the microstructure obtained at $t^*=80$, shown in Fig. 3c, is shown in Fig. 4a. The microstructure evolution during annealing at 760 °C is shown in Fig. 4. Reversion initiates at martensite lath boundaries and proceeds inwards of laths (arrows in Fig. 4), which is in good agreement with Refs. [12, 15]. The driving force for reversion of martensite is very high at such a high temperature and hence reversion can proceed inwards of laths, whereas at low temperatures reversion occurs only at lath boundaries due to low driving force [30]. Moreover, decrease in the internal stresses (Fig. 5) during annealing can shift the Gibbs energy minimum and facilitate the formation of reversed austenite [30].

2.3. Macroscopic FEA

A front bumper beam of an Audi A1 with dimensions of 1750 mm length x 200 mm height x 100 mm width x 10 mm thickness was designed using Autodesk Inventor [41]. Fig. 6 shows the bumper beam, energy absorber and the back plates. Finite element analysis, using ANSYS software [42] with rectangular finite elements, is performed to study the effect of reversed austenite on the mechanical behaviour of the bumper beam under the following loading conditions.

(a) Loading condition 1: The beam was subjected to a frontal impact with a stationary object. The impact force associated with the collision at speeds between 20–70 miles per hour (mph) were calculated using $F_{max} = \frac{mv^2}{2d}$, where m is mass of Audi A1 car, d is distance travelled during collision, v is speed (m/s) of the car before collision and F_{max} is impact force (kN).

(b) Loading condition 2: In this loading type, tension caused by a side impact of the bumper beam was investigated. It was assumed that the bumper

Figure 4: Microstructure evolution during the reversed austenite formation at an annealing temperature of 760 °C. Snapshots taken at (a) $t^*=80$ (as-quenched microstructure at $T = 263$ K), (b) $t^*=85$, (c) $t^*=90$, (d) $t^*=95$. Some regions where reversion occurred are marked by arrows. Red, blue and green colors represent the martensite variants in different orientations. Austenite on the $\{111\}^\gamma$ planes shown in the figure is in white.

beam was stationary and was impacted at an angle of 45° by another vehicle travelling at a given speed (v). The impact forces can be calculated using $F_{max} = \frac{mv^2 \cos \theta}{2d}$, where θ is angle of impact.

Figure 5: X-component of internal stress in the microstructure during (a) quenching at $t^*=80$ and (b) annealing at $t^*=85$, corresponding to the microstructures shown in Figs. 4a and 4b, respectively.

The maximum impact forces F_{max} under different loading conditions were calculated for different car speeds using the above relations, where $m = 1260$ kg, $d = 0.5$ m and $\theta = 45^\circ$. A fixed support was applied to both the back plates shown by ‘A’ to prevent movement in the x, y, and z directions (Fig. 6). A displacement constraint ‘B’ was placed on the edges on the joints between the back plate and the energy absorber (Fig. 6).

As martensite and reversed austenite (RA) fractions affect the yield strength

and ultimate tensile strength of steels, the mechanical properties considered in the macroscopic analysis of the bumper beam with RA were based on the phase fractions predicted by the phase-field model. The different phase fractions are 23% reversed austenite, 12% martensite and 65% retained austenite (Fig. 3d). The mechanical properties of 301 stainless steel (SS) with 23% RA were considered to be $\sigma_{yield} = 800$ MPa and $\sigma_{UTS} = 1250$ MPa, taken from Ref. [43] at an annealing temperature of 700 °C. The room temperature mechanical properties of 301 SS without martensite and RA are $\sigma_{yield} = 276$ MPa and $\sigma_{UTS} = 758$ MPa. The material is assumed to be homogeneous in all the macroscopic simulations.

Figure 6: Boundary conditions used in FE analysis of the bumper beam subjected to front loading.

The maximum impact forces F_{max} at different car speeds were applied on the bumper beam and the von Mises equivalent stresses were calculated, as shown in Figs. 7 – 9. The maximum equivalent stress is obtained in the energy absorber under all the loading conditions. The force at which the component would yield was predicted by comparing the lower limit of the

maximum von Mises equivalent stress (lower limit of the red region in the colour bars in Figs. 7 – 9) to the yield strength of the steel. Similarly, the force at which the component would fail was predicted by comparing the lower limit of the maximum von Mises equivalent stress (lower limit of the red region in the colour bars in Figs. 7 – 9) to the ultimate tensile strength (UTS) of the steel. The results are shown in Table 3.

Table 3: Critical forces and vehicle speeds at which the component would yield and fail. Steels considered are 301 stainless steels, with and without reversed austenite (RA).

Steel	Loading	Yield		Failure	
		Force (kN)	Speed (mph)	Force (kN)	Speed (mph)
With RA	Front	580	48	906	60
Without RA	Front	197	28	580	48
With RA	Side	314	42	519	54
Without RA	Side	71	20	344	44

When the front bumper beam was subjected to compression due to front impact, i.e. loading condition 1, the presence of martensite and reversed austenite in steels increased the force required to yield the bumper beam by a factor of 3 and the force required to failure by a factor of 1.5 (Table 3 and Fig. 7). The critical speed at which the beam yielded and failed has increased by 20 mph and 12 mph, respectively.

A similar increase in performance was observed when the bumper beam was subjected to tension due to side impact, i.e. loading condition 2 (Fig. 8). The presence of martensite and reversed austenite increased the critical speed

Figure 7: FE analysis of the bumper beam subjected to front impact. Bumper beam (a) with reversed austenite (RA) yields under a force of 580 kN (speed = 48 mph), (b) without RA yields under a force of 197 kN (speed = 28 mph), (c) with RA fails under a force of 906 kN (speed = 60 mph) and (d) without RA fails under a force of 580 kN (speed = 48 mph).

at which the beam yielded and failed by 22 mph and 10 mph, respectively.

The effect of reversed austenite (RA) content on deformation of the bumper beam during front impact was studied by considering (i) 40% RA with $\sigma_{yield} = 1223$ MPa [34] and (ii) 95% RA with $\sigma_{yield} = 758$ MPa [34]. The simulations show that the bumper beam would yield at 70 mph in the

Figure 8: FE analysis of the bumper beam subjected to side impact. Bumper beam (a) with reversed austenite (RA) yields under a force of 314 kN (speed = 42 mph), (b) without RA yields under a force of 71 kN (speed = 20 mph), (c) with RA fails under a force of 519 kN (speed = 54 mph) and (d) without RA fails under a force of 344 kN (speed = 44 mph).

case of 40% RA (Fig. 9a) and 50 mph in the case of 95% RA (Fig. 9b). An excessive amount of RA leads to reduced strength, despite giving rise to an increase in ductility. Therefore, a reduced performance of the bumper beam with a very high RA is observed. Nevertheless, the bumper beam with 95% RA performed better (50 mph, Fig. 9b) compared to that without RA (28 mph, Fig. 7b).

The choice of a static component reduced the variables involved in analysing

Figure 9: Effect of reversed austenite (RA) on the deformation of bumper beam subjected to front impact. Bumper beam (a) with 40% RA yields under a force of 1234 kN (speed = 70 mph) and (b) with 95% RA yields under a force of 629 kN (speed = 50 mph).

the yield and failure points. Consequently, the mechanical properties and changes in performance were analysed more accurately. In reality, however, the bumper beam with reversed austenite would have absorbed more energy as the applied compressive load coupled with the compressive internal residual stresses (Fig. 5) could transform the reversed austenite to martensite during front impact [27]. During the side impact, the applied tensile load would first need to overcome the compressive internal residual stresses and hence the beam would have tolerated slightly higher loads.

The above results show that the presence of martensite and reversed austenite has significantly improved the performance of the front bumper beam. Earlier research has showed that the steel composition, martensite and reversed austenite phase fractions, percentage of cold rolling and grain size can significantly affect the mechanical properties [34, 44]. By a careful selection of heat treatment temperature, time and percentage of cold rolling the

martensite and reversed austenite phase fractions can be tailored to improve the performance of bumper beams and other stainless steel components.

3. Conclusions

JMAK model is developed to study the kinetics of diffusional reversion of martensite, based on the experimental data. The coefficients in the JMAK equation and their dependence on annealing temperature are predicted. These coefficients can be used to predict the volume fractions of reversed austenite and martensite at any given temperature in the range of 650 – 750 °C.

The phase-field simulations of the diffusionless reversion of martensite at 760 °C show that reversion initiates at martensite lath boundaries and proceeds inwards of laths due to the high driving force at such high temperature. The simulations show that the internal stresses decrease during reversion, which facilitate the formation of reversed austenite.

The finite element analysis of the bumper beam showed that the presence of reversed austenite increased the critical speed at which the beam yielded and failed by 20 mph and 12 mph, respectively, during the front impact. Similarly, the presence of reversed austenite increased the critical speed at which the beam yielded and failed by 22 mph and 10 mph, respectively during the side impact. The simulations also show that the reversed austenite fraction can also affect the performance of the bumper beam.

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