TRANSFORMATION PLASTICITY IN DUCTILE SOLIDS

Annual Progress Report
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Abstract

Research has addressed the role of martensitic transformation plasticity in the enhancement of toughness in high-strength austenitic steels, and the enhancement of formability in multiphase low-alloy sheet steels. In the austenitic steels, optimal processing has achieved a significant increase in strength level, in order to investigate the interaction of strain-induced transformation with the microvoid nucleation and shear localization mechanisms operating at ultrahigh strength levels. The degree of transformation interaction is sensitive to both strength level and degree of constraint. The stress-state dependence of transformation and fracture mechanisms has been investigated in model alloys, comparing behavior in uniaxial tension and blunt-notch tension specimens. A reformulated numerical constitutive model for transformation plasticity has allowed a more thorough analysis of transformation/fracture interactions, including local processes of microvoid nucleation. Processing of a new low alloy steel composition has been optimized to stabilize retained austenite by isothermal bainitic transformation after intercritical annealing. Results show a good correlation of uniform ductility with the austenite amount and stability, and new compositions are designed for improved stability.

Progress Report

Personnel involved in our program in the subject period have included Professor G. B. Olson as Principal Investigator committing 11% academic year, Research Assistant Professor Gautam Ghosh performing transformation kinetic modelling, Research Assistant David Bergstrom studying transformation plasticity in austenitic steels, Graduate Fellow Mitch Brandt studying transformation plasticity in multiphase low alloy steels, and Administrative Assistant James Herman. Collaborative work at MIT under subcontract has involved Professor D. M. Parks as Principal Investigator and Research Assistant Simona Socrate performing finite-element modelling of transformation plasticity behavior.

Homogeneous Austenitic Model Alloys

Our experimental measurements of transformation toughening in γ -strengthened austenitic alloys are summarized in Fig. 1, where the increment of J_{IC} toughness relative to nontransforming material is plotted vs. phase stability as represented by the total acting transformation driving force ΔG^{tot} (evaluated for a crack-tip stress state at yielding) relative to its critical value at the characteristic temperature M_s^0 . The plots summarize results obtained varying both alloy composition and test temperature. In general, optimum toughening interaction occurs at conditions corresponding to the M_s^0 temperature for the crack-tip stress state.

Figure 1a depicts results for alloys strengthened to ~185 ksi yield strength (R_{C45} hardness) by thermomechanical treatment at 450C to 40% reduction followed by 8hr aging at 700C. The highest observed toughening corresponds to the recent thesis research of F. Stavehaug¹ employing three-point-bend (tpb) specimens of 0.225 in. thickness conforming to ASTM Standard E813 for single-specimen J_{IC} testing. The study employed room temperature toughness measurements on a series of 4Cr and 12Cr alloys with varying Ni content. Optimal conditions corresponding to the crack-tip M_s^0 gave a J_{IC} toughness enhancement by a factor of 7, corresponding to a peak K_{IC} toughness of 320 ksi $\sqrt{in}$.

Although Stavehaug's measurements satisfied ASTM requirements, recent measurements by graduate student David Bergstrom employing compact tension (ct) specimens with a greater thickness of 0.5 in. showed the far less dramatic toughening denoted by open symbols in Figure 1a, similar to the earlier thesis results of Ricardo Léal^{2,3} in which stability of related alloys (denoted 26Ni-4Cr, 31Ni 5Cr, and 31Ni in Figure 1a) was varied by test temperature. The peak toughness here corresponds to a K_{IC} of ~170 ksi $\sqrt{in}$. While there is still a significant

a)

b)

Figure 1. J_{IC} transformation toughening increment vs. thermodynamic stability for γ' strengthened austenitic steels warm-worked at 450C to reductions of (a) 40% and (b) 70%.

transformation toughness enhancement of ~60%, the behavior indicates a sensitivity to specimen constraint in transformation toughened materials which is much stronger than that anticipated by the ASTM test specifications for conventional materials.

Figure 1b depicts David Bergstrom's very recent results extending the Stavehaug alloy series to the higher strength level of 210 ksi yield (R_{c48} hardness) by a greater reduction of 70% at 450C followed by double aging at 675C-5.5hr/650C-8hr. Consistent with earlier observations of the influence of strength level on the M_s^0 temperature, the optimum toughening composition in the 12Cr series is found to shift from 17Ni to 19Ni. At this strength level transformation toughening doubles J_{IC} , corresponding to a peak K_{IC} toughness of 95 ksi $\sqrt{in}$. The baseline (nontransforming) toughness of these materials appears quite sensitive to increasing strength level, apparently diminishing the opportunity for transformation interaction. Metallography of sectioned crack tips shows a reduction of the transformation zone size from 750 μ m for the 185 ksi material to 100 μ m for the 210 ksi material.

Employing a phosphocarbide-strengthened austenitic alloy previously studied in the doctoral research of C. Young^{4,5}, Bergstrom has further quantified the stress-state dependence of the M_s^0 temperature by extending measurements to axisymmetric blunt-notch tensile specimens with a notch radius ratio of $r/R=1$. The measured dependence of M_s^0 on triaxiality ratio $\Sigma=\sigma_t/\bar{\sigma}$ is depicted in Figure 2 for stress states corresponding to uniaxial compression, uniaxial tension, blunt-notch tension, and the plane-strain crack tip. This provides important quantitative information for calibration of transformation plasticity constitutive models.

Our previous NASA-sponsored research on design of high-performance bearing steels⁶ called attention to the need for accurate prediction of martensitic M_s temperatures in high alloy steels. Toward a similar need for prediction of M_s^0 for control of transformation plasticity, research on the fundamental basis of austenite stability has continued under our DOE program. Research Assistant Professor Gautam Ghosh has developed a comprehensive model for solution hardening contributions to the composition dependence of the critical driving force for martensitic nucleation in complex multicomponent Fe-base alloys. The structure of the model was presented at the International Conference on Martensitic Transformations (ICOMAT92)⁷ and a manuscript describing a further refined model is in press⁸. Using the M_s^0 data from our model alloys summarized in Table 1, David Bergstrom has extended the model to describe stability with respect to mechanically induced transformation in the thermomechanically treated alloys. Employing our previously developed model for the nonlinear stress dependence of the mechanical driving force based on a nucleation site orientation distribution⁹, the data of Table 1

DATA FOR PHOSPHOCARBIDE STRENGTHENED
Fe-16Cr-10Ni-0.5Mn-0.3C-0.33P STEEL
AGED 19 HOURS AT 630°C

Figure 2. Measured stress-state dependence of M_s^σ temperature for phosphocarbide-strengthened austenitic steel.

TABLE 1

Thermomechanically-Strengthened Austenitic Alloys
(40% Reduction at 450°C)

Experimental M_s^σ Temperatures

Alloy Number	Strengthening Precipitate	Alloy Type	Alloy Composition	Aging Condition	$\Sigma = \sigma_h/\sigma$	M_s^σ	$\sigma_y(M_s^\sigma)$
1 ¹	Phosphocarbide	16Cr	16Cr-10Ni-0.5Mn	Overaged (630°C, 19hrs)	-0.333	275 K	1150 MPa
					0.333	326 K	1270 MPa
					0.8	346 K	1260 MPa
					1.1	366 K	1250 MPa
					2.16	398 K	1240 MPa
2a ²	γ'	6Cr	31Ni	Underaged (720°C, 1/2hr)	0.333	298K	1210 MPa
					0.8	333K	1180 MPa
					2.16	363 K	1150 MPa
2b	γ'	0Cr	34Ni-9Co	Underaged (720°C, 2hrs)	0.333	303 K	1250 MPa
					0.8	363 K	1240 MPa
					2.16	403 K	1240 MPa
2c	γ'	4Cr	26Ni-4Cr	Underaged (720°C, 2hrs)	0.8	273 K	1240 MPa
					2.16	328 K	1190 MPa
3a ³	γ'	4Cr	25Ni-4Cr	Peak Hardness (700°C, 8hrs)	0.333	300 K	1410 MPa
3b	γ'	4Cr	28Ni-4Cr	Peak Hardness (700°C, 8hrs)	2.16	300 K	1410 MPa
3c	γ'	12Cr	17Ni-12Cr	Peak Hardness (700°C, 8hrs)	2.16	300 K	1210 MPa

1) Alloy 1 is from the PhD Thesis of C.C. Young (M.I.T. 1988)

2) Alloys 2a,2b & 2c are from the PhD Thesis of R.E. Leal (M.I.T. 1984)

3) Alloys 3a,3b & 3c are from the PhD Thesis of F. Stavehaug (M.I.T. 1990)

was used to define a substructural work contribution W_f^{sub} to the frictional work of martensite interfacial motion, arising from the complex substructure of the thermomechanically treated γ' -strengthened alloys. As summarized in Table 2, W_f^{sub} is found to correlate with $\tau_y \gamma_T$ by a factor of 0.5 ± 0.26 , where τ_y is the alloy shear yield strength and γ_T is the transformation shear strain. This provides a guide to alloy design for M_s^σ control, but does not yet offer desired precision. In collaboration with researchers at LLNL, our model concepts have been applied to transformation plasticity in Pu alloys¹⁰

Under the doctoral research of R. Stringfellow with Prof. Parks, a three-dimensional constitutive model was developed based on the Olson-Cohen model of strain-induced transformation kinetics¹¹ and the Narutani-Olson-Cohen one-dimensional constitutive model¹² derived from experiments on 304UD stainless steel. A recent paper¹³ describing the model gives a fit to the high-strength austenite data of Young⁴ and applies it to the transformation enhancement of uniform ductility in uniaxial tension. The numerical implementation as a subroutine of the ABAQUS code is described in further detail in another recent paper¹⁴.

Preliminary application of the constitutive model to the problem of flow localization at a crack tip has been described¹⁵. The pressure-sensitive strain hardening associated with transformation plasticity appears highly effective in offsetting the void-softening phenomenon that drives crack-tip shear localization. This behavior and the related problem of transformation interactions with the process of microvoid nucleation has been studied further in the doctoral research of Simona Socrate with Prof. Parks. Socrate encountered difficulties with the earlier model¹³ in unloading effects during fracture processes and has reformulated the model for her study of transformation toughening mechanisms. In the new formulation, the number of state variables has been reduced, the number of nonlinear equations has been decreased from eight to four, and a two-level solution procedure has been devised where only the outer level, consisting of a single equation, is strongly nonlinear. Figure 3 presents the simulation of a transient in which a tensile specimen is deformed to 50% strain at $\dot{\epsilon}=0.025/\text{min}$ (Step 1), then strained an additional 1% at $\dot{\epsilon}=0.0012/\text{min}$ (Step 2), reverse strained back to 50% at $\dot{\epsilon}=0.0012/\text{min}$ (Step 3), and returned to its original length at $\dot{\epsilon}=0.025/\text{min}$ (Step 4). This behavior could not be simulated by the previous procedure. Simona Socrate is now applying the new numerical implementation of the constitutive model to both (a) the microscopic problem of fine-scale transformation plasticity interaction with the process of microvoid nucleation, and (b) the more macroscopic problem of transformation hardening interaction with "averaged" void softening and the process of shear localization at notches and crack tips. The first problem employs a cohesive zone model of the type introduced by Needleman¹⁶ and considers interactions of periodic void arrays as

TABLE 2

Substructure Hardening for Austenitic Alloys
T.M.T.-Strengthened to $\sigma_y = 1200\text{-}1410$ MPa

Alloy Number	Alloy Type	Aging Condition	σ_y (MPa)	W_i^{sub} (J/mol)	$W_i^{\text{sub}}/\tau_y\gamma_t$ ($\tau_y = \sqrt{3}\sigma_y$, $\gamma_t = 0.2$)
1	16Cr	Overaged (630°C, 19hrs)	1270	980	0.33
2a	0Cr	Underaged (720°C, 1/2hr)	1220	1200	0.41
2b	0Cr	Underaged (720°C, 2hrs)	1245	1290	0.44
2c	4Cr	Underaged (720°C, 2hrs)	1200	1920	0.67
3a	4Cr	Peak Hardness (700°C, 8hrs)	1410	1620	0.48
3b	4Cr	Peak Hardness (700°C, 8hrs)	1410	1650	0.49
3c	12Cr	Peak Hardness (700°C, 8hrs)	1210	1920	0.67
					Average = 0.50 $2\sigma = 0.26$

Figure 3. History of axial stress through the simulated loading/unloading/reverse loading transient.

treated by Tvergaard¹⁷. The output of this model will be incorporated in a Gurson/Needleman-Tvergaard model of the macroscopically averaged void softening driving the flow localization behavior to be treated in the second problem. A preliminary result for the first problem is summarized in Figure 4. Using interfacial strength estimates for the 0.1 μ m scale TiC particles observed in the experimental alloys, the figure shows the normalized interfacial opening separation as a function of angular position around a particle during void nucleation with increasing applied strain levels at a remote stress state of $\Sigma=1.12$. Comparing the transforming and nontransforming behaviors, transformation delays the onset of void nucleation and reduces the degree of debonding for a given applied strain. The computed transformation field also agrees reasonably well with electron microscopy observation of the distribution of fine strain-induced martensite around such a particle performed by Young⁴.

Employing the blunt-notch tensile specimens of the study of Figure 2, David Bergstrom has tested predictions of the model for the transformation gradient fields. Figure 5 compares the predicted and measured increase in martensite fraction Δf vs. axial position, and shows the corresponding predicted distribution of stress state Σ and equivalent strain $\bar{\gamma}$ underlying the inhomogeneous distribution. The stress-state sensitivity of transformation, which we believe to be crucial to the toughening phenomena, appears reasonably well represented by the model.

Multiphase Low-Alloy Steels

Supported by a fellowship from Inland Steel, Mitch Brandt has investigated the transformation enhancement of sheet formability in low alloy steels employing a novel composition prepared for us by Inland. To vary retained austenite stability and amount in ferrite/bainite/austenite microstructures, specimens intercritically annealed at 775C have been partially bainitically transformed at 350-400C for varying reaction times. Results were presented at the Gil Speich Symposium of ISS-AIME in Montreal, October 1992, and an updated paper¹⁸ has been published by ISS-AIME. The paper summarizes the measured evolution of austenite amount, carbon content and M_s^σ temperature with increasing isothermal reaction time. Increased austenite stability after saturation of carbon content is attributed to particle refinement. Correlation of uniform ductility with austenite amount and stability at a fixed 3% flow stress of 90 ksi demonstrates that a uniform ductility of 45% can be achieved with 16% austenite, and predicts that a desired plane-strain uniform ductility of 22% could be achieved with only 5% austenite if the plane-strain tension M_s^σ can be brought to room temperature. This would allow a substantial reduction in alloy carbon content, promoting desired weldability for automotive

Figure 4. Normalized opening separation, u_n/δ_n , as a function of angular position ϕ from the radial direction for transforming and nontransforming matrices at increasing levels of axial strain.

Figure 5. Comparison of measured martensite distribution in blunt-notch tensile specimen (after radial strain of -0.09) with predicted distributions of martensite content, stress triaxiality, and equivalent strain.

applications. The paper received the 1992 M. R. Tennenbaum Award of ISS-AIME, presented at the October 1993 meeting in Pittsburgh. Further work presented at the meeting has applied the martensite kinetic model⁸ to predict new alloy compositions with improved austenite stability.

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Invited lectures presenting results from this research program were also given by Prof. Olson at the following locations:

Case Western Reserve University	2/16/93
NASA Lewis Space Center	2/17/93
TMS-AIME Annual Meeting, Denver, CO	2/24/93
Gordon Research Conference on Materials by Design	8/2/93
Sagamore Army Materials Research Conference	9/1/93
TMS-AIME Fall Meeting, Pittsburgh, PA	10/17/93
ISS,-AIME Mechanical Working Conference Pittsburgh, PA	10/25/93
Naval Research Laboratory	10/27/93
DOE (Trans. Matls.)	11/23/93
Allegheny Ludlum Steel, Pittsburgh, PA	12/2/94
Purdue University	1/24/94
Colorado School of Mines	2/24/94
TMS-AIME Annual Meeting, San Francisco, CA	3/1/94
Northwestern University (Baxter Healthcare Day)	4/8/94
American Ceramic Society, Indianapolis, IN	4/25/94
Oak Ridge National Laboratory	4/28/94
Ford Motor Company, Dearborn, MI	5/19/94

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