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Pierre Serrano, Louise Toualbi, Pascale Kanoute, Alain Couret. Cyclic deformation of TiAl generic microstructures at room and high temperature: Bauschinger effect & strain rate sensitivity. 2019. hal-02386237v1

HAL Id: hal-02386237

<https://hal.science/hal-02386237v1>

Preprint submitted on 29 Nov 2019 (v1), last revised 10 Jul 2020 (v2)

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Cyclic deformation of TiAl generic microstructures at room and high temperature: Bauschinger effect & strain rate sensitivity.

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Abstract

The cyclic deformation of four TiAl common microstructures is studied experimentally at room and high temperature. Multilevel and multirate tests are performed to highlight the microstructure impact on the Bauschinger effect and the strain rate sensitivity. The mechanical behaviors are linked to their corresponding deformation mechanisms. Results can directly be used to develop microstructure-sensitive modeling of the mechanical behaviors of TiAl alloys.

Keywords: A. Intermetallics (aluminides), B. Cyclic plasticity, B. Plastic deformation mechanisms, D. Microstructure, E. Yield behavior, F.

Mechanical testing

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1. Introduction

Technological advances in aircraft engine design require the use of lightweight materials at increasingly high temperatures. Therefore, intermetallics titanium aluminide alloys based on γ -TiAl have been introduced in the most recent civil turbo-engines as low pressure turbine blades [1]. To extend the use of this material to other application technologies, new alloys are being developed with enhanced mechanical properties [2].

Recently, it has been shown that a significant Bauschinger effect occurs at room temperature on TiAl alloy upon strain reversal loading [3]. Even if this effect has been mentioned in some works [4, 5], few hysteresis loops analysis are available. It can even be stated that the link between the microstructure and the mechanical behavior is mostly understood upon uniaxial and monotonic loadings [6, 7, 8, 9].

Indeed, the thermomechanical behavior of TiAl alloys has been studied only on already optimized microstructures with balanced properties [10, 11, 12]. In [13], a comparison is made between a near- γ microstructure and a lamellar microstructure but tests are only performed at room temperature. Other works discuss the cyclic behavior but only by means of the stress or strain amplitude evolution [14, 5, 15, 16, 17]. On cited works, neither the Bauschinger effect nor the strain rate sensitivity were studied.

Hysteresis loop analysis give additional information on the link between the macroscopic behavior and microstructural mechanisms [18]. Moreover, such results are extremely valuable to develop refined plasticity theory as new field of integrated computational materials engineering can help material design [19].

26 The aim of this work is to study the link between TiAl microstructures
 27 and their corresponding mechanical behavior. Four generic TiAl microstruc-
 28 tures are studied to correlate the macroscopic behavior to the corresponding
 29 microstructural mechanisms. Emphasis is made on the Bauschinger effect
 30 and the strain rate sensitivity. Results can directly be used to develop new
 31 microstructure-sensitive models to describe the mechanical behavior of TiAl
 32 alloys.

33 2. Material and methods

34 2.1. Microstructures

35 The material used is the G4 alloy (Ti-47Al-1Re-1W-0.2Si (at.%)) developed
 36 at the Onera and obtained via the powder metallurgy route [20]. The ingots
 37 have been casted at Howmet Casting facilities and the powder produced by
 38 argon gas atomization at Crucible Industries. Hot Isostatic Pressing (HIP)
 39 was performed by Bodycote at 140 MPa for 4h at 1250 °C. The chemical
 40 analysis of the powder compacts is given in Table 1.

Ti (at. %)	Al (at. %)	Re (at. %)	W (at. %)	Si (at. %)	C (ppm)	O (ppm)
50.85	47.01	0.95	0.95	0.24	175	1240

Table 1. Chemical composition of the studied G4 alloy.

41 Cylindrical blank were machined from the powder compacts. Heat treat-
 42 ments were directly applied on those specimens to control the microstructure.
 43 Temperature induced porosity (TIP) is observed after the treatments be-
 44 cause of gas entrapped inside the powder after the atomization. The same
 45 observations as in [21] were made : the occurrence of TIP after temperature

46 annealing depends on the grain size and the annealing time. TIP reduces
47 drastically fatigue lifetime. However, in our case they have no impact on the
48 macroscopic mechanical behavior and the hysteresis loop shape because of
49 their low volume fraction ($< 1\%$ for all microstructures) [22].

50 For microscopic observations, samples were ground with a series of emery
51 papers, then polished with colloidal silica paste abrasives down to $0.25\ \mu\text{m}$.
52 Microstructures were examined with a scanning electron microscope (SEM)
53 by back scattered electron images (BSE). Microstructural parameters were
54 quantified by image segmentation using ImageJ, a Java-based image processing
55 program [23]. The apparent surface of grains was measured. The grain
56 size is taken as the equivalent diameter of the measured shape. Series of
57 micrographs were examined to ensure that the observations were statistically
58 representatives. The lamellae spacing was measured following the methodology
59 proposed in [24] for two types of cooling heat treatments: furnace and air
60 cooling. The sample was cut in half and the apparent lamellar spacing and
61 angle were measured on both side after polishing. A stereological correction is
62 then applied to access the real lamellar spacing. Again, series of measurements
63 were made to ensure that the observations were statistically representatives.

64 SEM images of the studied microstructures are shown in Fig. 1. The
65 post-HIP microstructure is a near- γ microstructure (Fig. 1a) that contains
66 mainly small equiaxed γ grains with a mean size of $5\ \mu\text{m}$. Smaller β_0 (\sim
67 2.5%) and α_2 ($\sim 2.5\%$) equiaxed grains are also observed with a mean size
68 of $2\ \mu\text{m}$.

69 The duplex microstructure (Fig. 1b) is obtained following a heat treatment
70 at $1340\ ^\circ\text{C}$ during 4 hours followed by an air cooling. This microstructure

71 contains equiaxed γ grains ($\sim 5 \mu\text{m}$) and lamellar colonies ($\sim 15 \mu\text{m}$). The
72 grains are surrounded by borders consisting of γ phase and β_0 precipitates as
73 observed in the IRIS alloy [25].

74 The near-lamellar microstructure (Fig. 1c) is obtained following a heat
75 treatment at 1360°C during 1 hour followed by an air cooling. This mi-
76 crostructure contains mainly relatively small lamellar colonies ($\sim 90\%$, ~ 50
77 μm). Some equiaxed γ grains ($\sim 10\%$, $\sim 8 \mu\text{m}$) are still present. All phases
78 are surrounded by borders again.

79 Finally, the lamellar microstructure (Fig. 1d) is obtained following a
80 heat treatment at 1370°C during 1 hour with a furnace cooling. This
81 microstructure contains large lamellar grains ($\sim 200 \mu\text{m}$) surrounded by
82 the border phase. The results of the microstructural characterization are
83 given in Table 2.

84 It has to be noticed that getting accurate measurements of the TiAl
85 microstructural attributes is difficult even by Electron BackScatter Diffraction
86 (EBSD) because of the lamellae size and the pseudo-symmetry of the γ -phase.
87 For our case, statistical measurement performed by hand was find to be the
88 most relevant method.

89 *2.2. Mechanical testing*

90 For mechanical testing, cylindrical specimens were machined with the
91 geometry specified in Fig. 2. As described in [14], the size of the gauge
92 section was optimized to ensure that it contains at least 250 grains for every
93 investigated microstructure. Room temperature and high temperature tests at
94 750°C were conducted in air atmosphere using a MTS servohydraulic machine.
95 Tests were performed under controlled total strain. Extensometers attached

	γ		α_2		β_0		$\alpha_2 + \gamma$		
	VF	GS	VF	GS	VF	GS	VF	GS	LS
	(%)	(μm)	(%)	(μm)	(%)	(μm)	(%)	(μm)	(μm)
Near- γ	95	5	2.5	2	2.5	2	-	-	-
Duplex	50	8	-	-	-	-	50	15	0.08
Near-lamellar	10	8	-	-	-	-	90	50	0.08
Lamellar	-	-	-	-	-	-	100	200	0.3

Table 2. Results of the microstructural characterization. VF stands for Volume Fraction, GS stands for Grain Size, LS stands for Lamellae Size.

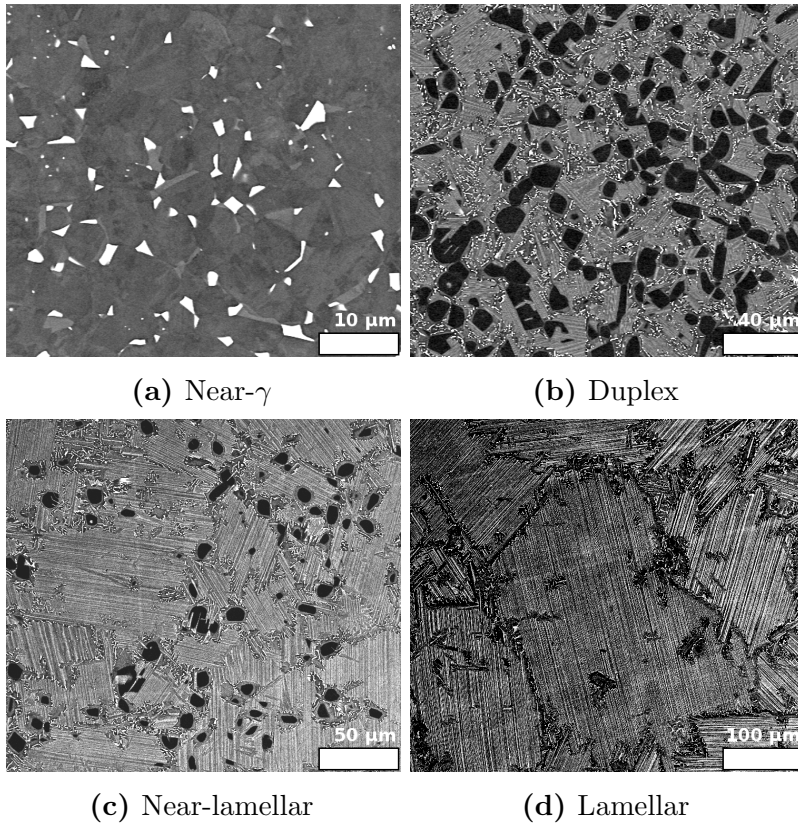


Fig. 1. SEM micrographs of the generic microstructures studied in this work.

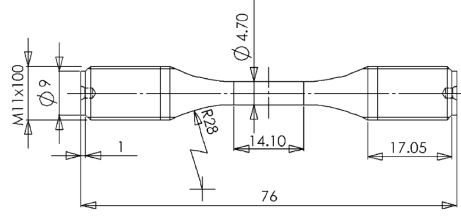


Fig. 2. Test specimen geometry.

96 directly to the gauge part of the specimens were used. High temperature tests
 97 were performed using a furnace monitored by three thermocouples attached
 98 to the specimen.

99 At both room temperature and 750 °C, a tensile test is first performed.
 100 Results were used to determine appropriate strain range level for each mi-
 101 crostructure and to compare monotonic and cyclic behaviors. The strain rate
 102 at room temperature is $\dot{\epsilon} = 10^{-3} \text{ s}^{-1}$. At 750 °C, the viscous behavior was
 103 investigated by changing the strain rate to $\dot{\epsilon} = 10^{-5} \text{ s}^{-1}$ during the test, then
 104 by stopping the test at $\epsilon = 0.8 \%$ and performing a 8 hours relaxation to
 105 study the mechanical behavior upon very low strain rate.

106 Multilevel cyclic tests were performed in symmetric tension-compression
 107 cycle ($R_{\epsilon} = -1$) at $\dot{\epsilon} = 10^{-3} \text{ s}^{-1}$ for room temperature tests and multiple
 108 strain rates for high temperature tests. Strain range levels were defined
 109 based on tensile test results. This type of cyclic tests highlights the major
 110 characteristics of the mechanical behavior with a limited number of specimens
 111 and is suited to the development of refined plasticity theories.

112 2.3. Bauschinger effect analysis

113 The mechanical behavior of material upon strain reversal loading is usually
 114 characterized by the Bauschinger effect, defined as a reduction of the yield

115 stress upon load reversal [26]. A scheme showing the typical stress-strain
116 behavior under strain controlled symmetric tension-compression tests is shown
117 in Fig. 3. Quantities detailed below are measured and used to discuss the
118 microstructure influence on this effect.

119 For tensile test and the first cycle of cyclic tests, the yield stress σ_0 and
120 0.2 % yield stress $\sigma_{0.2\%}$ are respectively defined as the lowest stress point at
121 which permanent deformation can be measured and the stress at 0.2 % plastic
122 strain. A Bauschinger effect is observed if the compressive yield stress σ_c is
123 lower than the yield stress such that $|\sigma_c| < |\sigma_0|$. This effect can be caused by
124 different phenomena.

125 It has been stated that in the case of TiAl alloys, the Bauschinger effect is
126 mainly caused by a significant transient softening [3]. This transient softening
127 can be seen as a decrease of the initial elastic domain ED_0 defined as $ED_0 =$
128 $2\sigma_0$, that becomes ED_C upon load reversal [27, 28]. The transient softening
129 can therefore be quantified as $TS_{OC} = ED_0 - ED_C$.

130 Even in the case where $ED_0 = ED_C$, a Bauschinger effect is still observed
131 if there is kinematic hardening. This is defined as the displacement of the
132 initial elastic domain center, the point A on the scheme, that becomes point
133 B upon load reversal. This leads once again to a lower compressive yield
134 stress σ_c as $|\sigma_c| < |\sigma_0|$.

135 Cyclic plasticity experiments with $R_\epsilon = -1$ can also reveal a tension-
136 compression asymmetry [29]. Such asymmetry is usually discussed by studying
137 the difference between the stress at the maximal peak strain σ_1 and the stress
138 at the minimal peak strain, σ_2 . Another interesting way to reveal a tension-
139 compression asymmetry is to compare the size of the elastic domain upon

140 compression, ED_C , to the size of the elastic domain upon tension, ED_T .

141 It should be noted that the Bauschinger effect can also be caused by
 142 a permanent softening, which is defined by a loss of strength between the
 143 forward and reverse parts of the test [30]. As it has already been shown that
 144 it does not happen in the case of TiAl alloys in [3], it will not be mentioned
 145 thereafter.

146 Finally, the evolution of the elastic domains, the peak stresses and the
 147 hysteresis loop shapes over the course of the test are studied to get insight
 148 over a potential cyclic hardening or softening.

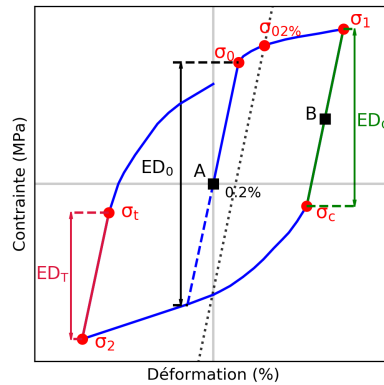


Fig. 3. Cyclic stress-strain behavior scheme. σ_0 is the yield stress, $\sigma_{0.2\%}$ the 0.2% yield stress, σ_1 and σ_2 are the stresses respectively at the maximum and minimum peak strain, σ_C and σ_T are respectively the compressive and tensile yield strength during a fully reversed cycle. ED_0 , ED_C and ED_T are respectively, the initial elastic domain, the compressive elastic domain and the tensile elastic domain. Points A and B are the centers of their corresponding elastic domains.

149 **3. Results**

150 *3.1. Room temperature tests*

151 Room temperature tensile properties are illustrated in Fig. 4. The ductility
152 is limited regardless of the microstructure. The microstructures exhibit various
153 behavior. The near- γ shows the highest stress state with an initial bump. The
154 duplex microstructure shows a steep entry in plasticity and linear hardening.
155 For the near-lamellar and the lamellar microstructure the elastic-plastic
156 transition is smoother. Their yield stresses are equals, but differences in
157 hardening led to different $\sigma_{0.2\%}$.

158 Multilevel cycle tests were designed to study the elastic-plastic transition
159 by performing 5 cycles at $\Delta\varepsilon = 0.1\%$, 5 cycles at $\Delta\varepsilon = 0.2\%$ and cycles
160 up to specimen failure at $\Delta\varepsilon = 0.4\%$. Results are shown in Fig. 5. Poor
161 powder quality induced failure after a small number of cycles, but enough
162 were performed to analyze the cyclic stress strain behavior.

163 For all microstructures, the mechanical behavior during the first strain
164 range level is elastic as no permanent strain is observed and σ_0 is not reached.
165 The initial elastic domain is therefore clearly defined by $ED_0 = 2\sigma_0$. Then, a
166 typical Bauschinger effect is observed for all microstructure after the onset
167 of plasticity. This effect is mainly caused by a significant transient softening
168 (i.e. ED_0 is reduced to ED_C and ED_T (see section 2.3)) but a kinematic
169 hardening is also observed. The stabilized hysteresis loop is immediately
170 reached as only the level transition cycles (dashed lines on the figures) are
171 different from the others. Almost no cyclic hardening or softening are observed
172 for all microstructures and there is no modification of the loop shapes until
173 failure. When comparing the near-lamellar and lamellar microstructures, it

174 can observed that plasticity starts in both cases at $\Delta\varepsilon/2 = 0.2 \%$ as the yield
175 stress are the same, but that the hysteresis loop is more open for the lamellar
176 microstructure.

177 To discuss the Bauschinger effect causes, the stress is plotted as a function
178 of the plastic strain for the stabilized hysteresis loops corresponding to
179 $\Delta\varepsilon/2 = 0.4 \%$ in Fig. 6a. The kinematic hardening observed for the near-
180 lamellar microstructure is more pronounced than the one of the lamellar
181 microstructure. Indeed, for both microstructures, the initial elastic domains
182 ED_0 and their associated centers are identical. But it can be observed in
183 Fig. 6a that at $\Delta\varepsilon/2 = 0.4 \%$, the elastic domain center of the near-lamellar
184 microstructure is now at a higher position than the one of the lamellar
185 microstructure.

186 The elastic domain sizes can be easily measured from those hysteresis loops,
187 as they correspond to the stress range for which no plastic strain occurs. The
188 elastic domain sizes upon compressive and tensile stress (ED_C and ED_T) are
189 measured, and the transient softening is quantified as $TS_{OC} = ED_0 - ED_C$
190 and $TS_{OT} = ED_0 - ED_T$. The evolution of the elastic domains size and
191 transient softening as a function of the γ phase volume fraction are shown in
192 Fig. 6b.

193 The transient softening increases dramatically with the γ phase volume
194 fraction. The comparison between the elastic domain sizes upon compressive
195 and tensile stress reveals a pronounced tension-compression asymmetry for
196 the two microstructures that contains a significant γ phase volume fraction.
197 Regarding both lamellar microstructures, their elastic domain sizes and
198 transient softenings are equals.

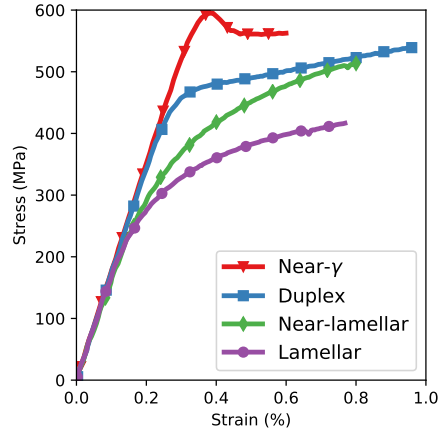


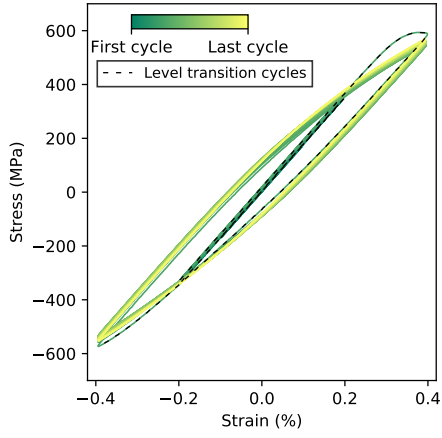
Fig. 4. Tensile curves at room temperature, $\dot{\varepsilon} = 10^{-3} \text{ s}^{-1}$.

199 *3.2. High temperature tests*

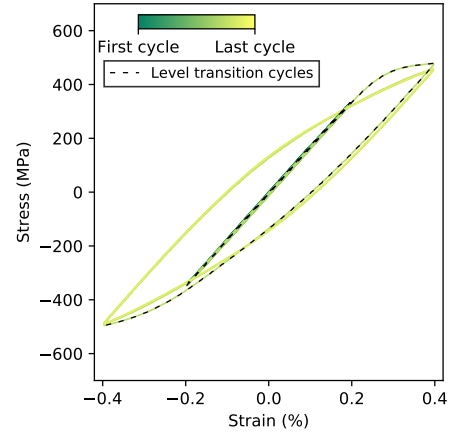
200 Tensile tests at two strain rates followed by a 8 hours relaxation were
 201 performed at 750 °C. The results are shown in Fig. 7. The strain rate
 202 modification was made at $\varepsilon = 0,4 \%$ and $\varepsilon = 0.6 \%$ based on the results at
 203 room temperature to avoid early failure (see Fig. 7a).

204 The behavior is now ductile. A decrease of the mechanical properties
 205 (Young modulus, yield stresses) is observed compared to room temperature
 206 tests. Nevertheless, the microstructure strength hierarchy is the same, and
 207 the observations made regarding the plasticity and hardening behavior are
 208 still true. It is not possible to say if the bump on the near- γ microstructure
 209 has disappeared, as it might have occurred simultaneously with the first strain
 210 rate change.

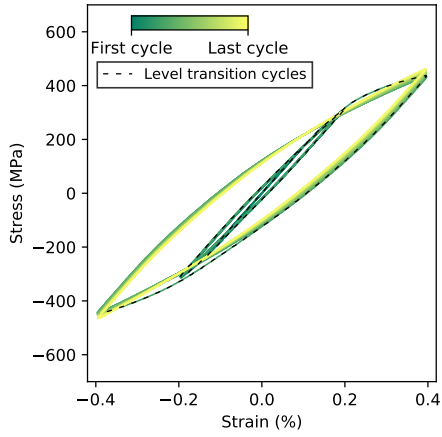
211 The strain rate modification reveals the microstructure impact on the
 212 viscosity. The strain rate sensitivity is discussed through the stress gap
 213 that occurs during the strain rate modification. The near- γ microstructure
 214 presents the most viscosity effects, followed by the duplex. The near-lamellar



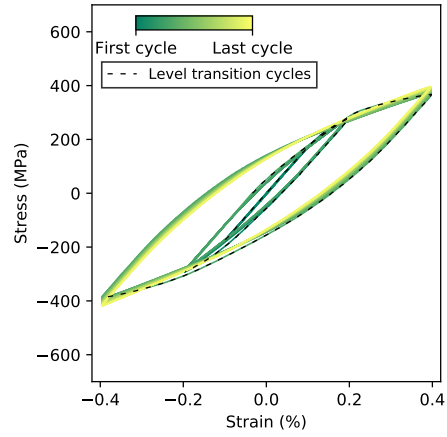
(a) Near- γ



(b) Duplex

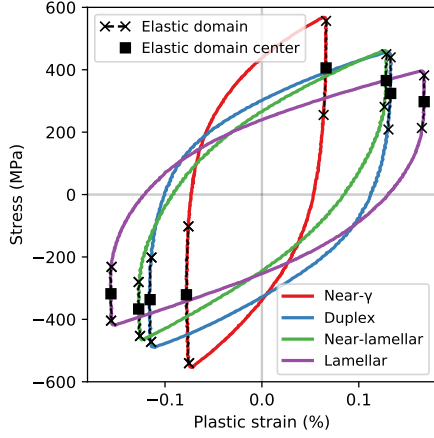


(c) Near-lamellar

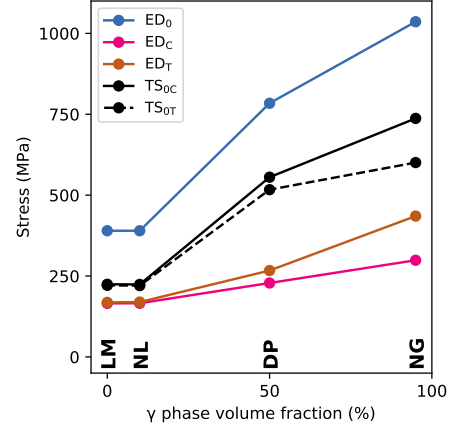


(d) Lamellar

Fig. 5. Room temperature multilevel cyclic tests results.



(a) Hysteresis loops for $\Delta\varepsilon = 0.4\%$.



(b) Elastic domain evolution.

Fig. 6. Bauschinger effect analysis at room temperature. NG, DP, NL and LM respectively stand for Near- γ , Duplex, Near-lamellar and Lamellar microstructure. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

215 and lamellar microstructures show almost no strain rate sensitivity. During
 216 the 8 hours relaxation, the mechanical behavior upon very low strain rate is
 217 revealed (Fig. 7b). The lamellar microstructure shows low relaxation whereas
 218 the near-lamellar has almost the same behavior as the duplex and near- γ
 219 microstructure. Therefore, a small amount of globular γ phase on a TiAl
 220 microstructure significantly modifies the low strain rate mechanical behavior.

221 Multilevel and multistrain cyclic tests are conducted in tension-compression
 222 under strain controlled at 750 °C. At each strain amplitude, 64 cycles are per-
 223 formed at a strain rate $\dot{\varepsilon} = 10^{-3} \text{ s}^{-1}$, 32 at $\dot{\varepsilon} = 10^{-4} \text{ s}^{-1}$ and 8 at $\dot{\varepsilon} = 10^{-5} \text{ s}^{-1}$.
 224 Successive strain amplitudes were defined to get enough data from each mi-
 225 crostructure based on their room temperature and high temperature tensile
 226 test results to avoid early failure. The amplitudes are 0.4 %, 0.6 %, 0.8 %

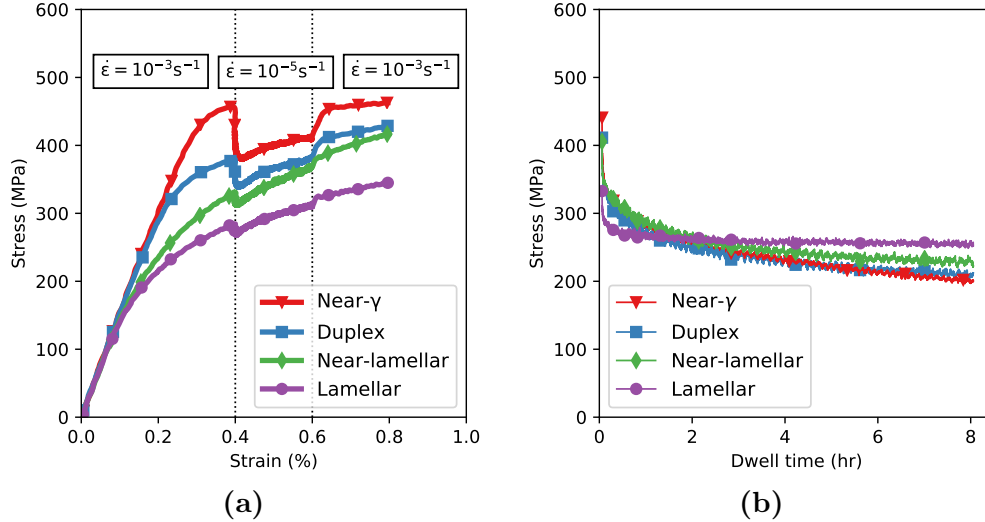


Fig. 7. High temperature tensile tests at two strain rates (a) follow by an 8 hours relaxation (b).

227 and 1 % for the near- γ and duplex microstructures. The amplitudes are 0.2
 228 %, 0.4 %, 0.6 % and 0.8 % for the near-lamellar and lamellar microstructures.
 229 Results are shown in Fig. 8.

230 Once again, stabilized cycle is reached immediately and the strain rate
 231 sensitivity increases with increasing γ phase volume fraction. For the near- γ
 232 microstructure, an important initial transient softening is observed. This
 233 might indicate that the mechanisms responsible for the bump at room tem-
 234 perature are still activated at 750 °C as shown by the zoom in Fig. 8a. No
 235 cyclic hardening or softening was observed regardless of the microstructure.

236 As for the room temperature results, the stress as a function of the plastic
 237 strain for the stabilized $\Delta\epsilon/2 = 0.6$ % hysteresis loops and the evolution of
 238 the elastic domain sizes are studied. The results are shown in Fig. 9a and
 239 Fig. 9b. Remarkably, the transient softening observed for each microstructure

240 is almost the same at 750 °C than the one observed at room temperature.
241 Finally, the tension-compression asymmetry of the near- γ microstructure has
242 decreased and is almost insignificant.

243 4. Discussion

244 At room temperature and 750 °C and for strain rate in the range from
245 10^{-3} s^{-1} to 10^{-5} s^{-1} , plastic deformation in TiAl occurs by glide of ordinary
246 dislocations and twinning [7, 31]. At 750 °C, the deformation is eased by the
247 activation of cross slip. Based on the experimental results, the mechanical
248 behavior of TiAl microstructures can be classified in two categories.

249 The first type of behavior corresponds to microstructures with a high γ
250 phase volume fraction, in our case the near- γ and duplex. Their behavior is
251 characterized by a steep entry into plasticity, with an initial bump for the
252 near γ microstructure, followed by a pronounced transient softening upon
253 reverse flow stress. The bump phenomena was linked to the activation of the
254 first twinning systems in [32, 33]. It might be related to the fact that twin
255 nucleation is more difficult than twin propagation [34]. Detailed TEM and
256 neutron diffraction investigations during cyclic tests suggest that major twins
257 are nucleated when the strain range increase, i.e. during the first cycle of
258 the considered strain range level [35]. This twin nucleation during the first
259 loading part creates interfaces. TEM investigations and dislocation dynamic
260 simulations confirmed that those boundaries are obstacles to dislocation
261 movement, and therefore back stress generators [36, 37]. Furthermore, it was
262 observed on steel that this back stress do create a significant Bauschinger
263 effect caused by transient softening [38].

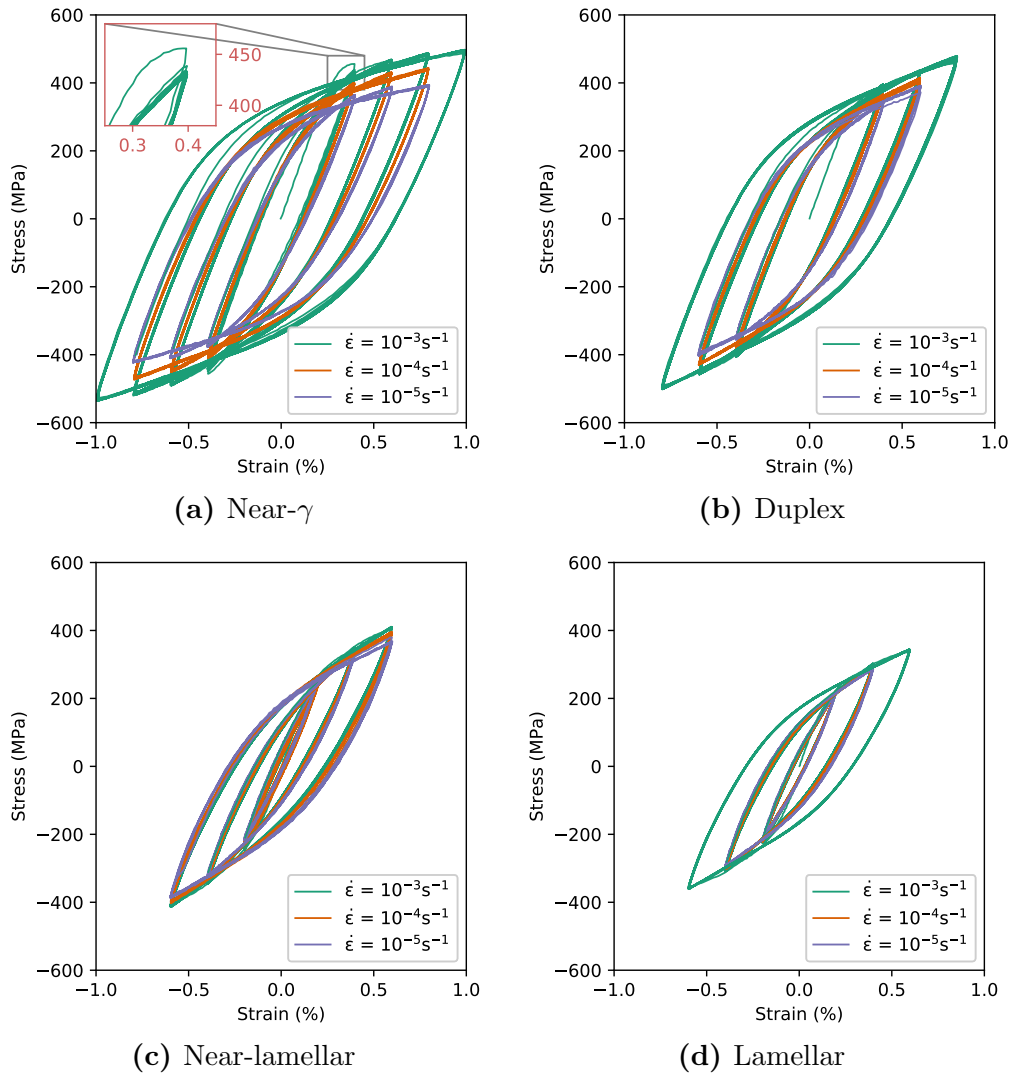
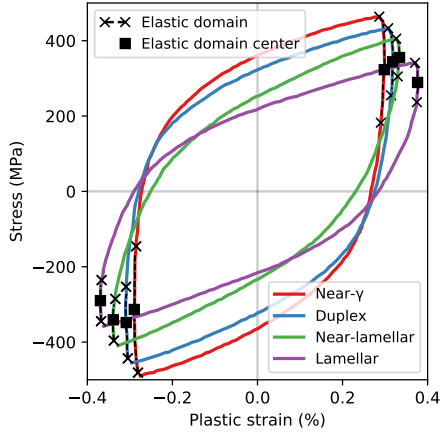
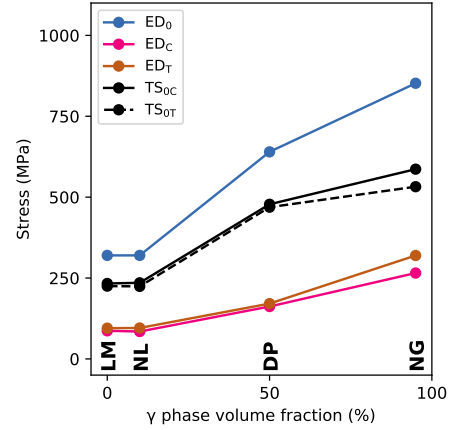


Fig. 8. Multilevel and multirate cyclic tests at 750 °C results. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)



(a) Hysteresis loops for $\Delta\varepsilon = 0.6\%$.



(b) Elastic domain evolution.

Fig. 9. Bauschinger effect analysis at 750 °C. NG, DP, NL and LM respectively stand for Near- γ , Duplex, Near-lamellar and Lamellar microstructure. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)

264 Based on the expensive microstructural analysis available in the literature,
 265 the following scenario can be defined. Twin are created during the first
 266 loading part of cyclic tests, therefore creating new boundaries within grains
 267 and an important back stress when interacting with dislocations. Because the
 268 shortness of their Burgers vector and since only one twinning dislocation can
 269 propagate in each plane, twinning is able to bring only a moderate amount
 270 of strain. Hence, the subsequent strain is largely due to glide of ordinary
 271 dislocations, the movement of which being impacted by the twins forming
 272 obstacles to their propagation. During the compression strain application,
 273 partial back movement of twin dislocations, nucleation and propagation of
 274 new twinning systems compatible with the compression strain as well as glide
 275 of ordinary dislocations should be activated. These three kinds of movement

276 are facilitated by the back stress created during the tensile strain, leading to
277 the tension-compression asymmetry. As a result, a pronounced Bauschinger
278 effect caused mainly by transient softening is observed during the compression
279 part. In fact, if another test was performed by starting in compression first,
280 we suspect that the asymmetry might change direction. When cycling at the
281 same strain range, ordinary dislocations which are easily able to multiply and
282 to accommodate both compression and tension strains propagate the applied
283 deformation. The stress does not increase and therefore the twin network
284 does not change drastically as twins thicken. Hence, the stabilized cycle is
285 immediately reached. The same scenario occurs at high temperature. The
286 bump is only less pronounced as deformation by ordinary dislocations is
287 eased by the activation of cross slip.

288 The small cyclic hardening observed at room temperature is similar to
289 the cyclic stress strain behavior that has been observed on an equiaxed
290 near- γ microstructure in [39], but different from the one observed on cast
291 material for which a significant hardening was observed [13]. That hardening
292 is usually associated to the formation of a vein-like dislocation structure and
293 twin-dislocation interactions [5]. The mechanisms responsible for the absence
294 of cyclic hardening at high temperature are unclear but are most certainly
295 related to the capability of dislocation to cross-slip, promoting the dislocation
296 annihilation processes, thus limiting the hardening.

297 The second type of behavior corresponds to microstructures with a high
298 volume fraction of lamellar colonies. This behavior is characterized by a
299 smooth entry to plasticity. The two investigated microstructures exhibit the
300 same yield stresses but different 0.2 % yield stresses. This can be explain by

301 the important plastic anisotropy of lamellar colonies that has been revealed
302 by studying lamellar single colonies [40]. This anisotropy leads favorably
303 oriented lamellar colonies to yield well before the macroscopic yield stress
304 [41, 42]. Therefore when performing tests at the macroscopic scale, the grain
305 size and lamellae size effects are only observed on the 0.2 % yield stresses
306 following a Hall-Petch law. This is why in this work, from a macroscopic point
307 of view, the microstructural attributes affect mostly the kinematic hardening
308 and not the apparent yield stress.

309 During cyclic tests, a Bauschinger effect caused by transient softening
310 is observed. The transient softening is far less pronounced than the one of
311 microstructures with a high volume fraction of γ grains. Nevertheless, TEM
312 observations suggest that the phenomena causing this softening are most
313 certainly similar but less striking because of the multiscale aspect of lamellar
314 microstructures [5]. As the deformation is constrained within lamellae, those
315 phenomena are not highlighted during macroscopic tests.

316 Regarding the strain rate sensitivity, multirate tensile test results show
317 that the microstructure sensitivity to viscosity effects increases with the
318 γ grain volume fraction. The relaxation part of the test reveal that the
319 mechanical behavior upon very low strain rate is drastically modified by
320 adding a small volume fraction of γ phase. It thus appears that at low strain
321 rate, the deformation only propagates in the soft γ areas, as in a composite
322 material made of deformable and undeformable parts. This is an important
323 observation as near-lamellar microstructures that consists of lamellar colonies
324 with a fraction of globular γ grains are often considered as the optimal
325 microstructure in TiAl alloys because of their balanced mechanical properties

326 [43, 25].

327 5. Conclusions

328 The mechanical behavior of four generic TiAl microstructures has been
329 studied at room and high temperature by means of mechanical testing,
330 including cyclic plasticity experiments. The phenomena observed at the
331 macroscopic scale are linked with their corresponding microscopic mechanisms.
332 The mechanical behaviors can be classified in two categories.

333 Microstructures containing an important volume fraction of γ grains
334 exhibit a pronounced Bauschinger effect caused mainly by a spectacular
335 transient softening. This sudden softening is attributed to the onset of
336 twinning and the dislocation-twin interactions. At room temperature, those
337 microstructures exhibit a tension-compression asymmetry during cyclic tests
338 that manifests as different elastic domain sizes depending on the flow stress
339 direction.

340 Microstructure with a high volume fraction of lamellar colonies show
341 little distinction between the elastic and plastic domains because of the
342 multiscale aspect of the microstructure and the pronounced plastic anisotropy
343 of lamellar colonies. A Bauschinger effect is also observed, partly caused by a
344 transient softening that is far less significant than the one described above, but
345 mostly due to a pronounced kinematic hardening. At the macroscopic scale,
346 the impact of the lamellar microstructural attributes appears only on the
347 kinematic hardening because of the multiscale aspect of the microstructure.

348 At 750 °C, the microstructure strength hierarchy and the observed phe-
349 nomena are the same than those observed at room temperature. Particularly,

350 the transient softening levels are almost exactly similar to the ones observed
351 at room temperature. The strain rate sensitivity is shown to increase with
352 the globular γ phase volume fraction. Relaxation tests revealed that even
353 a low amount of globular γ grains deeply modifies the mechanical behavior
354 upon very low strain rate.

355 To conclude, components made in TiAl alloys must be designed carefully as
356 significant unwanted plasticity might occurs upon strain reversal, particularly
357 if the mechanical behavior is closed to the one observed for the near- γ
358 and duplex microstructures. The given experimental results open a fruitful
359 opportunity for the development of microstructure-sensitive plasticity theories
360 and the modeling of TiAl alloys mechanical behavior.

Acknowledgement

The authors would like to thank our colleagues Camille Liard for performing the experiments and Marc Thomas for providing the material and helpful discussions.

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