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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, the Bauschinger effect is not 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 [19, 20]. In order to develop models that are able to describe the material behavior under the conditions seen by low pressure turbine blade, the cyclic behavior

must be known over a range of various strain ranges and strain rates [21]. To that attend, it has been shown that only a single multilevel and multirate cyclic test can be used [22].

The aim of this work is to study the link between TiAl microstructures and their corresponding mechanical behavior. The four generic microstructures of TiAl alloys are studied to correlate the macroscopic behavior to the corresponding microstructural mechanisms. Emphasis is made on the Bauschinger effect, but strain rate sensitivity is also considered so that the results can directly be used to develop advanced microstructure-sensitive models.

2. Material and methods

2.1. Microstructures

The material used is the G4 alloy (Ti-47Al-1Re-1W-0.2Si (at.%)) developed at the Onera and obtained via the powder metallurgy route [23]. The ingots have been casted at Howmet Casting facilities and the powder produced by argon gas atomization at Crucible Industries. Hot Isostatic Pressing (HIP) was performed by Bodycote at 140 MPa for 4h at 1250 °C. The chemical 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.

Cylindrical blank were machined from the powder compacts. Heat treatments were directly applied on those specimens to control the microstructure.

45 Temperature induced porosity (TIP) is observed after the treatments be-
46 cause of gas entrapped inside the powder after the atomization. The same
47 observations as in [24] were made : the occurrence of TIP after temperature
48 annealing depends on the grain size and the annealing time. TIP reduces
49 drastically fatigue lifetime. However, in our case they have no impact on the
50 macroscopic mechanical behavior and the hysteresis loop shape because of
51 their low volume fraction (< 1 % for all microstructures) [25].

52 For microscopic observations, samples were ground with a series of emery
53 papers, then polished with colloidal silica paste abrasives down to $0.25\text{ }\mu\text{m}$.
54 Microstructures were examined with a scanning electron microscope (SEM)
55 by back scattered electron images (BSE). Microstructural parameters were
56 quantified by image segmentation using ImageJ, a Java-based image processing
57 program [26]. The apparent surface of grains was measured. The grain
58 size is taken as the equivalent diameter of the measured shape. Series of
59 micrographs were examined to ensure that the observations were statistically
60 representatives. The lamellae spacing was measured following the methodology
61 proposed in [27] for two types of cooling heat treatments: furnace and air
62 cooling. The sample was cut in half and the apparent lamellar spacing and
63 angle were measured on both side after polishing. A stereological correction is
64 then applied to access the real lamellar spacing. Again, series of measurements
65 were made to ensure that the observations were statistically representatives.

66 SEM images of the studied microstructures are shown in Fig. 1. The
67 post-HIP microstructure is a near- γ microstructure (Fig. 1a) that contains
68 mainly small equiaxed γ grains with a mean size of $5\text{ }\mu\text{m}$. Smaller β_0 (\sim
69 2.5 %) and α_2 (~ 2.5 %) equiaxed grains are also observed with a mean size

	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.

of 2 μm .

The duplex microstructure (Fig. 1b) is obtained following a heat treatment at 1340 °C during 4 hours followed by an air cooling. This microstructure contains equiaxed γ grains ($\sim 5 \mu\text{m}$) and lamellar colonies ($\sim 15 \mu\text{m}$). The grains are surrounded by borders consisting of γ phase and β_0 precipitates as observed in the IRIS alloy [28].

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

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

It has to be noticed that getting accurate measurements of the TiAl

87 microstructural attributes is difficult even by Electron BackScatter Diffraction
 88 (EBSD) because of the lamellae size and the pseudo-symmetry of the γ -phase.
 89 For our case, statistical measurement performed by hand was find to be the
 90 most relevant method.

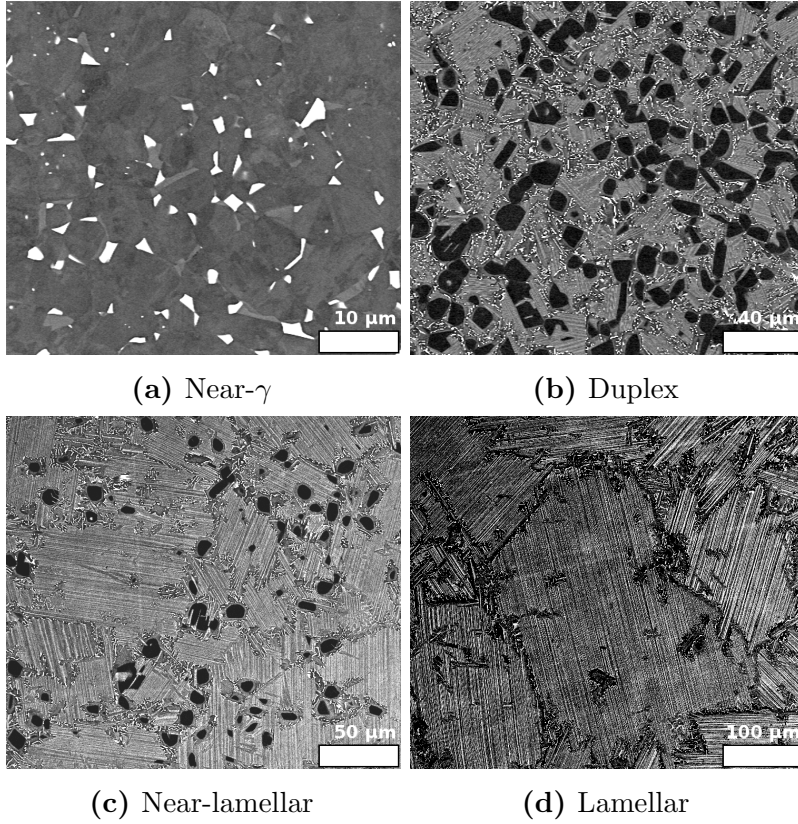


Fig. 1. SEM micrographs of the generic microstructures studied in this work.

91 2.2. Mechanical testing

92 For mechanical testing, cylindrical specimens were machined with the
 93 geometry specified in [Fig. 2](#). As described in [\[14\]](#), the size of the gauge
 94 section was optimized to ensure that it contains at least 250 grains for every

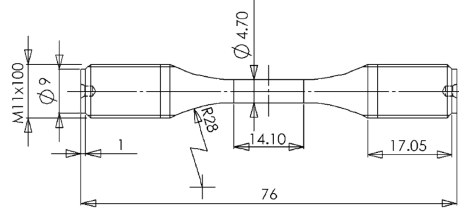


Fig. 2. Test specimen geometry.

95 investigated microstructure. Room temperature and high temperature tests
 96 at 750 °C were conducted in air atmosphere using a MTS servohydraulic
 97 machine. High temperature tests were performed using a furnace monitored
 98 by three thermocouples attached to the specimen. Extensometers attached
 99 directly to the gauge part of the specimens were used. Tests were performed
 100 in total mechanical strain control with a triangular waveform. Hence, the
 101 plastic strain rate is not constant [29]. Nevertheless, this is the case in various
 102 works in which both the Bauschinger effect and strain rate sensitivity were
 103 investigated [3, 18, 30]. As all the specimens undergo the same type of loading,
 104 we assume that it has a limited impact on the observed mechanical behaviors
 105 and the discussion [31].

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

113 Multilevel cyclic tests were performed in symmetric tension-compression

114 cycle ($R_\epsilon = -1$) at $\dot{\epsilon} = 10^{-3} \text{ s}^{-1}$ for room temperature tests and multiple
 115 strain rates for high temperature tests. Strain range levels were defined
 116 based on tensile test results. This type of cyclic tests highlights the major
 117 characteristics of the mechanical behavior with a limited number of specimens
 118 and is suited to the development of refined plasticity theories.

119 2.3. Bauschinger effect analysis

120 The mechanical behavior of material upon strain reversal loading is usually
 121 characterized by the Bauschinger effect, defined as a reduction of the yield
 122 stress upon load reversal [32]. A scheme showing the typical stress-strain
 123 behavior under strain controlled symmetric tension-compression tests is shown
 124 in Fig. 3. Quantities detailed below are measured and used to discuss the
 125 microstructure influence on this effect.

126 For tensile test and the first cycle of cyclic tests, the yield stress σ_0 and
 127 0.2 % yield stress $\sigma_{0.2}$ are respectively defined as the lowest stress point at
 128 which permanent deformation can be measured and the stress at 0.2 % plastic
 129 strain. A Bauschinger effect is observed if the compressive yield stress σ_c is
 130 lower than the yield stress such that $|\sigma_c| < |\sigma_0|$. This effect can be caused by
 131 different phenomena.

132 It has been stated that in the case of TiAl alloys, the Bauschinger effect is
 133 mainly caused by a significant transient softening [3]. This transient softening
 134 can be seen as a decrease of the initial elastic domain ED_0 defined as $ED_0 =$
 135 $2\sigma_0$, that becomes ED_C upon load reversal [33, 34]. The transient softening
 136 can therefore be quantified as $TS_{OC} = ED_0 - ED_C$.

137 Even in the case where $ED_0 = ED_C$, a Bauschinger effect is still observed
 138 if there is kinematic hardening. This is defined as the displacement of the

139 initial elastic domain center, the point A on the scheme, that becomes point
 140 B upon load reversal. This leads once again to a lower compressive yield
 141 stress σ_c as $|\sigma_c| < |\sigma_0|$.

142 Cyclic plasticity experiments with $R_\epsilon = -1$ can also reveal a tension-
 143 compression asymmetry [20]. Such asymmetry is usually discussed by studying
 144 the difference between the stress at the maximal peak strain σ_1 and the stress
 145 at the minimal peak strain, σ_2 . Another interesting way to reveal a tension-
 146 compression asymmetry is to compare the size of the elastic domain upon
 147 compression, ED_C , to the size of the elastic domain upon tension, ED_T .

148 It should be noted that the Bauschinger effect can also be caused by
 149 a permanent softening, which is defined by a loss of strength between the
 150 forward and reverse parts of the test [35]. As it has already been shown that
 151 it does not happen in the case of TiAl alloys in [3], it will not be mentioned
 152 thereafter.

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

156 The size of the elastic domain is measured on the stabilized hysteresis
 157 loops by using Cottrell's method [36]. This method has been widely used and
 158 discussed elsewhere [18, 37, 38, 39, 40]. It consists in extracting the elastic
 159 part of the hysteresis loop by considering that it corresponds to all the data
 160 points located between two parallel lines. Those lines have a slope equal to
 161 Young's modulus and are shifted by a strain offset. This offset parameter
 162 is defined based on the sensitivity of the extensometer. In our case, we use
 163 $\epsilon_{\text{offset}} = (3 \pm 2) \times 10^{-5}$ as in [41]. A scheme illustrating the technique is shown

on the right part of Fig. 3. In some cases, the elasticity modulus can change during the test and has to be adjusted for the elastic part detection [42]. This was not necessary in our study.

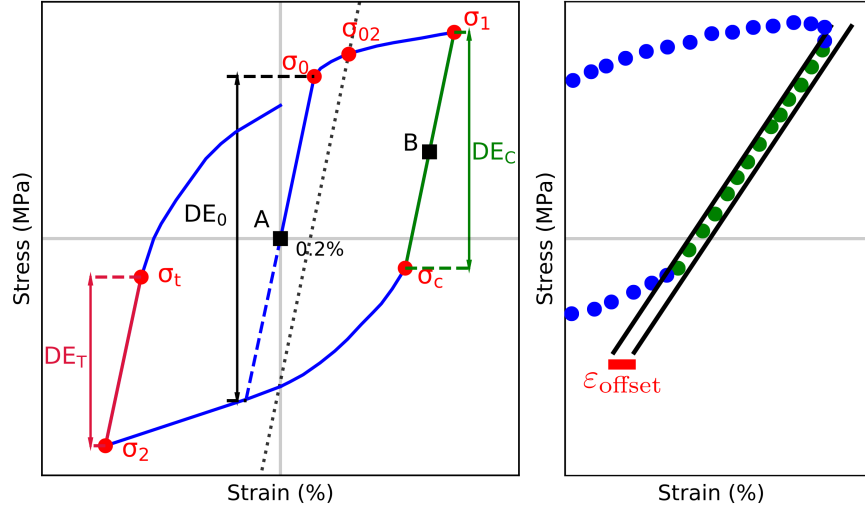


Fig. 3. Cyclic stress-strain behavior scheme. σ_0 is the yield stress, $\sigma_{0.2}$ the 0.2% yield stress, σ_1 and σ_2 are the stresses respectively at the maximum and minimum peak strain, σ_c and σ_t are respectively the compressive and tensile yield strength during a fully reversed cycle. ED_0 , 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. The right part of the scheme illustrates the detection technique of the linear part based on the use of an offset parameter ϵ_{offset} .

3. Results

3.1. Room temperature tests

Room temperature tensile properties are illustrated in Fig. 4. The ductility is limited regardless of the microstructure. The microstructures exhibit various

171 behavior. The near- γ shows the highest stress state with an initial bump. The
 172 duplex microstructure shows a steep entry in plasticity and linear hardening.
 173 For the near-lamellar and the lamellar microstructure the elastic-plastic
 174 transition is smoother. Their yield stresses are equals, but differences in
 175 hardening led to different $\sigma_{0.2\%}$.

176 Multilevel cycle tests were designed to study the elastic-plastic transition
 177 by performing 5 cycles at $\Delta\varepsilon = 0.1\%$, 5 cycles at $\Delta\varepsilon = 0.2\%$ and cycles
 178 up to specimen failure at $\Delta\varepsilon = 0.4\%$. Results are shown in [Fig. 5](#). Poor
 179 powder quality induced failure after a small number of cycles, but enough
 180 were performed to analyze the cyclic stress strain behavior.

181 For all microstructures, the mechanical behavior during the first strain
 182 range level is elastic as no permanent strain is observed and σ_0 is not reached.
 183 The initial elastic domain is therefore clearly defined by $ED_0 = 2\sigma_0$. Then, a
 184 typical Bauschinger effect is observed for all microstructure after the onset
 185 of plasticity. This effect is mainly caused by a significant transient softening
 186 (i.e. ED_0 is reduced to ED_C and ED_T (see [section 2.3](#))) but a kinematic
 187 hardening is also observed. The stabilized hysteresis loop is immediately
 188 reached as only the level transition cycles (dashed lines on the figures) are
 189 different from the others. Almost no cyclic hardening or softening are observed
 190 for all microstructures and there is no modification of the loop shapes until
 191 failure. When comparing the near-lamellar and lamellar microstructures, it
 192 can observed that plasticity starts in both cases at $\Delta\varepsilon/2 = 0.2\%$ as the yield
 193 stress are the same, but that the hysteresis loop is more open for the lamellar
 194 microstructure.

195 To discuss the Bauschinger effect causes, the stress is plotted as a function

196 of the plastic strain for the stabilized hysteresis loops corresponding to
 197 $\Delta\varepsilon/2 = 0.4\%$ in Fig. 6a. The kinematic hardening observed for the near-
 198 lamellar microstructure is more pronounced than the one of the lamellar
 199 microstructure. Indeed, for both microstructures, the initial elastic domains
 200 ED_0 and their associated centers are identical. But it can be observed in
 201 Fig. 6a that at $\Delta\varepsilon/2 = 0.4\%$, the elastic domain center of the near-lamellar
 202 microstructure is now at a higher position than the one of the lamellar
 203 microstructure.

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

211 The transient softening increases dramatically with the γ phase volume
 212 fraction. The comparison between the elastic domain sizes upon compressive
 213 and tensile stress reveals a pronounced tension-compression asymmetry for
 214 the two microstructures that contains a significant γ phase volume fraction.
 215 Regarding both lamellar microstructures, their elastic domain sizes and
 216 transient softenings are equals.

217 3.2. High temperature tests

218 Tensile tests at two strain rates followed by a 8 hours relaxation were
 219 performed at 750 °C. The results are shown in Fig. 7. The strain rate
 220 modification was made at $\varepsilon = 0.4\%$ and $\varepsilon = 0.6\%$ based on the results at

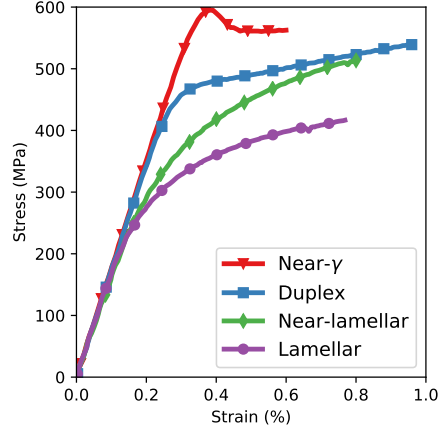
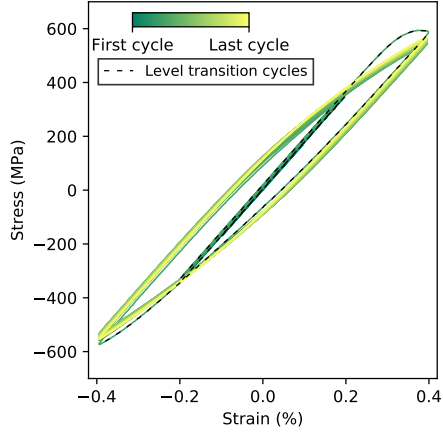


Fig. 4. Tensile curves at room temperature, $\dot{\epsilon} = 10^{-3} \text{ s}^{-1}$.

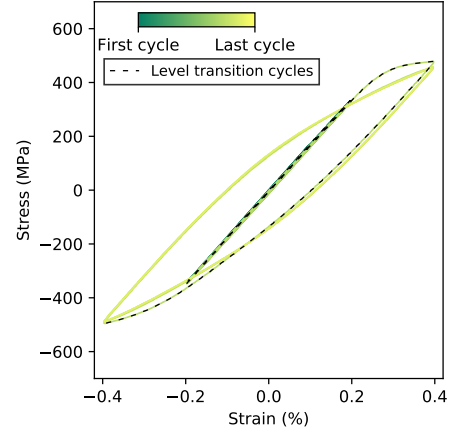
room temperature to avoid early failure (see Fig. 7a).

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

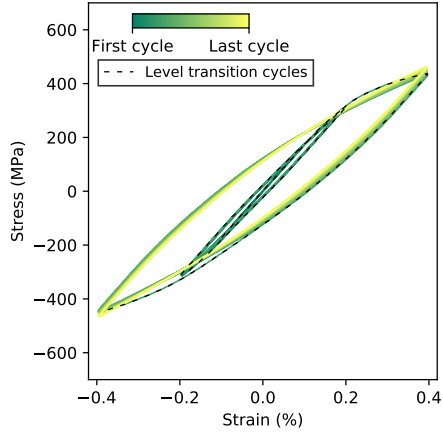
The strain rate modification reveals the microstructure impact on the viscosity. The strain rate sensitivity is discussed through the stress gap that occurs during the strain rate modification. The near- γ microstructure presents the most viscosity effects, followed by the duplex. The near-lamellar and lamellar microstructures show almost no strain rate sensitivity. During the 8 hours relaxation, the mechanical behavior upon very low strain rate is revealed (Fig. 7b). The lamellar microstructure shows low relaxation whereas the near-lamellar has almost the same behavior as the duplex and near- γ



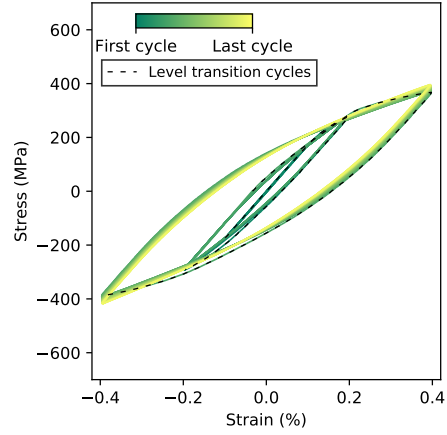
(a) Near- γ



(b) Duplex

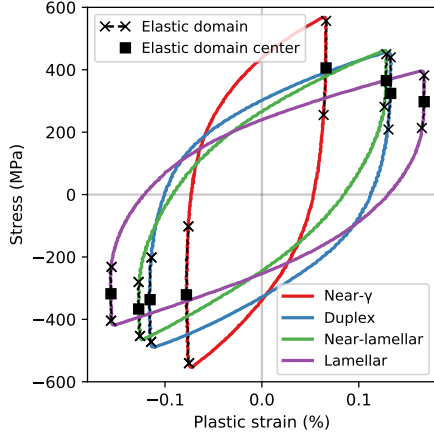


(c) Near-lamellar

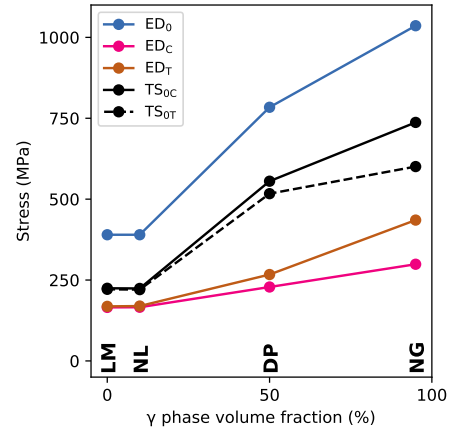


(d) Lamellar

Fig. 5. Room temperature multilevel cyclic tests results, $\dot{\epsilon} = 10^{-3} \text{ s}^{-1}$.



(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.)

microstructure. Therefore, a small amount of globular γ phase on a TiAl microstructure significantly modifies the low strain rate mechanical behavior.

Multilevel and multistrain cyclic tests are conducted in tension-compression under strain controlled at 750 °C. At each strain amplitude, 64 cycles are performed at a strain rate $\dot{\varepsilon} = 10^{-3} \text{ s}^{-1}$, 32 at $\dot{\varepsilon} = 10^{-4} \text{ s}^{-1}$ and 8 at $\dot{\varepsilon} = 10^{-5} \text{ s}^{-1}$. Successive strain amplitudes were defined to get enough data from each microstructure based on their room temperature and high temperature tensile test results to avoid early failure. The amplitudes are 0.4 %, 0.6 %, 0.8 % and 1 % for the near- γ and duplex microstructures. The amplitudes are 0.2 %, 0.4 %, 0.6 % and 0.8 % for the near-lamellar and lamellar microstructures. Results are shown in Fig. 8.

Once again, stabilized cycle is reached immediately and the strain rate

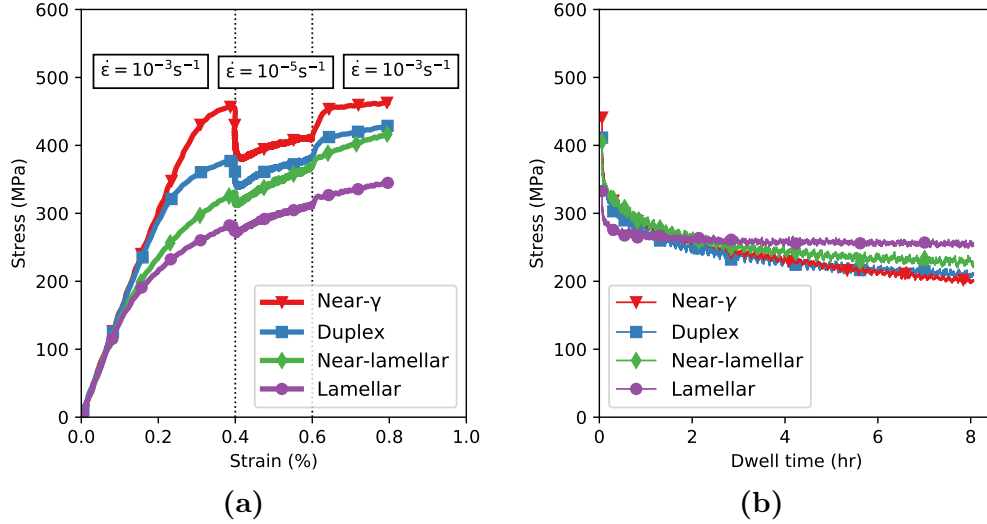


Fig. 7. High temperature tensile tests at two strain rates (a) follow by an 8 hours relaxation (b).

249 sensitivity increases with increasing γ phase volume fraction. For the near- γ
 250 microstructure, an important initial transient softening is observed. This
 251 might indicate that the mechanisms responsible for the bump at room tem-
 252 perature are still activated at 750 °C as shown by the zoom in Fig. 8a. No
 253 cyclic hardening or softening was observed regardless of the microstructure.

254 As for the room temperature results, the stress as a function of the plastic
 255 strain for the stabilized $\Delta\epsilon/2 = 0.6$ % hysteresis loops and the evolution of
 256 the elastic domain sizes are studied. The results are shown in Fig. 9a and
 257 Fig. 9b. Remarkably, the transient softening observed for each microstructure
 258 is almost the same at 750 °C than the one observed at room temperature.
 259 Finally, the tension-compression asymmetry of the near- γ microstructure has
 260 decreased and is almost insignificant.

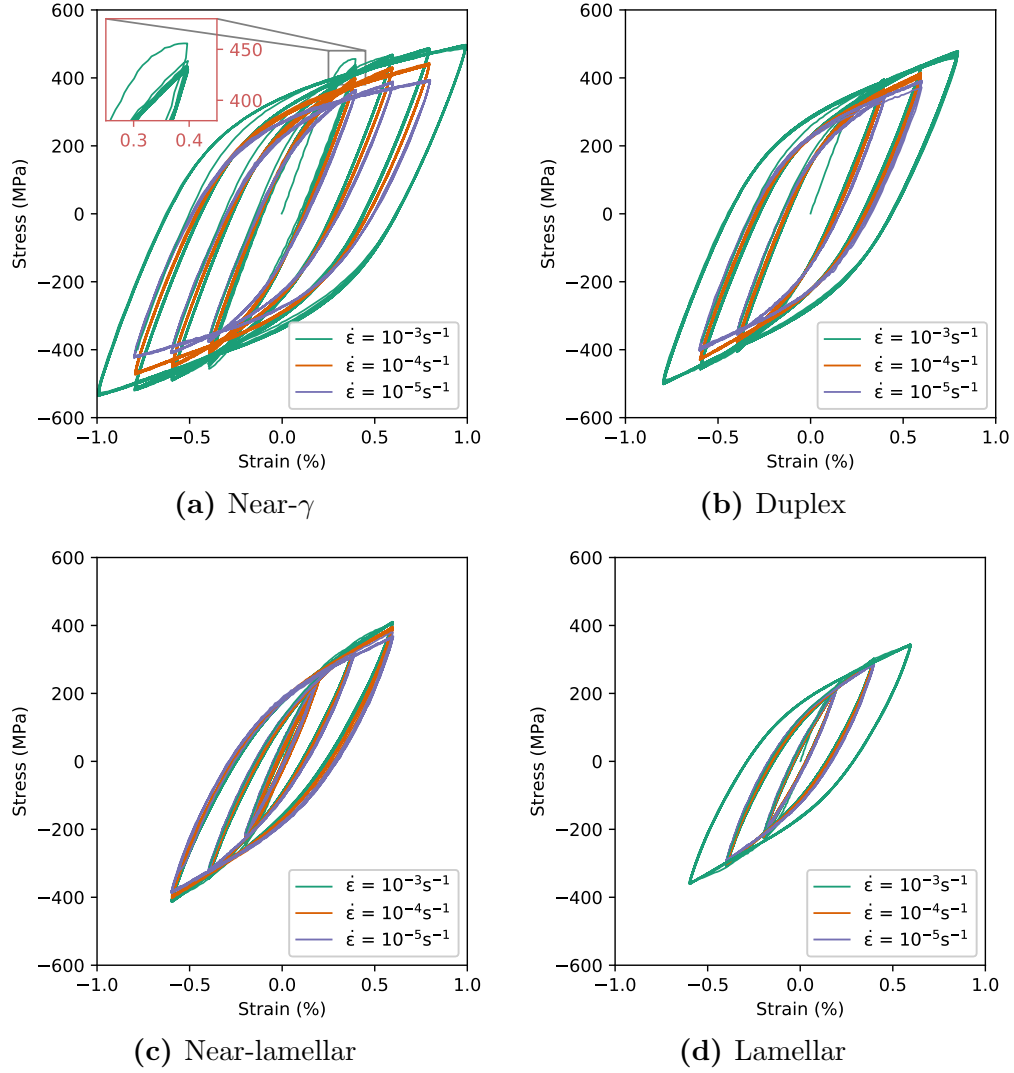
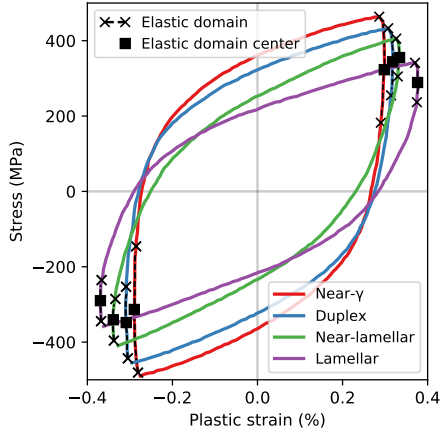
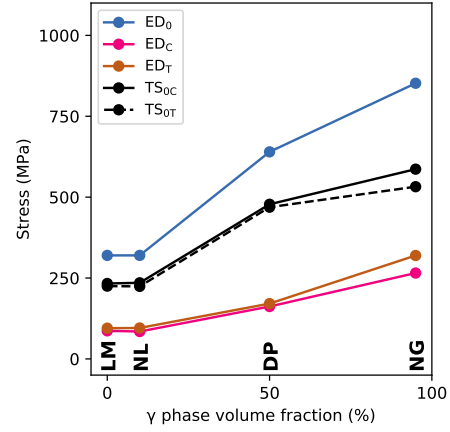


Fig. 8. Multilevel and multirate cyclic tests at 750 °C results. (For interpretation of the references to color in this figure legend, the reader is referred to the Web version of this article.)



(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.)

261 4. Discussion

262 The microstructure strength hierarchy observed here is similar to the
 263 one commonly observed at room temperature in the literature [6, 43]. A
 264 classical Hall-Petch relationship between yield stress and the grain/colony
 265 size is followed as observed elsewhere [44]. Indeed, even if in the case of the
 266 fully lamellar microstructure the lamellae thickness is sub-micrometric, once
 267 the soft colonies are deformed the mean free path of the dislocation within
 268 the lamellae habit plane is very important because of the lamellar colony
 269 size. We also point out that the lamellae width affects the yield strength for
 270 microstructures with similar colony size [45].

271 At room temperature and 750 °C and for strain rate in the range from

272 10^{-3} s^{-1} to 10^{-5} s^{-1} , plastic deformation in TiAl occurs by glide of ordinary
273 dislocations and twinning [7, 46]. At 750 °C, the deformation is eased by
274 the activation of cross slip. Superdislocations are generally reported as
275 a deformation mechanism for the γ phase. However, as they are almost
276 never observed experimentally in conventional alloys and in the investigated
277 alloy their contribution to the deformation is supposed very small [47, 48].
278 Therefore, they are not considered in the following discussion. Based on the
279 experimental results, the mechanical behavior of TiAl microstructures can be
280 classified in two categories.

281 The first type of behavior corresponds to microstructures with a high γ
282 phase volume fraction, in our case the near- γ and duplex. Their behavior is
283 characterized by a steep entry into plasticity, with an initial bump for the
284 near γ microstructure, followed by a pronounced transient softening upon
285 reverse flow stress. The bump phenomena was linked to the activation of
286 the first twinning systems in [49, 50]. It might be related to the fact that
287 twin nucleation is more difficult than twin propagation [51]. Detailed TEM
288 and neutron diffraction investigations during cyclic tests suggest that major
289 twins are nucleated when the strain range increase, i.e. during the first cycle
290 of the considered strain range level [52]. This twin nucleation during the
291 first loading part creates interfaces. TEM investigations of TiAl deformation
292 and dislocation dynamic simulations confirmed that those boundaries are
293 obstacles to dislocation movement, and therefore back stress generators [53, 54].
294 Furthermore, it was observed on steel that this back stress does create a
295 significant Bauschinger effect caused by transient softening [55].

296 Based on the extensive microstructural analysis available in the literature,

the following scenario can be defined. Twins are created during the first loading part of cyclic tests, therefore creating new boundaries within grains and an important back stress when interacting with dislocations. Because the shortness of their Burgers vector and since only one twinning dislocation can propagate in each plane, twinning is able to bring only a moderate amount of strain. Hence, the subsequent strain is largely due to glide of ordinary dislocations, the movement of which being impacted by the twins forming obstacles to their propagation. During the compression strain application, partial back movement of twin dislocations, nucleation and propagation of new twinning systems compatible with the compression strain as well as glide of ordinary dislocations should be activated. These three kinds of movement are facilitated by the back stress created during the tensile strain, leading to the tension-compression asymmetry. As a result, a pronounced Bauschinger effect caused mainly by transient softening is observed during the compression part. In fact, if another test was performed by starting in compression first, we suspect that the asymmetry might change direction. When cycling at the same strain range, ordinary dislocations which are easily able to multiply and to accommodate both compression and tension strains propagate the applied deformation. The stress does not increase and therefore the twin network does not change drastically as twins thicken. Hence, the stabilized cycle is immediately reached. The same scenario occurs at high temperature. The bump is only less pronounced as deformation by ordinary dislocations is eased by the activation of cross slip.

The small cyclic hardening observed at room temperature is similar to the cyclic stress strain behavior that has been observed on an equiaxed

322 near- γ microstructure in [56], but different from the one observed on cast
323 material for which a significant hardening was observed [13]. That hardening
324 is usually associated to the formation of a vein-like dislocation structure
325 and twin-dislocation interactions [5]. The mechanisms responsible for the
326 absence of cyclic hardening at high temperature are unclear but are most
327 certainly related to the capability of dislocations to cross-slip, promoting the
328 dislocation annihilation processes, thus limiting the hardening.

329 The second type of behavior corresponds to microstructures with a high
330 volume fraction of lamellar colonies. This behavior is characterized by a
331 smooth entry to plasticity. The two investigated microstructures exhibit the
332 same yield stresses but different 0.2 % yield stresses. This can be explain by
333 the important plastic anisotropy of lamellar colonies that has been revealed
334 by studying lamellar single colonies [57]. This anisotropy leads favorably
335 oriented lamellar colonies to yield well before the macroscopic yield stress
336 [58, 59]. Therefore when performing tests at the macroscopic scale, the grain
337 size and lamellae size effects are only observed on the 0.2 % yield stresses
338 following a Hall-Petch law. This is why in this work, from a macroscopic point
339 of view, the microstructural attributes affect mostly the kinematic hardening
340 and not the apparent yield stress.

341 During cyclic tests, a Bauschinger effect caused by transient softening
342 is observed. The transient softening is far less pronounced than the one of
343 microstructures with a high volume fraction of γ grains. Nevertheless, TEM
344 observations suggest that the phenomena causing this softening are most
345 certainly similar but less striking because of the multiscale aspect of lamellar
346 microstructures [5]. As the deformation is constrained within lamellae, those

347 phenomena are not highlighted during macroscopic tests.

348 Regarding the strain rate sensitivity, multirate tensile test results show
349 that the microstructure sensitivity to viscosity effects increases with the γ
350 grain volume fraction. The relaxation parts of the tests reveal that the
351 mechanical behavior upon very low strain rate is drastically modified by
352 adding a small volume fraction of γ phase. Overall, it thus appears that the
353 strain rate sensitivity is closely related to the microstructure γ phase volume
354 fraction. This is an important observation as near-lamellar microstructures
355 that consist of lamellar colonies with a fraction of globular γ grains are often
356 considered as the optimal microstructure in TiAl alloys because of their
357 balanced mechanical properties [28, 60].

358 5. Conclusions

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

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

371 Microstructure with a high volume fraction of lamellar colonies show
372 little distinction between the elastic and plastic domains because of the
373 multiscale aspect of the microstructure and the pronounced plastic anisotropy
374 of lamellar colonies. A Bauschinger effect is also observed, partly caused by a
375 transient softening that is far less significant than the one described above, but
376 mostly due to a pronounced kinematic hardening. At the macroscopic scale,
377 the impact of the lamellar microstructural attributes appears only on the
378 kinematic hardening because of the multiscale aspect of the microstructure.

379 At 750 °C, the microstructure strength hierarchy and the observed phe-
380 nomena are the same than those observed at room temperature. Particularly,
381 the transient softening levels are almost exactly similar to the ones observed
382 at room temperature. The strain rate sensitivity is shown to increase with the
383 globular γ phase volume fraction. The relaxation parts of the tests revealed
384 that even a low amount of globular γ grains deeply modifies the mechanical
385 behavior upon very low strain rate.

386 To conclude, components made in TiAl alloys must be designed carefully as
387 significant unwanted plasticity might occur upon strain reversal, particularly if
388 the mechanical behavior is close to the one observed for the near- γ and duplex
389 microstructures. The given experimental results open a fruitful opportunity
390 for the microstructure-sensitive modeling of TiAl alloys mechanical behavior.
391 Ongoing work focus on modeling the observed cyclic deformation by means
392 of rate-dependent crystal plasticity and computational homogenization.

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