Effect of deviatoric plastic strain on the mechanical behaviour of composite powder compacts with large amount of hard phase

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Published online: 25 August 2005

The effect of increasing amounts of deviatoric plastic strain on the mechanical behaviour of powder composite compacts is investigated. The study focuses on a highly charged composite of soft Aluminium particles with hard Nickel based super-alloy particles. Three mechanical tests, imposing different stress states, are carried out at various temperatures on powder compacts that have been submitted to increasing amount of deviatoric plastic strain. These tests are used to gather information on the alterations that such deviatoric strains cause on the powder compact mechanical response. It is shown that the ductility and the yield stress of the powder compacts increase with increasing amounts of cumulated plastic strain. The particulate nature of the compact fades, but some aspects of the mechanical behaviour (macroscopic rate dependence in particular) are still characteristic of the original particulate material even after significant amount of accumulated deviatoric strain. Microstructural observations are carried out to provide a reasonable scenario for the mechanisms responsible of the alterations that deviatoric strains bring.

1. Introduction

Powder metallurgy is an efficient process to form ceramic-metal composites with high volume fractions of hard phase. Generally, powder composites are produced by cold compaction followed by sintering at high temperature. An alternative to pressureless sintering consists in forming the powder compact by extrusion, rolling or forging to give its final shape to the part and/or to reduce the residual porosity left after cold compaction. In general, forming is carried out at high homologous temperature or through a combination of high and low temperatures forming steps [1–4]. The forming stage may be followed by a final heat treatment that promotes sintering. In any case, the presence of hard particles may lead to defects during the forming stage, especially when deviatoric or tensile components are at play. This is because the particulate nature of the compact is kept, as compared to sintering, all along the forming process and is reinforced by the presence of non deformable (ceramic) or hard (metallic) particles.

There is now a large body of experimental [5], theoretical [6] and numerical [7] literature concerning the cold or hot compaction behaviour of powder composites. These studies show that the presence of hard particles retard the densification of the powder compact. Two effects are generally accepted for the retardation of densification. First, there exists an excluded volume around the hard particles that the soft particles must fill by deforming more heavily as compared to a compact made of soft particles only [5–7]. Second, the load necessary for the plastic densification of the soft powder is not entirely transmitted to the deforming particles because of the formation of a continuous network of hard particles that supports a portion of the load [5, 7]. Experimental [8] and numerical studies [9] show also that when a highly charged composite is sought (more than 20%vol. hard particles), it is favourable to choose a combination of small soft particles and large hard particles. This is because the soft particles form a continuous network that decorates the hard particles, thus delaying the percolation of the hard particles that is particularly damaging for densification.

The stress states involved in compaction are not representative of those encountered in forming processes like extrusion, forging or rolling. Indeed, powder compaction imposes isostatic or close to isostatic stress states, whereas forming processes involve much more deviatoric stress states. The mechanisms that are behind the retardation of densification in compaction processes may also play an important role in more deviatoric

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0022-2461
DOI: 10.1007/s10853-005-1294-3

TABLE I Yield stresses and failure stresses from the various mechanical tests

Accumulated plastic strain ε_c^{pl}	Average relative density D	Yield stress (MPa)* Channel die (Normal stress)			Yield stress (MPa)* Simple compression			Failure stress (MPa) Diametrical compression (axial failure strain in%)		
Temperature (°C)		20	300	370	20	300	370	20	300	370
0	0.91	126	n.a	82	103	n.a	60	4 (0.6)	9 (3)	16 (4)
0.06	0.92	234	119	110	190	76	70	38 (5)	27 (7)	17 (8)
0.62	0.96	290	155	142	240	100	90			
1.75	0.99	372	167	148	312	112	105			

*Measured from the maximum stress or from the inflexion point for samples with large accumulated strain (low aspect ratio)

forming processes [10]. However, there is a need to understand the specific mechanisms that operate when deforming particulate compact mixtures under deviatoric or tensile stress components. We have already studied in a previous work the behaviour of metal-ceramic composites under such stress states for compacts that had been submitted to compaction alone (no prior rolling, extrusion or forging operation) [10]. We have shown in particular that the presence of hard particles reinforce the particulate nature of the compact. For example, we have observed that, for a given relative density, increasing the amount of hard phase tends to increase the dilation extent during the plastic deformation of the compact in simple compression tests.

The purpose of this study is to provide some more insight into this problem by performing high temperature rolling on a highly charged composite compact and testing mechanically the resulting material after various steps of the forming operation. High temperature rolling was chosen over extrusion or forging because it allows the sample to be submitted to increasing amounts of accumulated deviatoric strains in a controlled and simple manner. However, the qualitative findings of the present study should be valid for any forming operation that involves significant deviatoric strains on a composite powder compact. The mechanical tests to which the rolled powder compact is submitted to, involve stress states that are close to rolling, or stress states that are more deviatoric than rolling. They give valuable quantitative information on the alteration of the constitutive behaviour of the composite material as rolling proceeds.

2. Materials and experimental procedure

The composite powder studied here is a mixture of a Nickel based super-alloy powder (Astroloy, 55% Ni, 17% Co, 15% Cr, 5.3% Mo, 4% Al, 3.5% Ti, 0.06% C and 0.03% B) and a commercially pure aluminium powder (99.5% Al). We denote the Astroloy particles as the hard particles and the Aluminium particles as the soft particles, although both metallic particles may deform. The yield stress of Astroloy (1000 MPa at $T = 20°C$ [11]) is approximately 35 times the yield stress of pure aluminium (28 MPa at $T = 20°C$). As discussed in the introduction, the soft aluminium particles are smaller (average diameter of 23 μm) than the hard Astroloy particles (average diameter of 70 μm). Both particles are obtained by atomization but the aluminium particles are typically slightly ovoid whereas the Astroloy particles may be considered as spherical.

The composite powder is made of 60 vol% hard particles that are carefully mixed with the Aluminium particles to obtain a homogeneous mixture. We have chosen such a high amount of hard particles to ensure that the hard particles form easily a percolating network and thus that particulate features are accentuated. The composite powder is compacted in a close die at room temperature under a 580 MPa axial stress. The relative density of the compacts obtained after this step is approximately 0.91. The next step in the preparation of the samples consists in applying various amounts of deviatoric strain to the compacts. This was carried out simply by using a laboratory rolling mill in which the compacts are deformed at high temperature ($T = 370°C$) to ensure the integrity of the samples. Three different cumulated plastic strains: $\varepsilon_{pl}^c = 0.06$, 0.62 and 1.75 have been applied during rolling. Relative density was carefully measured before testing the samples, and we observed that the rolling operation leads to a densification of the powder compact (from 0.91 relative density before rolling to 0.99 on average for the largest accumulated plastic strain $\varepsilon_{pl}^c = 1.75$, see Table I).

Once rolled, the specimen have been subjected to various mechanical tests that induce states of stress that are less deviatoric or more deviatoric as compared to the stress state that is typical of the rolling operation. First, we have chosen to apply plane strain compressions in a channel die. This test leads to a slight dilation of the sample and the stress state is close to the one applied to the sample during rolling (somewhat more deviatoric). The second test is simple compression and is more deviatoric compared to the channel die test. It leads to a more severe dilation of the sample as compared to the channel die test. The last test consists in applying a tensile strain to the sample by diametrical compression (also known as Brazilian test). Note that compacts that have not been rolled ($\varepsilon_{pl}^c = 0.$) are also subjected to mechanical testing for comparison with other compacts. The experimental procedure is summarized in Fig. 1.

Fig. 1 shows in particular the compaction and rolling directions (L, T, N indicating respectively the Longitudinal, Transverse and Normal directions) that should lead to an anisotropic microstructure of the samples. This possible anisotropy, although not detectable in our microstructural observations (we could not observe any significant flattening of the deformed particles

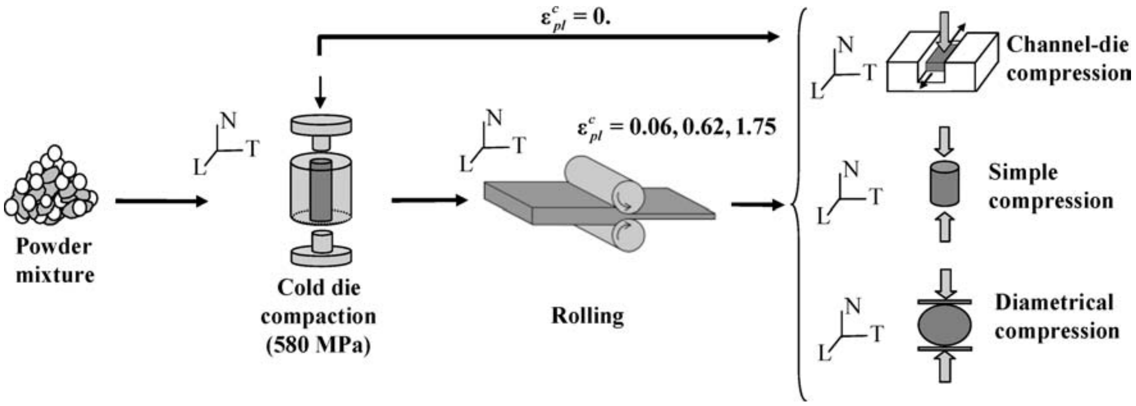


Figure 1 Schematic of the experimental procedure, with L, T, N indicating respectively the Longitudinal, Transverse and Normal directions that are characteristic of the rolling stage.

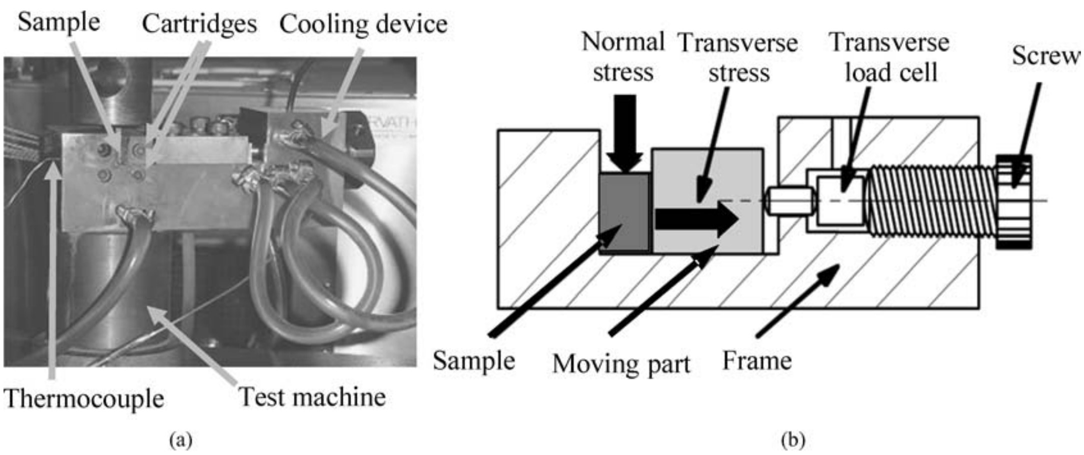


Figure 2 (a) Channel-die device, and (b) Simplified schematic section during channel-die test.

in a specific direction) is taken into account for the subsequent rheological tests. Indeed, during the simple compression and the channel-die tests, the compression direction is the normal direction N, so that the sample continues to experience compressive strains all along in the same direction (see Fig. 1). This condition could not be fulfilled for the diametrical compression since it was not possible to properly machine a cylinder in the small thickness left after the rolling operation. Instead, the compressive direction is the T axis for this last test. The three tests described above are conducted at three different temperatures (room temperature, 300°C and 370°C). The highest temperature corresponds to 0.7 times the melting temperature of the aluminium phase. Thus, we expect the soft phase to exhibit rate-dependence while the Astroloy, which is a nickel-based super-alloy, is known to be creep resistant at 370°C [12]. Rate dependence of the composite compact has been investigated by deforming the samples in the channel die at three different strain rates: 0.01, 0.1 and 1 s^{-1}.

We now describe the channel die test that constitutes the central test in this study and that has not been used yet, to our knowledge, to test particulate materials. The experimental set-up is represented in Fig. 2 and more details may be found in reference [13]. Plane strain compression is attained by deforming a parallepipedic sample in a rectangular channel. A load is applied on the sample in the perpendicular direction to the channel axis (N). The sample is free to flow only along the channel axis (L). The width of the channel is adjustable to the sample size to insure a perfect contact between the sample and the channel walls from the very beginning of the test. The sample is heated with four cartridges located in the die around the channel. A thermocouple located close to the sample controls the temperature. Two load cells, measuring respectively the normal and transverse loads during the test, allow the stress state to be determined accurately.

Friction between the sample surfaces and the die is reduced by applying a molybdenum disulfur based lubricate on both sample and die surface. We have also observed that using samples with a large initial aspect ratio (height over length) was beneficial for reducing the detrimental effect of friction on the measurement of loads (the power dissipated by friction causes an overestimation of the flow stress) and for reducing strain heterogeneity in the sample [14]. We have used samples made of monolithic aluminium to validate channel-die test conditions. It may be shown that, for such a von Mises incompressible material, the transverse stress should be half the normal stress. This condition is achieved for normal strains less than 0.30 and with samples having a height over length ratio larger than

0.35 (but less than 0.7 to avoid buckling). For larger axial strain (>0.30), the lubricant is not able to cover properly all the surfaces in contact and the effect of friction becomes dominant.

3. Experimental results

In the following, we describe the main effects that we have observed during the rheological tests that follow the forming operation. As mentioned in Section 2, we have studied compacts that have not been submitted to any significant deviatoric strains ($\varepsilon^c_{pl} =$ 0.) and compacts that have been submitted to three different accumulated plastic strains through rolling ($\varepsilon^c_{pl} = 0.06, 0.62,$ and1.75). Except when explicitly stated otherwise, a constant strain rate of 10^{-2} s^{-1} is applied to the sample. Since channel-die tests are not common for particulate materials, we start by describing the general trends that we have observed with this test. Then the main effects (relative density, temperature, accumulated strain during rolling, strain rate) that dictate the mechanical behaviour of the composite compact are discussed in the following sections. Table I summarizes the main quantitative results that have been obtained from the mechanical tests used here.

3.1. Main features of the channel-die test results

Fig. 3 shows the stress evolution of various samples when submitted to a channel-die test at high temperature ($T = 370°$C). As mentioned above, we are able to collect both the transverse and the axial stresses. The evolution of the transverse stress is similar to the evolution of the normal stress: stress increases with an inflexion of the curve that appears approximately at the same strain than for the normal stress. The transverse stresses are smaller than the normal stresses with a ratio smaller then 0.5, thus indicating that the material does not behave as a standard Von-Mises material.

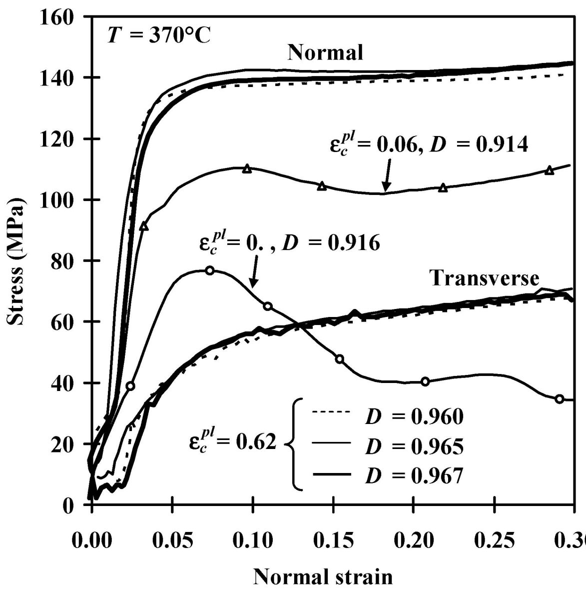


Figure 3 Normal and transverse stresses for a cumulated plastic strain of 0.62 for three different specimens, and normal stress evolution for two specimens having approximately the same relative density ($D \approx 0.915$) but with different strain histories ($\varepsilon^{pl}_c = 0.$ and $\varepsilon^{pl}_c = 0.06$). All curves have been obtained from channel-die tests at 370°C.

Fig. 3 also shows that the behaviour of compacts that have been submitted to rolling differ quite substantially to those that are directly tested after cold compaction. This effect will be discussed in more detail in Section 3.4.

3.2. Effect of relative density

In general, it is acknowledged that relative density is the main parameter affecting the mechanical behaviour of powder compacts under compressive stress states. We have shown that the hardening effect of increasing relative density also plays a role under deviatoric stress states on compacts that have not been submitted to rolling [10]. In the present study, the experimental data does not allow the effect of relative density to be weighted precisely because rolling involves both some densification and the accumulation of deviatoric strains. Thus, the decoupling of each effect is not possible. However, Fig. 3 indicates that relative density may only play a secondary role as compared to the effect of accumulated deviatoric strain in the present study.

First, consider the two curves that characterize the normal stress evolution for no rolling ($\varepsilon^c_{pl} = 0.$) and for a small amount of accumulated strain under rolling ($\varepsilon^c_{pl} = 0.06$). The two samples tested have nearly the same relative density ($D \approx 0.915$) but differ very much in their behaviour. The sample that has not been submitted to any deviatoric strain exhibits a fragile behaviour while the sample that has been slightly rolled is harder and more ductile.

Also, Fig. 3 shows the typical evolution of transverse and normal stresses for samples deformed in the channel die after a rolling operation that has induced a 0.62 accumulated plastic strain. The relative density of the samples has increased, as compared to the initial stages of rolling (from 0.91 to 0.96). It should be noticed that the three sets of curves characterizing the transverse and normal response of the samples are from three different samples that originate from the same plate. However the three samples exhibit some unavoidable variations in relative density (note that the error on the measure of relative density was estimated to be less than ±0.002). Fig. 3 indicates that these slight density variations do not induce noticeable differences on the resulting stress-strain curves. The differences in relative density in the three samples are not large enough to allow a clear conclusion concerning the role of relative density. However, together with the observation of the two other curves that have the same density but different strain history, they indicate that relative density is not the primary factor affecting the mechanical behaviour of rolled compacts. Finally, these curves show that the reproducibility of the channel-die test may be considered satisfactory (simple compression and diametrical compression tests give the same type of reproducibility). Finally, it should be clear that our observation that relative density plays a secondary role is only valid for

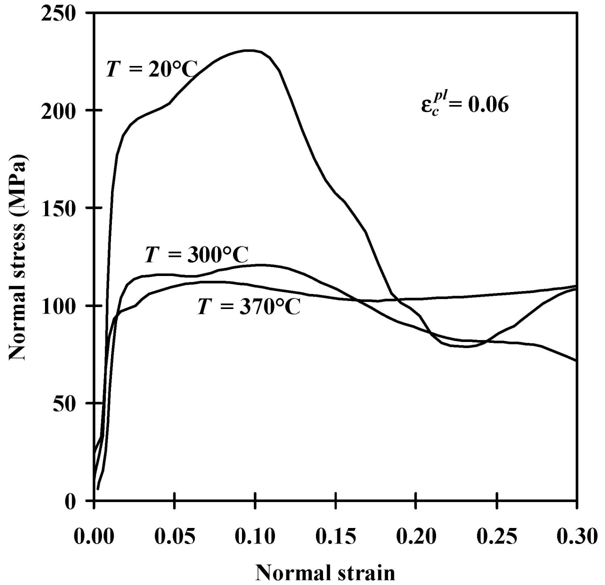


Figure 4 Evolution of the normal stress during channel-die tests at three temperatures for a cumulated plastic strain of 0.06 and a strain rate of 10^{-2} s^{-1}.

the range of relative density that we have studied (0.90–0.99). In any case, some plastic densification is needed to generate some cohesion and a porosity increase may have deleterious consequences on the ductility of the compact.

3.3. Effect of temperature

Fig. 4 shows the effect of temperature on normal strain-stress curves at low cumulated plastic strain ($\varepsilon_{pl}^{c} = 0.06$) during a channel die test. At low temperature, the compact shows evidence of a fragile behaviour with a maximum normal stress followed by a sudden decrease that characterizes the rupture of the sample. At high temperature, the compacts exhibit ductile behaviour, with the stress versus strain curve increasing steadily to reach a plateau. The softening effect of the temperature is also clear from Fig. 4, with increasing maximum stress with decreasing temperature.

3.4. Effect of the cumulated plastic strain

Figs 5a and b show the effect of the plastic strain cumulated through rolling stages on the stress-strain curves collected from channel-die tests at 370°C. In accordance with Fig. 3, Fig. 5a demonstrates that samples that have been submitted to rolling ($\varepsilon_c^{pl} > 0.$) exhibit a ductile behaviour at 370°C. In contrast, the compact tested directly after cold compaction, with no rolling operation ($\varepsilon_c^{pl} = 0.$), exhibits a fragile behaviour that is corroborated by our direct observation of the sample (macroscopic fracture). Fig. 5a indicates that a small value of ε_c^{pl} is sufficient at 370°C, to make the powder compact to behave in a ductile manner. Conversely, and in agreement with Fig. 4, we observed that only compacts that have been submitted to severe rolling ($\varepsilon_c^{pl} \geq 1.75$), exhibit ductility at room temperature.

Also, Figs 5a and b show that the accumulated plastic strain during rolling induces a clear increase in stress. This 'strain hardening' has been observed at the three temperatures studied here (room temperature, 300°C and 370°C).

The effect of the cumulated plastic strain was further confirmed by submitting powder compacts to simple compression tests, which impose a more deviatoric stress state as compared to the channel-die test. Fig. 6 shows great similarity with Fig. 5. In particular, samples that have not been submitted to rolling ($\varepsilon_c^{pl} = 0.$) exhibit a fragile behaviour while compacts that have been rolled deform plastically without fracture. Again, the accumulated plastic strain during rolling has a clear hardening effect on the flow stress during simple compression of the compact.

For a cumulated plastic strain of 1.75, stress appears to increase significantly both during the channel die test and during the simple compression test (Figs 5 and 6). This would indicate that strain hardening is taking place during these tests for this specific cumulated plastic strain. In fact this stress increase does not reflect the true behaviour of the material but is due to the low height to length ratio of these specific samples that have been heavily deformed. Only the very beginning of the

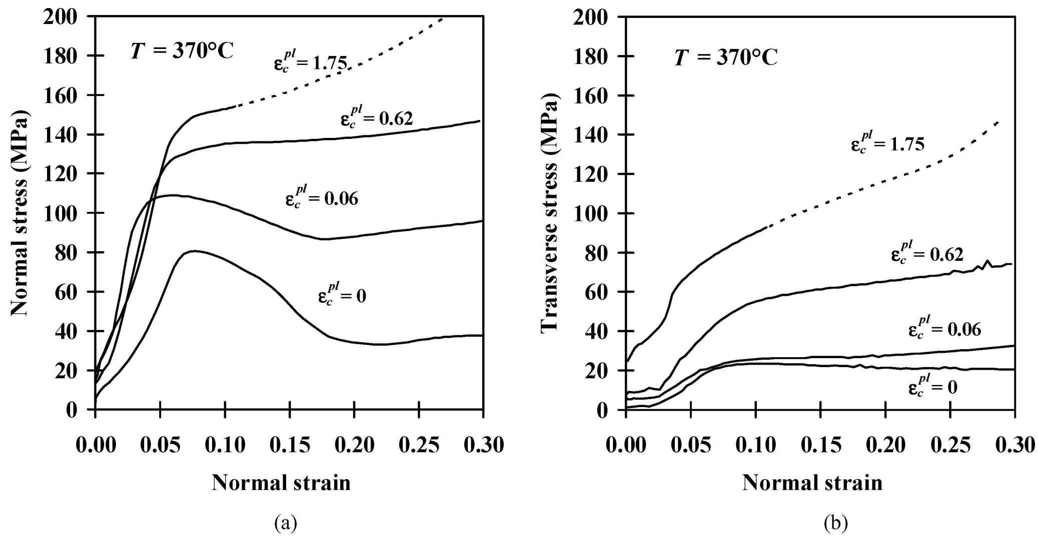


Figure 5 Results of the channel-die tests for the four cumulated strains, at 370°C and a strain rate of 10^{-2} s^{-1}. (a) Evolution of the normal stress and (b) of the transverse stress.

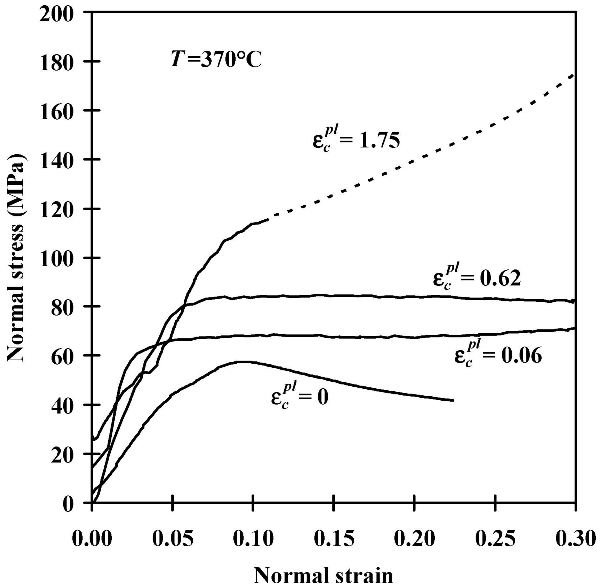


Figure 6 Stress-strain curves during simple compression tests for the four cumulated strains at 370°C and a strain rate of 10^{-2} s^{-1}.

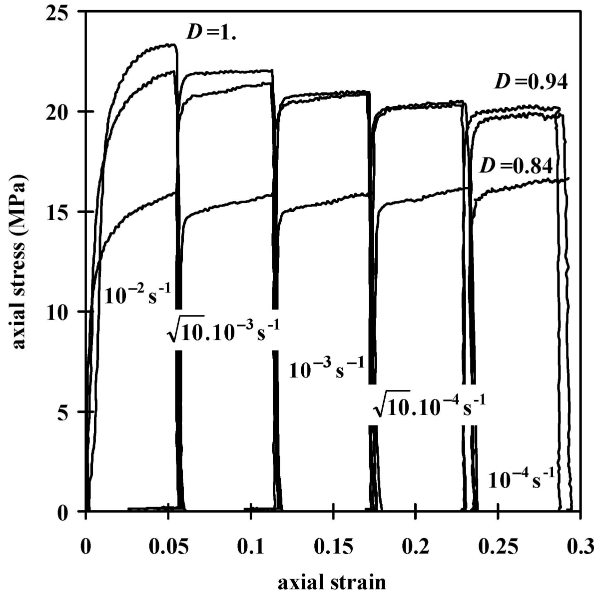


Figure 7 Evolution of stress during simple compression tests conducted on pure aluminium powder compacts at 450°C and various relative densities. Strain rate drops are imposed during the test to measure the rate dependence of the compacts [13].

curves that indicates the plastic yielding of the compact should be considered in that case (the remaining of the curves is dotted to indicate that it should not be considered).

3.5. Strain-rate sensitivity

We have already mentioned that the compact behaviour is clearly affected by temperature (Fig. 4) and since the soft matrix material, aluminium, is obviously rate dependent at the test temperature of 370°C, one might anticipate that the compact behaviour exhibits rate dependency at this high homologous temperature (0.7 times the melting temperature T_m). We have carried out channel-die tests with three different strain rates: 0.01, 0.1 and 1 s^{-1} at 370°C. No significant difference could be observed on the resulting stress-strain curves, whatever the thermomecanical history of the powder compact ($0 \leq \varepsilon_c^{pl} \leq 1.75$). In order to clarify this point, we have conducted simple compression tests on samples made only of the soft aluminium particles compacted at various relative densities (between 0.84 and unity) [13]. Tests were carried out at very high temperature (450°C for these tests, 0.77 T_m) to accentuate strain-rate effects. Tests consisted in strain-rate drops between 10^{-2} s^{-1} and 10^{-4} s^{-1} on samples that have been cold compacted with no rolling operation involved. Fig. 7 shows the resulting stress versus strain curves, indicating that rate effects exist but are very weak. The lower density specimen exhibits nearly no discernable rate effects while the full density specimen exhibits rate effects that may be evaluated using a power law type equation relating the normal stress σ to the strain-rate $\dot{\varepsilon}$:

$$\sigma = K(T)\,\dot{\varepsilon}^{1/n}, \tag{1}$$

where $K(T)$ is a temperature dependent parameter. We determine apparent values of n of approximately 30 for the fully dense compact. Such high values are much larger than the typical value of 5 for monolithic aluminium at the same temperature [12]. The presence of an oxide layer on the aluminium particle surface has been proposed as a possible explanation for the very low rate sensitivity of these powder compacts [16]. Mohamed [17] suggested the presence of a threshold stress for creep due to the interaction between moving dislocations and oxide particles present in aluminium alloys. Moreover, Fig. 7 shows that the fully dense sample exhibits some strain-rate sensitivity while the samples that have not been fully densified do not exhibit any strain-rate sensitivity. This difference in behaviour suggests that particle rearrangement, which should be of greater magnitude for partially densified samples, may also explain the very low rate sensitivity of powder compacts.

3.6. Diametrical compression test results

Diametrical compression (also called Brazilian test) enables to evaluate rather simply the tensile properties of fragile materials. For the powder compacts studied here, this test allows the drastic alterations that the rolling process induces to the compact to be studied in more details. The test consists in loading a circular disc along its diameter. Providing that failure is initiated by tensile strains at the centre of the disc, the applied load P at failure gives the tensile strength:

$$\sigma_f = \frac{2P}{\pi d t}, \tag{2}$$

where d is the disc diameter and t its thickness [18]. Fahad [19] has shown that Equation 2 is a reasonable approximation as compared to finite element simulation results, providing that the load is applied on a small flat area or alternatively that a padding material is inserted between the material and the

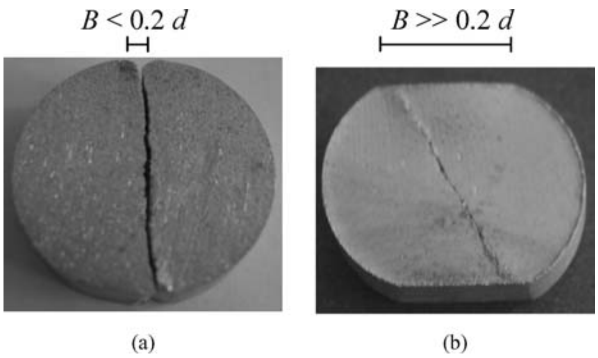


Figure 8 Samples fractured after diametrical tests at 370°C. (a) sample after cold compaction ($\varepsilon_c^{pl} = 0.$) and (b) after a cumulated plastic strain of 0.62.

compressing surface [20]. The flat loading condition ensures that compressive and shear stresses close to the contact with the compressive surfaces are reduced and that fracture is initiated along the diameter of the disc by tensile stresses. This condition is fulfilled for our powder compacts due to the presence of the soft particles that deform plastically early during the test. However, Fahad also showed that Equation 2 ceases to be valid if the flat size (B) becomes too large.

Fig. 8 shows how drastically rolling affects the tensile properties of the compact. Fig. 8a pictures a compact that has not been rolled and that has been fractured at 370°C under diametrical compression conditions. The sample fails clearly in a fragile manner. Conversely, Fig. 8b shows a sample that has cumulated a plastic strain of 0.62 after compaction. In that case, the sample fails only after a large deformation as revealed by the large flats at the contact with the compressive surfaces. Clearly, the sample shown in Fig. 8b falls in the category of test for which $B > 0.2\ d$ and for which Equation 2 does not apply. We have collected in Table I the failure stresses for various test conditions for which Equation 2 may be used ($B < 0.2\ d$). Note that the reproducibility of force versus displacement curves used for calculating the failure stresses, although not as good as with the channel-die and simple compression tests, was still very much acceptable. Table I shows that when the compact has not been submitted to rolling ($\varepsilon_c^{pl} = 0$), the fracture stress increases with increasing temperature and decreases with increasing temperature for compacts that have been submitted to rolling ($\varepsilon_c^{pl} > 0.$). This is a direct consequence of the very fragile behaviour of compacts that have not been submitted to rolling and that fail very early on at room temperature.

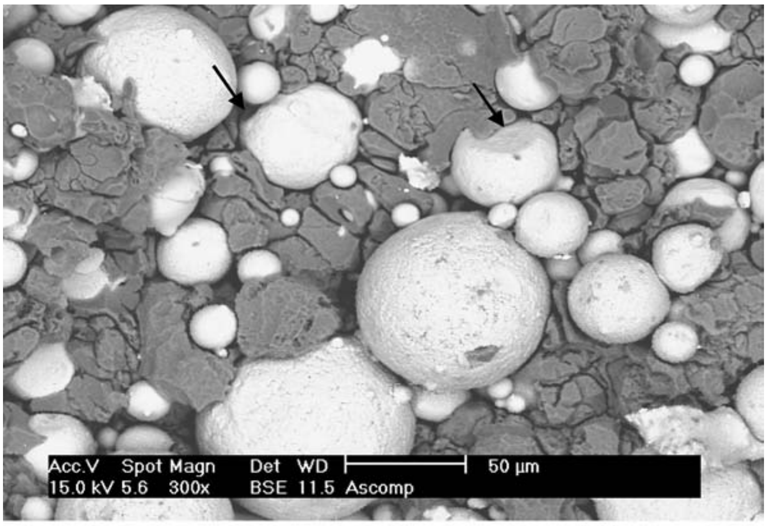
4. Microstructural SEM observations

Microstructural observations of the samples before and after rolling give some valuable information on the mechanisms acting during rolling and that lead to the significant alteration of the powder compacts macroscopic behaviour. Fig. 9 shows SEM micrographs of the compacts before rolling (Fig. 9a) and after rolling and channel-die test (Fig. 9b). The contrast between the two micrographs is unambiguous.

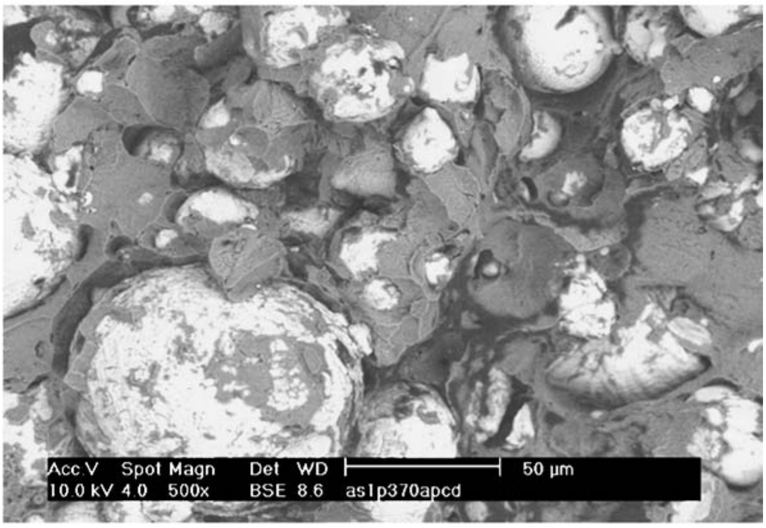
Fig. 9a shows that the Al particles, although heavily deformed after cold compaction, are still distinguishable and form a discrete population. Most of the densification that has taken place during close die compaction is due to Al plastic deformation, although some signs of Astroloy-Astroloy deformed contacts may be perceived (arrows on the micrograph). As demonstrated experimentally [5] and numerically [7], the deformation of Al particles is mainly due to contact plastic flattening of the soft Al spherical particles. While shearing at contacts is certainly present in close die compaction, it should be of limited amplitude [21, 22]. Thus, it is likely that the oxide skin that forms quasi instantaneously on Al particles is broken upon contact deformation but remains a weakening factor of the contact adhesive properties [23]. Hence, the macroscopic cohesion of the composite after cold compaction is mainly the result of the normal plastic indentation of the soft Al particles together with the adhesion brought by some metal-metal contacts weakened by the presence of oxide [23, 24].

Once the compact has been rolled at 370°C, Fig. 9b demonstrates that the Al particles have been submitted to intense shearing that has led to a continuous Al matrix instead of a discrete Al packing. The other important feature shown by Fig. 9b, in contrast with Fig. 9a, is the clear spreading of the Al matrix on the Astroloy particles. While Fig. 9a reveals Astroloy particles with clean surface (and some signs of decohesion at the Astroloy-Al interface that are linked to the elastic unloading stage after close die compaction [24]), Fig. 9b shows that the intense shearing brought by the rolling operation has made Al to adhere to the Astroloy particles. Notice also the thin Al films in Fig. 9b that demonstrate that the Al matrix has been forced in between hard particles. This feature, together with the continuous Al matrix that has formed during rolling, explains the gain in ductility that has been evidenced by diametrical compression tests in Section 3.6.

It is difficult to ascertain the mechanisms of the hardening of the composite compact with increasing accumulated strain that has been measured with channel die and simple compression tests (Section 3.4, Figs 5 and 6). We have already mentioned that rolling is accompanied by densification of the powder compact (see Table I). This densification alone may account for the apparent hardening that we have observed when testing compacts after an increasing number of rolling pass. Fig. 10 provides an additional mechanism for this apparent hardening. The figure shows a cluster of Astroloy particles that are heavily deformed. Although this kind of clusters was not a standard feature from our observations (Fig. 9 is a more representative view of a typical compact), it shows that under certain geometrical configurations, hard Astroloy particles are forced to deform. These clusters of heavily deformed hard particles should form only if a percolating network of hard particles develops. Since we observed that such clusters were more frequent as rolling passes increase, we believe that percolation of the hard particles is promoted by the large deviatoric strains imposed by rolling. This percolating network is geometrically



(a)



(b)

Figure 9 SEM micrographs of fractured sample showing the mixture of Astroloy particles (white and spherical) within the Al matrix (grey). (a) Al-Astroloy compact sample after cold compaction (no rolling, $\varepsilon_c^{pl} = 0.$), notice the few contacts marked by arrows between Astroloy particles. (b) Similar sample submitted to rolling ($\varepsilon_c^{pl} = 0.06$) and 0.30 strain in the channel-die at high temperature ($T = 370°C$).

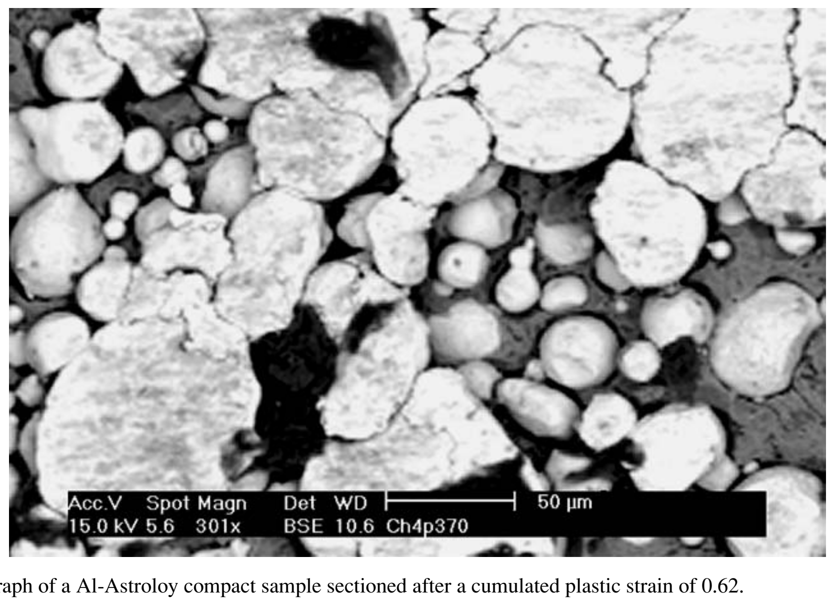


Figure 10 SEM micrograph of a Al-Astroloy compact sample sectioned after a cumulated plastic strain of 0.62.

possible because of the large fraction of Astroloy particles (60 vol%) in the mixture. Hence percolation of the Astroloy particles may account, together with the increase in relative density and the alteration of the Al particles to a continuous matrix, for our observation of the apparent hardening of the powder compact with increasing rolling strain. Strain hardening of the Al material itself may also account for such behaviour. However, the high homologous temperature at which rolling is carried out should preclude, through dynamic recrystallization, any significant strain hardening of Al particles.

5. Concluding remarks

An important feature of this study has been that deviatoric plastic strains alter significantly the mechanical response of powder composites through an increase of the yield stress and an increase of the ductility of the deformed compacts. For the highly charged composite studied here the increase of the yield stress is linked to the densification of the compact and to the formation of hard particle clusters as rolling proceeds. The increase in ductility is the result of the large deviatoric strains that the soft Al phase is submitted to. This produces a continuous cohesive matrix that gives good ductile properties to the final composite. The cohesion of the mixture is also certainly increased as the soft phase is forced in between the hard particles. It is very likely that this geometric form of cohesion plays an important role. Its precise weight should be studied further.

These modifications would indicate that the initial powder compact loses its particulate characteristics when it is deformed heavily in deviatoric conditions and that it tends toward a Von-Mises monolithic material. The high temperature simple compression tests that we have conducted both on the powder compacts composite and on the Al matrix alone to characterize the strain-rate dependence of the powder compacts show in fact that it keeps some particulate characteristics. Without proper sintering process, the composite and the Al matrix alone will not exhibit rate dependency as one would expect at high homologous temperature. This result, confirmed by creep tests carried out by other researchers [16, 17] may be specific to the Al presence for the composite studied here. Indeed, Geindreau *et al.* [25] have conducted a detailed study on lead powder compacts and have shown that at 0.7 T_m, the powder compacts exhibit the same strain-dependence than the monolithic lead material. Their results, obtained at various relative densities, would confirm that the strain rate independence of the powder compacts observed in the present study is not a general result but is mainly due to the oxide layer that forms so easily on Al particles.

Finally it should be pointed out that the rheological information that can be collected during channel-die compaction, simple compression, and diametrical compression together with the data that can be easily obtained from closed die compaction could be useful to propose a yield surface in the deviatoric stress space for such mixture powders.

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Received 1 December 2004
and accepted 31 March 2005