WARM FORGING OF SPHEROIDISED ULTRAHIGH CARBON STEEL


Abstract

Liquid phase sintered and spheroidised Fe-1.4C-0.65Si-0.85Mo specimens were warm forged to discs at 750 and 700°C. The former experiments were conducted on a screw press and the latter, using a Gleeble instrumented tester, at strain rates of $10^{-3}$, $10^{-2}$, $10^{-1}$ and 1 s$^{-1}$ to ~ 1.15 natural strain. Ferrite grain size of the spheroidised PM steel, ~30 μm, diminished as a result of the forging to 6-7 μm, with a fine distribution of sub-micron carbides. The discs were tested in diametral compression and a procedure is presented for the determination, in this testing geometry, of the (compressive) yield strength. These values, above 740 MPa, compare favourably with 350-410 MPa, determined directly in tension, for the as-spheroidised material.

Keywords: ultrahigh carbon ductile steels, spheroidisation, warm forging

INTRODUCTION

Liquid phase sintering, heat treatment, microstructure and mechanical properties of Powder Metallurgy, PM, spheroidised molybdenum-silicon-ultrahigh carbon, UHC, steels are being reported in a concurrent publication [1]. The base powder was Fe-0.85Mo and the processing aims included the speeding up of diffusion of Si into the base powder and the the formation of a transient Fe-Si-C liquid phase at ~ 1080°C, by the reaction of carbon and silicon with the Fe-Mo powder. The proposed reaction was theoretically studied using ThermoCalc and experimentally substantiated; the results are fully described in Ref. [1].

These UHC steels have yield and tensile strengths above 400 and 900 MPa, respectively and plastic strains of ~ 15%. A further aim was to examine in detail the resultant microstructures, especially in the contexts of increased (room temperature) strength and the possibility of superplastic elevated temperature forming [2].

EXPERIMENTAL PROCEDURES

Dried [1] Höganäs Astaloy Mo85HP (Fe-0.85Mo) was used as the base iron-molybdenum powder. 0.6% silicon was introduced as 0.86% of fine Carborundum <9 μm silicon carbide, and 1.35% carbon as fine Grafitwerk UF4 graphite (of 99.5% purity). Turbula dry mixing of the base powder and SiC was carried out for 20 min. Liquid paraffin, with a density of 0.88 g.cm$^{-3}$ at a concentration of 0.5 cm$^{-3}$/100 g of powder, was introduced into the powder mix, thereby coating the metal powders with paraffin in order to bind the graphite to the base powder particles. This addition increased the base carbon level by about 0.05%, thus creating more liquid phase during sintering. Graphite was eventually

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added and mixing resumed for 20 min. Rings of outside and inside diameter 30 and 10 mm, respectively, and height 26.5 mm were pressed at 550 MPa to give green densities of ~ 6.8 g.cm$^{-3}$.

Sintering of Fe-1.4C-0.6Si-0.85Mo at 1300°C was carried out for 1 h in nearly full semi-closed steel containers [1,3] pushed into a mullite tube furnace in nitrogen plus 0-10% hydrogen, with a gas flow of ~500 cm$^3$ min$^{-1}$ and an inlet dew point no worse than -60°C. The rings were cooled slowly from the sintering temperature, austenitised at 950°C for 1 h, then quenched into a warm fan assisted oven at ~130°C, followed by air cooling and refrigeration, then spheroidised at 750°C for 3 h [1], slow cooled to room temperature, to give densities of ~7.2 g.cm$^{-3}$ and grain sizes of ~ 30 μm.

Two types of forging experiments were subsequently carried out. In one, the rings were heated to the working temperature in argon for 30 min and forged on a screw press between flat plates heated to 200°C. Examined were specimens after 1 strike at 700°C and after a similar strike, heating to 750°C, and a subsequent strike. The second set of experiments was carried out on discs of 8 mm diameter and 12 mm in height (cut from the rings) on a Gleeble HDV-40 machine at TUBA, Freiberg. The specimens were heated in argon to 700°C and then forged at strain rates of $10^{-3}$, $10^{-2}$, $10^{-1}$ and 1 s$^{-1}$ to (recorded) ~ 1.15 natural (logarithmic) strain, Fig.1. The resultant discs had diameters of ~ 13 mm and were 3.15 mm thick.

![PM Steel 700 °C](image)

**Fig.1.** Compressive stress – natural strain relationships for Fe-1.4C-0.65Si-0.85Mo PM steel at 700°C at strain rates in the range of $10^{-3}$ - 1 s$^{-1}$.

These forged discs had unsuitable geometry for conventional mechanical testing. Accordingly, it was decided to employ diametral compression to the discs: adapt the procedure of determination of brittle fracture strength [4,5] to the meeting of plastic zones at the disc centre [5]. The tests were carried out in a specially constructed jig on an Instron machine at a compression rate of $5.10^{11}$ s$^{-1}$. 


RESULTS

Density and microstructure

The as-spheroidised microstructures, density of ~ 7.2 g.cm$^{-3}$, consisted of ferrite plus, generally, fine carbides, e.g. Fig.2. Occasionally the original cementite network has not "balled" up completely and showed a cementite necklace in places. The one forging strike at 700°C did not weld up the pores completely but already evident were more and smaller carbides, Fig.3. The second, at 750°C, strike started to break up ferrite grain size and gave an even better carbide distribution, Fig.4. Gleeble 700°C forging resulted in densities approaching 7.8 g.cm$^{-3}$ and microstructures with no pores, sub-grains and a uniform fine distribution of sub 1-2 micron-sized carbides, Figs.5 and 6. These specimens were tested in diametral compression.

![Fig.2. Microstructure of as-spheroidised Fe-1.4 C-0.6 Si-0.85 Mo.](image)

![Fig.3. Microstructure of as-spheroidised Fe-1.4 C-0.6 Si-0.85 Mo forged on a screw press at 700°C. Note the fineness of the carbides, occasionally in “necklaces”.](image)
Fig.4. Microstructure of as-spheroidised Fe-1.4 C-0.6 Si-0.85 Mo forged on a screw press at 700°C, reheated and given a second strike at 750°C. Note the improved carbide distribution.

Fig.5. Uniform microstructure of ferrite grains and fine sub-micron spheroidised carbides after forging Fe-1.4 C-0.6 Si-0.85 Mo at 700°C at a strain rate of $10^{-3} \text{s}^{-1}$.

Fig.6. Uniform microstructure of ferrite grains and fine sub-micron carbides after forging Fe-1.4 C-0.6 Si-0.85 Mo at 700°C at a strain rate of $10^{-2} \text{s}^{-1}$.
Yield strength

The as-spheroidised specimens had yield and tensile strengths above 400 and 900 MPa, respectively and plastic strains of ~ 16%, determined in conventional tensile tests. To estimate the as-forged yield strength, the diametral disc compression test was adapted [4, 5]. This test is known also as Brazilian disc test and the indirect tensile test. Axial loading induces variable biaxial stresses: compressive, $\sigma_3$, and tensile, $\sigma_1$, in the transverse direction of the applied compressive load. It is used as a mechanical testing technique to determine the (brittle) tensile fracture strength (under transverse compression) of (linearly) elastic materials such as concrete, ceramics, composites, pharmaceutical tablets, PM compacts. The relevant failure region is the disc centre where a splitting crack originates [4,5]. The principal stresses have been computed by Hertz [6] and at the disc centre $\sigma_1 = 2P/\pi Dt$ and $\sigma_3 = -6P/\pi Dt$, where $P$ is the applied compressive load, $D$ the diameter and $t$ the specimen thickness. Photoelasticity experiments of Frocht [7] show clearly the complex stress distribution and accord with the Hertz analysis. Because of the ease of testing and the simple specimen geometry, this test has been applied to materials which exhibit limited macroscopic plasticity before fracture and Procopio et al. [5] have performed finite element calculations for the elastic and perfectly plastic situations in order to incorporate the effects of limited ductility.

In our experiments with work-hardening materials it was observed that plastic zones spread from the platens and meet at the disc centre (Fig.7). This PM disc, 2.15 mm thick, had initial and final heights of 13.5 and 9.2 mm, respectively. The critical event of plastic zones meeting was chosen to try to evaluate the yield stress. Neglecting plasticity, the principal stresses predict the yield stress to equal $K P/\pi Dt$, where the factor $K$ equals 8 and 7.2, respectively, according to Tresca and Huber-Mises yielding criteria. The incorporation of plasticity into the finite element model, however, leads to substantial deviation between the analytical elastic expressions and the numerical elastoplastic solution. The maximum principal stress is reported to be still in the transverse direction, but that the location of this stress shifts away from the centre and that at (only) 2% diametrical strain, its magnitude is approximately 2.5–3 times the level predicted by the elastic solution. Furthermore, the volume over which all of the maximum transverse stress is acting showed a significant reduction in comparison with the purely elastic simulations. Thus it is completely unrealistic to use the elastic solution for our steel and it was decided to evaluate $K$ experimentally: by conducting experiments on mild steel discs of a determined tensile yield stress of 225 MPa. Three experiments with discs evaluated $K$ as 1.82, 1.84 and 1.82, respectively. Accordingly $K = 1.83$ is now used with confidence to evaluate the yield stress of forged discs of the materials under investigation.

Assuming uniaxial yield stress to equal $1.83 P/\pi Dt$, the yield stresses after warm forging at $10^{-3}$, and $10^{-2}$ sec$^{-1}$ evaluate to 769 and 744 MPa, respectively. Sub-grains formed and grain sizes were in the range 6-7 μm. The yield strength thus increased substantially, from ~ 410 MPa, through warm forging of the spheroidised material.
DISCUSSION

PM spheroidised steel, with yield and fracture strengths above 400 and 900 MPa and plastic strains of ~ 16% already has a very useful combination of mechanical properties. These can be further enhanced, to yield strengths above 740 MPa, by warm forging at ~ 700°C. This technique has the added advantage of accurate dimensional control. Depending on strain rate, compressive peak stresses of only 150-470 MPa were required. Superplasticity, however, was not observed in this set of experiments. Further work, including with as-sintered materials, is planned.

The proposed new method of evaluating yield strength of discs was shown to be acceptable by carrying out experiments on mild steel. The methodology was extended to specimens for which the yield strength could not be directly determined. Further validation, especially regarding the general applicability of the calibration factor, is required.

The yield strength increase through warm forging results from a drastically reduced (mean) grain size, \(d\), from ~ 30 to 6-7 \(\mu m\), formation of sub-grains, and probably an increase in the friction stress, \(\sigma_0\), consistent with the Hall-Petch relation:

\[
\sigma_y = \sigma_0 + k_y d^{1/2}
\]

where \(\sigma_y\) is yield strength and \(k_y\) the Hall-Petch strengthening coefficient. Syn et al [8], for spheroidised steels, went on to express \(\sigma_0\) in terms of the inter carbide spacing, which is reduced somewhat by the warm forging. The present set of results is insufficient to apply quantitatively the Syn et al relation; a tentative value for the parameter \(\sigma_0\) is in the range 200-300 MPa.

CONCLUSIONS

Forging of spheroidised PM Fe-1.4 C-0.65 Si-0.85 Mo at 700°C reduced the ferrite grain size from ~30 to 6-7 \(\mu m\), with fine dispersion of submicron carbides.

As a result of warm forging, the yield stress increased from ~ 400 to above 700 MPa. A method commonly used to determine the tensile strength of brittle materials, diametral compression of discs, has been adapted to the evaluation of the yield stress of a ductile material.
These preliminary experiments indicate that warm forging promises improvement of both properties and dimensional control for knowledge transfer to an industrial situation, e.g. for (high-density) engine connecting rods, hubs, rings, gears.

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REFERENCES