Abstract—In the field of power electronics device function leads to high operating temperatures. High stresses and strains are induced as a result of mismatch in Coefficient of Thermal Expansion (CTE) leading to plastic deformation in constrained joints. The thermomechanical stresses stimulate mechanisms such as dislocation glide or creep. Especially when the homologous temperature increases, time dependent creep failure becomes a dominant issue in the joint reliability. This work is devoted to the development of a temperature dependent material model for pressure assisted silver sintered joints. This model is validated on the basis of stress relaxation experiments aside from measurements of shear strength and mechanical fatigue. For this purpose, Ag-sintered copper joints were manufactured (0-hour) and heat treated at 250 °C for 250 hours in air and in protective atmosphere. Investigations of microstructure were made by scanning electron microscopy (SEM). Shear and stress relaxation tests were conducted in a tensile machine with thermal chamber at temperatures of 25 °C, 130 °C and 200 °C. For lifetime estimation of the samples Weibull probability plots for low cycle fatigue were determined. Further, Norton power law was employed to determine material parameters such as stress exponent $n$ and creep activation energy $Q_c$. In conclusion, a unified model of plasticity and creep was established.

I. INTRODUCTION

In the field of power electronics device function leads to high operating temperatures. High stresses and strains are induced as a result of mismatch in Coefficient of Thermal Expansion (CTE) leading to plastic deformation in constrained joints. The thermomechanical stresses stimulate mechanisms such as dislocation glide or creep. Especially when the homologous temperature increases, time dependent creep failure becomes a dominant issue in the joint reliability. This work is devoted to the development of a temperature dependent material model for pressure assisted silver sintered joints. This model is validated on the basis of stress relaxation experiments aside from measurements of shear strength and mechanical fatigue. For this purpose, Ag-sintered copper joints were manufactured (0-hour) and heat treated at 250 °C for 250 hours in air and in protective atmosphere. Investigations of microstructure were made by scanning electron microscopy (SEM). Shear and stress relaxation tests were conducted in a tensile machine with thermal chamber at temperatures of 25 °C, 130 °C and 200 °C. For lifetime estimation of the samples Weibull probability plots for low cycle fatigue were determined. Further, Norton power law was employed to determine material parameters such as stress exponent $n$ and creep activation energy $Q_c$. In conclusion, a unified model of plasticity and creep was established.

II. SAMPLE PREPARATION

In the present study, we are aiming at a phenomenological approach of the material behavior with over 60 % Ag content.

A. 0-hour Samples

These lap-joints manufactured as described are called 0-hour samples. These lap-joints are cut from copper strips of 50 mm length and 3 mm width with a thickness of 1 mm, then the Ag-paste was applied by stencil printing (mask thickness 100 µm) forming a pad area of ca. 10 mm². The Ag-paste was dried at 130 °C prior to sintering at 230 °C and under the pressure of 70 MPa for 30 minutes to achieve a thickness of ca. 0.75 mm. The weight/volume density of the sintered silver corresponds to ca. 6.5 g/cm³. The porosity of the section of the sintered silver has a dense microscopic structure as shown in Fig. 1.d. The weight/volume density of the sintered silver corresponds to ca. 6.5 g/cm³ with an average thickness of ca. 70- 75 µm after sintering as shown in Fig. 1.d. Unlike the edge corners of the sample with more porous parts as shown in Fig. 1.c, the middle section of the sintered silver has a dense microscopic structure as shown in Fig. 1.d. The weight/volume density of the sintered silver corresponds to ca. 6.5 g/cm³ with an average thickness of ca. 70- 75 µm after sintering. The Ag-paste was dried at 130 °C prior to sintering at 230 °C and under the pressure of 70 MPa for 30 minutes to achieve a thickness of ca. 0.75 mm.
Fig. 1. Cleaned copper surface is first sputtered with silver (ca. 1 µm), then a pad of Ag-paste (100 µm) is applied (a) to sinter the copper joints (b). Images of the lap-joint are showing the dense middle section of the sample (c), and the regular microscopic structure of the sintered Ag (d).

B. Thermal Treatment

The samples obtained immediately after sintering are here called 0-hour samples. In comparison, 250-hours specimens were produced as follows: two kinds of lap-joint series were heat treated at 250 °C up to 250 h. One kind has undergone thermal treatment in regular air; the change of the microscopic structure is shown in Fig. 2 a. The second series were put in protective sealed glass as in Fig. 2 b to prevent further oxygen flow, and its microstructure is shown in Fig. 2 c. For the former case, coarsening of the pores as well as grain growth is observed. Further, on the sputtered junction layer between copper and silver formation of copper-oxide was detected, which was not observed in the latter case of thermal treatment without oxygen flow. These lap-joints manufactured as described are called 250-hours air-aged or glass-aged samples, respectively.

III. Shear Strength, Mechanical Lifetime and Stress Relaxation

For determination of force-displacement measurements a universal testing machine from Messphysik Austria equipped with a load cell (resolution 0.1 mN) was used. With the help of a thermal chamber experiments could be performed at elevated testing temperatures.

A. Shear Strength

For lap-joint samples tested on shear strength at room temperature values were mainly observed between 25-40 MPa leading to an average of ca. 32 MPa as shown in Fig. 3 a. Increasing the testing temperature to 130 °C led especially for the 250-hours glass-aged samples to a decrease of shear strength as shown in Fig. 3 b.

B. Mechanical Lifetime

Cyclic mechanical fatigue tests were performed in shear mode in the stress range of 10-30 MPa with a cross head speed of 2 mm/min corresponding to a testing frequency of about 0.1 Hz. The lifetime \( N_f \) was captured for 0-hour samples in comparison to glass-aged and air-aged specimens at room temperature as plotted in Fig. 4. The Weibull fracture probability curves show that the 250-hours specimens have a higher 50 % lifetime expectation of ca. 5.000 (glass-aged) and 7.000 (air-aged) cycles, compared to 3.600 cycles for non-aged ones; i.e., heat-treatment at 250 °C for 250-hours results in a clear improvement of lifetime.

C. Stress Relaxation

To observe the creep behavior of the Ag-sintered copper lap-joints, the decay of stress \( \sigma \) was measured as a function of time after the samples were stretched to a defined load \( \sigma_{peak} \), which was selected according to mean shear strength values. The relaxation curves are plotted in Fig. 5. A power law could be implemented on the measured series according to Norton creep:

\[
\dot{\varepsilon}_c = C \exp\left\{ \frac{Q}{RT} \right\} \cdot q^n
\]

For the 0-hour and 250-hours air-aged samples the selected \( \sigma_{peak} \) values (defined as 100 %), values for \( \sigma_{end} \) after 60 minutes of testing time as end-percentages, and derived values of the stress exponent \( n \), as average of several samples, are listed in Table 1 for testing temperatures 25 °C, 130 °C and 200 °C.
Creep Fracture

While some samples relaxation behaviour was as shown in previous section, other samples, which were stressed with a force leading to a higher absolute value in $\sigma_{\text{peak}}$, were soon afflicted by total fracture as shown in Fig. 6. For these individual 0-hour samples tested at 200 °C the shear creep lifetime was not significant more than 10 minutes.

According to an analysis of McClintock [12] and Rice and Tracey [13], stress concentrations occur at the holes of porous metals, as in this case of sintered silver, which induce plastic deformation and finally lead to rupture. Therefore, a unified model of Gurson plasticity and Norton creep is here developed.

IV. Unified Model of Plasticity and Creep

The model proposed here utilizes an orthogonal decomposition of stresses into hydrostatic and deviatoric parts. In the present article, the material parameters related to deviatoric deformations will be determined from fits to shear experiments. The determination of the remaining material parameters from fits to experiments under tensile load can be found in reference [11].

Constitutive equations

The flow rule of the GTN model writes as

$$\Phi = \left( \frac{q}{\sigma_y} \right)^2 + 2qf \cdot \cosh \left( -\frac{3q2p}{2\sigma_y} \right) - \left( 1 + q3f^2 \right) = 0$$

where $\sigma_y$ is the flow stress of the dense material, $q$ is the von Mises stress, $p$ is the hydrostatic pressure stress and the porosity $f$ is the volume fraction of the pores. Thus, the rate of plastic strain consistent with this flow rule becomes

$$\dot{\varepsilon}_p = \dot{\lambda} \frac{\partial \Phi}{\partial \sigma} = \dot{\lambda} \left( -\frac{1}{3} \frac{\partial \Phi}{\partial p} I + \frac{3}{2q} \frac{\partial \Phi}{\partial q} S \right)$$

where $\dot{\lambda} > 0$. Here $S = \sigma + p \cdot I$. 

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TABLE 1: SHEAR STRESS PEAK VALUES $\sigma_{\text{peak}}$ (DEFINED AS 100%) FOR RELAXATION, END PERCENTAGE LEVEL OF STRESS $\sigma_{\text{end}}$ AFTER 60 MIN. AND STRESS EXPONENT VALUES $n$ FOR THE SELECTED SAMPLES TESTED AT ROOM AND ELEVATED TEMPERATURES

<table>
<thead>
<tr>
<th></th>
<th>Room Temperature 25 °C</th>
<th>Elevated Temperature 130 °C</th>
<th>Elevated Temperature 200 °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear Stress $\sigma_{\text{peak}}$ (MPa)</td>
<td>30</td>
<td>30</td>
<td>23</td>
</tr>
<tr>
<td>End Percentage $\sigma_{\text{end}}$ (%)</td>
<td>89</td>
<td>69</td>
<td>57</td>
</tr>
<tr>
<td>Stress Exponent $n$</td>
<td>64</td>
<td>15</td>
<td>9</td>
</tr>
</tbody>
</table>

Following Tvergaard [7], we will hereafter assume that $q_3 = q_1^2$. In absence of hydrostatic pressure $p$, equation (1) simplifies to

$$q_2 = \sigma_y y_2 (1 - q_1 f)^2$$

For simplicity, we here assume $q_1 = 1$, as suggested by Gurson [6]. In conclusion, the material behavior under purely deviatoric stress is equivalent to a von Mises material, where the flow stress is reduced in proportion to the porosity. In this case, equation (2) reduces to

$$\dot{\varepsilon}_{pl} = \dot{\lambda} \frac{3}{\sigma_y} S$$

$$\|\dot{\varepsilon}_{cr}\| = C \cdot (1 - f) \cdot \exp\left(-\frac{Q}{R \cdot T}\right) \cdot q^n$$

$$\Delta \varepsilon_{Ag} \cdot T H_{Ag} \cong -\Delta \varepsilon_{Cu}^{\text{last}} \cdot L_{Cu}$$

![Fig. 6. Creep fracture of individual Ag-sintered Cu-lap-joints at elevated test temperature.](image)

![Fig. 7. The measurements of the temperature dependent relaxation behavior of silver sintered copper joints are described through fit parameters (as in Table 2) of modified Gurson model for 0-hour (a) and 250-hours air-aged (b) Cu-Ag-Cu samples.](image)
A comparison between the stress relaxation curves at three different testing temperatures (25 °C, 130 °C and 200 °C) was conducted to study the effect of thermal treatment on the material's behavior. For the plotted curves, a power-law relationship was observed, with a higher relaxation rate for 0-hour samples compared to those treated at 250 °C for 250 hours (in air and protective atmosphere) varied mainly around 32 MPa at room temperature; however, the mechanical cyclic tests revealed a considerable increase in lifetime of the latter joints.

In the case of air-aged samples, investigations in SEM revealed an enlargement of grain size and a different crystal structure compared to the as-sintered samples. The formation of copper-oxide was detected, which was not observed in the case of thermal treatment with no oxygen flow. Further, on the Ag-sputtered junction layer between copper and silver, formation of copper-oxide was detected, which was not observed in the case of thermal treatment with no oxygen flow.

A unified material model of plasticity and creep was implemented to designate the specific material constant $C$ in the stress exponent $n$. The activation energy $Q$ in various thermal testing conditions and define the creep parameter $C$ in the stress exponent $n$ were deduced. The less the number is, the more distinct is the relaxation.

<table>
<thead>
<tr>
<th></th>
<th>25 °C</th>
<th>130 °C</th>
<th>200 °C</th>
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<tbody>
<tr>
<td>0-hour</td>
<td></td>
<td></td>
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</tr>
<tr>
<td>$Q$ (kJ/(mol K))</td>
<td>133</td>
<td>133</td>
<td>133</td>
</tr>
<tr>
<td>$C$</td>
<td></td>
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<td></td>
<td>1.5 · 10^8</td>
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<tr>
<td>250-hours</td>
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<tr>
<td>$Q$ (kJ/(mol K))</td>
<td>133</td>
<td>133</td>
<td>133</td>
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<tr>
<td>$C$</td>
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**ACKNOWLEDGMENT**

We would like to thank Prof. J. Fleig and A. Opitz from Div. Electrochemistry CTA Research, Technology and Development is gratefully acknowledged. The financial support by the Austrian Federal Ministry for Digital and Economic Affairs & the National Foundation for Research, Technology and Development is gratefully acknowledged.

**REFERENCES**