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A Test Procedure for Measurement of Solder Volume Effect on Reliability

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ABSTRACT

The acquisition of solder materials data is essential to predict and model solder joint reliability for surface mount electronic assemblies. However, such testing is time-consuming and expensive, therefore alternatives to the traditional methods of solder joint fatigue assessment are assessed. An additional driver is the progression of the industry to use components that require smaller and finer solder joints. Traditional acquisition of materials data has used the typical dumb bell shape sample. Here we propose a methodology that uses realistic volumes of solder that reflect today's microelectronics industry. Furthermore, this test procedure is based on a stress relaxation method as opposed to a creep measurement method. The procedure proposed here outlines a new sample configuration and loading regime. The illustrating results indicate that the solder joint volume has a major impact on stress relaxation during strain dwells.

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CONTENT

1. INTRODUCTION

SnPb solders have been widely used in the electronics industry for a long time. However, their toxicity gave rise to proposals for anti-lead legislation in the USA more than ten years ago. These proposals, although rebutted at that time, have created a momentum for lead-free electronics, which shifted to Europe, and has led to the incorporation of lead-elimination measures in the EU's WEEE Directive. This Directive aims firstly at the prevention of waste from electrical and electronic equipment, secondly at the re-use, recycling and other forms of recovery of such wastes, and thirdly at minimising the risks and impacts to the environment associated with the treatment and disposal of end-of-life electrical and electronic equipment.

The identification and introduction of suitable lead-free solders in the electronics industry require deeper studies of reliability and failure modes of solder joints. In line with identified failure modes accelerated tests such as cyclic loading can be applied and lifetime of joints assessed. Solder used in electrical interconnection can be stressed through various ways by:

- CTE mismatch between components and assembly substrates
- Mechanical vibrations in use
- Handling during transports (bending, impact)

The main variables in assessment of material lifetime are **strain** and **stress**. Strain is simply a relative displacement of material particles per unit length and stress is a force per unit area generated by the relative displacement of various components. The stress generated by applied strain can result in elastic and/or plastic deformations. All elastic and some plastic deformation happens instantaneously. Most of the plastic deformation in solders develops with time, however, and is called **creep strain,** which is a function of **applied stress**. If the resultant stress occurs due to the application of a fixed strain the accumulated stress naturally decreases with time, this behaviour is called **stress relaxation** and is expressed as a function of the **strain** initially applied (i.e. behaviour of material <u>after</u> a strain is reached).

The materials data for solders in the literature has been measured on dumb bell sized samples with a gauge diameter of a few millimetres. Today's electronic assemblies have joints that are measured in microns, and hence are a few multiples of the grain size. This work proposes smaller more representative sample geometries, which allow exploration of the solder volume influence on the solder materials properties.

In developing the new procedure creep and stress relaxation factors are discussed.

1.1 Creep Behaviour

When an external force is applied to a solid block at a specific temperature, atoms of the material start to change their location elastically. This phenomenon takes a very short time and in engineering practices is extrapolated to a zero time interval. Beyond the elastic strain limit materials start to yield, and are in the primary stage of plastic deformation, which is combined with an instant plastic deformation. Providing the stress is high enough atoms start to shift at a constant **creep strain rate** (secondary stage), as the stress increases and the amount of secondary creep that can be accommodated is exceeded then the creep rate becomes non-linear (third stage). If the stress is too high then rupture can occur and a crack initiates, as the stress exceeds the bond energy.

The various stages of deformation and creep are shown in Figure 1 [Ref 1]. The primary creep stage is crossed very quickly and it is then secondary creep that determines the material performance. If the stress is higher still, tertiary creep begins and rupture occurs within a short time.

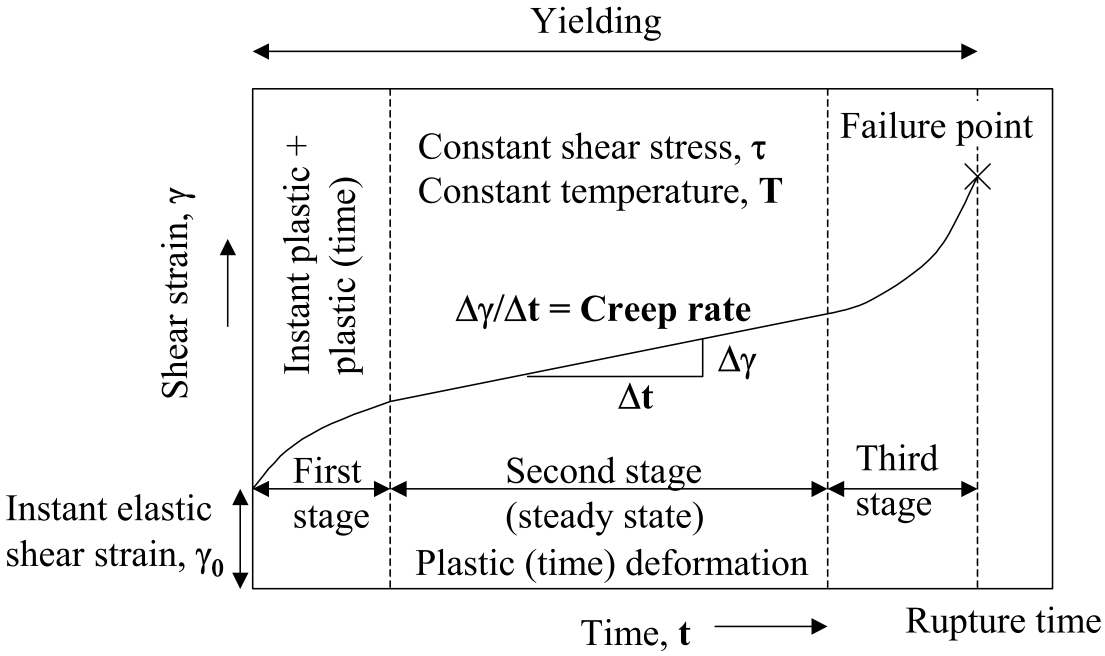


Figure 1 Schematic of various creep regimes

Solder alloys under stress and used above 60% of their homologous temperature (homologous temperature=100% * $T/T_{\text{melting point}}$), may experience creep. Strain relaxation is accomplished by microstructural changes (diffusional flow, dislocation creep) and causes material **fatigue** by initiation and propagation of microcracks. For modelling the secondary creep strain is taken to apply.

1.2 Stress Relaxation Behaviour

When a specific strain (γ) is applied at constant strain rate ($\partial\gamma/\partial t > 0$), the initial response is first with an instant elastic (reversible) shift to a point called the proportional stress limit. Equation 1 can be used to obtain the shear elastic modulus from Young's modulus providing Poisson's ratio ν is known.

$$G = \frac{E}{2(1+\upsilon)} \qquad (1)$$

where:
E is Young's modulus in normal (tensile) direction = σ/ε [Pa]
G is shear modulus
ν is Poisson's ratio

Exceeding the proportional elastic limit of stress, plastic time-independent (irreversible) deformation takes place and is combined with creep (time dependent) and stress relaxation. If the strain rate applied is high enough (E is independent of strain rate), the contribution of time dependent stress relaxation is minimal and strain is purely caused by creep and instant elastic and plastic part as seen from equation 2 [Ref 2].

$$\gamma = \gamma_{el} + \gamma_{pl} + \gamma_{cr} = const. \tag{2}$$

where:
γ is the total strain reached at controlled strain rate
γ_{el} is time-independent elastic strain
γ_{pl} is time independent plastic strain
γ_{cr} is time-dependent creep strain

Hence creep rate can be calculated (3) by differentiation of equation 2 with respect to time. This means that creep strain rate in inelastic plastic deformation region is numerically proportional to stress relaxation rate in a certain time period.

$$\frac{\partial \gamma_{cr}}{\partial t} = -\frac{1}{AG} \cdot \frac{\partial F}{\partial t} \tag{3}$$

where:
A is shear area
G is shear modulus
F is force acting on shear area in stress relaxation period (while γ is constant)

Figure 2 illustrates the effect of applying a constant strain rate and the shear stress response.

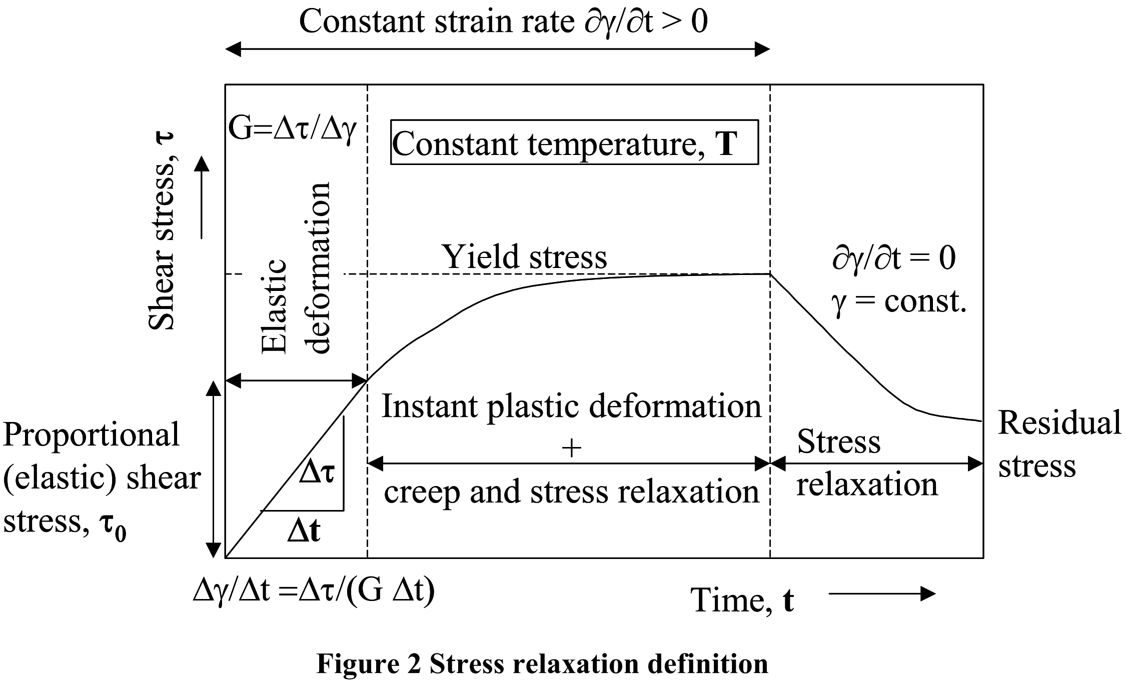


Figure 2 Stress relaxation definition

In addition the applied stress can be cyclic and hence amplitude and frequency are critical. If the amplitude of the total strain is such that significant strain plasticity occurs, the lifetime is

likely to be short (**Low Cycle Fatigue** or LCF; strain life approach). If the stresses are low enough that the strains are elastic, the lifetime is likely to be long (High Cycle Fatigue or HCF; stress-life approach).
All of the above factors must be considered in setting up the appropriate materials test when measuring properties.

2. BUILDING A TEST VEHICLE

As part of a previous programme NPL has developed an instrument for obtaining stress and strain data – the electro-thermo mechanical tester (ETMT). The ETMT is ideally suited for measuring small samples under a range of mechanical and thermal conditions, and was used in this work. Here stress relaxation data and stress strain hysteresis loops were obtained for SnAgCu solder.

The details of the experimentally tested samples are shown in Figures 3, 4 and 5. the arrangement below removes any rotation force being generated within the joint, and hence the joint is in pure shear. If a single lap joint is used then rotation forces will be experienced by the solder joint, as the strain generated from the either side of the sample is not axially symmetric. The Basic material used to form the sample arms was FR4, a glass reinforced epoxy, commonly used in electronics manufacture. Copper pads on the samples, formed by etching, are the typical size used for the appropriate surface mount chip components. Solder paste was applied to these pads through a 150 µm stencil and the sandwich structure assembled by aligning parts B on either side of part A, and the whole assembly reflowed. Again this process is representative of industrial practice for PCA assembly. By this method 8 samples of 4 different joint sizes were obtained after a single reflow. This assembly was subsequently cut into individual samples for testing. Tested samples are seen in Figure 5. The solder joint height was controlled by inserting 100µm thick foil shims of and secured by clamps.

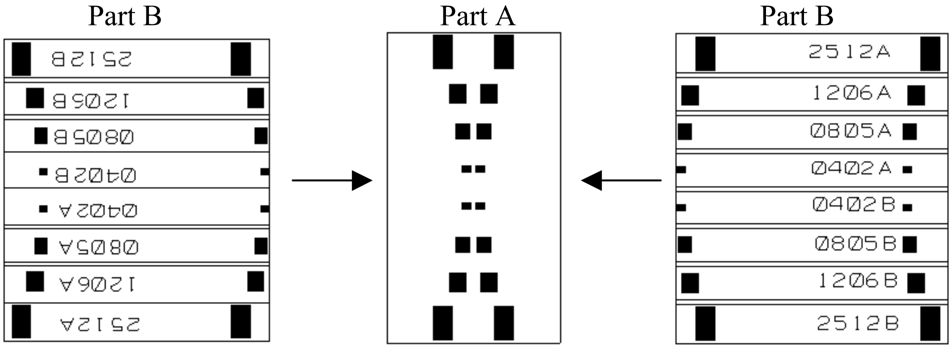


Figure 3 PCBs used in sandwich assembly

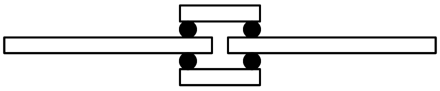


Figure 4 Final sandwich assembly (side view)

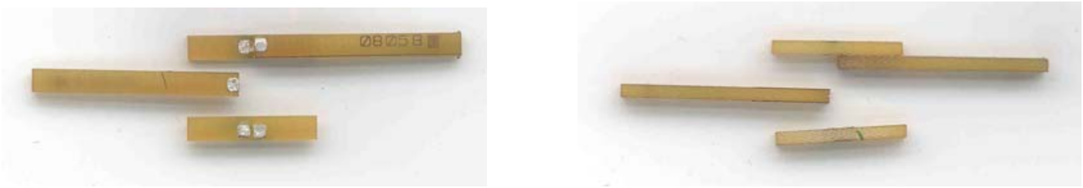


Figure 5 Top and side view of the testing sample

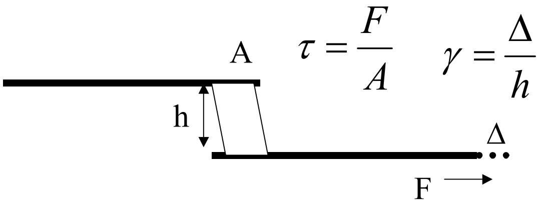
The pad size and solder joint height are given in Table 1.

Table 1 Solder pad sizes

Pad	L [mm]	W [mm]	Area [mm^2]	Gap (solder joint height) [µm]
2512	3.2	1.8	5.76	100
1206	1.8	1.6	2.88	100
0805	1.5	1.3	1.95	100
0402	0.7	0.9	0.63	100

2.1 Equivalent Solder Joint Arrangements

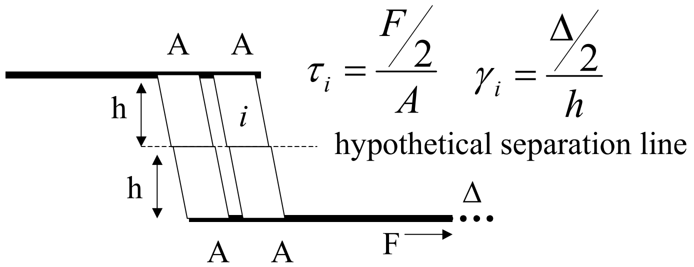
In Figure 4 the sample arrangement shows 4 symmetrically arranged solder joints in the one sample. In Figures 6-8 the equivalence of various solder joint arrangements are considered. A mathematical description of shear stress, strain and shear modulus on equivalent solder joint arrangements is presented.



$$\tau = \frac{F}{A} \qquad \gamma = \frac{\Delta}{h}$$

$$G = \frac{\tau}{\gamma} = \frac{F \cdot h}{A \cdot \Delta}$$

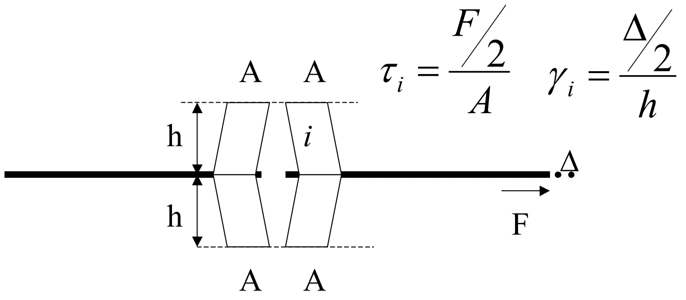
Figure 6 Single lap joint between two parallel planes



$$\tau_i = \frac{F/2}{A} \qquad \gamma_i = \frac{\Delta/2}{h}$$

$$G = \frac{\tau}{\gamma} = \frac{F/2 \cdot h}{A \cdot \Delta/2} = \frac{F \cdot h}{A \cdot \Delta}$$

Figure 7 Four single lap joints between two parallel planes



$$\tau_i = \frac{F/2}{A} \qquad \gamma_i = \frac{\Delta/2}{h}$$

$$G = \frac{\tau}{\gamma} = \frac{F/2 \cdot h}{A \cdot \Delta/2} = \frac{F \cdot h}{A \cdot \Delta}$$

Figure 8 Four single lap joints attached to two planes; mirror image of arrangement in figure 7

An important conclusion of the calculations represented in Figure 6 to Figure 8 is that the obtained Shear Modulus (G) is the same as for a single joint as it is for four single lap joints attached in the symmetrical arrangement shown. Therefore the samples used in this procedure (symmetrically designed to minimise bending and distortion), will yield the same data as for a single solder joint in test, if it were pulled without generating normal forces.

3. TEST ARRANGEMENT

Testing is conducted to measure stress relaxation in two ways. First, constant displacement of 100 µm is applied at two different strain rates. Examples of applied strain rates are given in Table 2, and the corresponding displacement curve is shown in Appendix A. The Second method is to apply a strain cycle (Figure 10), ranging from 0 to 30µm displacement with varying constant strain rate and time dwells. The displacement should be designed with relation to strain levels seen on assemblies (i.e. CTE mismatch, multiplied by the temperature range and nominal length of component). Examples of strain rates for cyclic stress-strain hysteresis loops at various temperatures are summarized in Table 3.

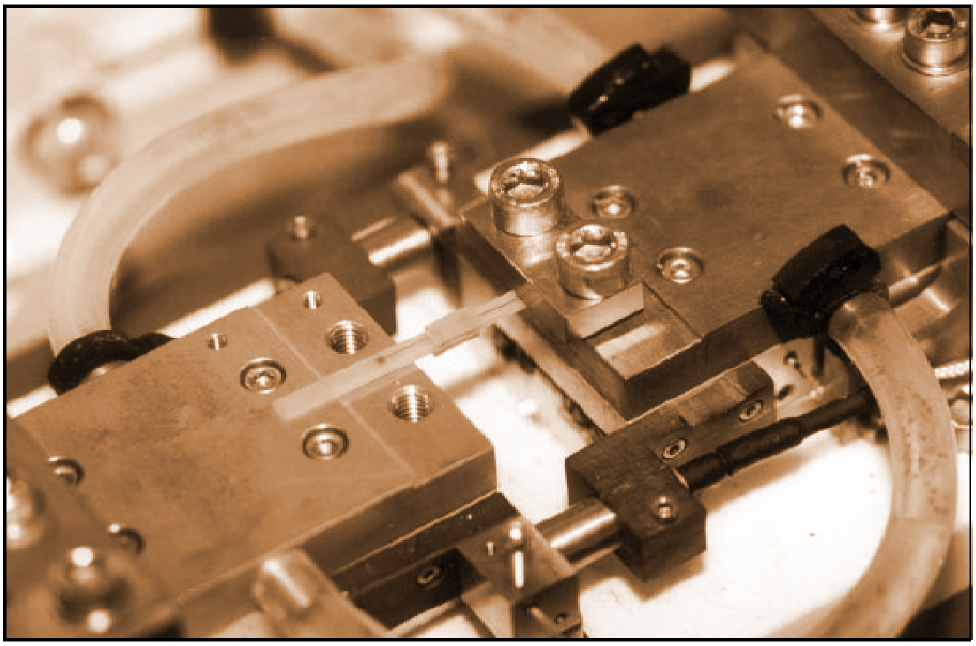


Figure 9 A sample secured on right hand side in the testing machine grip

Strain rate was kept at constant value of 0.005/s, which is close to temperature ramps in accelerated reliability assessment [4].

Table 2
Strain rate for various sample sizes, & index for figures in Appendix A

Appendix A Figure	Joint size	Strain Rate [s^{-1}]
12	0805	0.003
13	1206	0.003
14	2512	0.003
15	All	0.003
16	0805	0.016
17	1206	0.016
18	2512	0.016
19	All	0.016

Table 3
Strain rate for various temperatures, & index for figures in Appendix B

Appendix B Figure	Temperature [°C]	Strain Rate [s^{-1}]
20	25	0.005
21	50	0.005
22	75	0.005
23	100	0.005

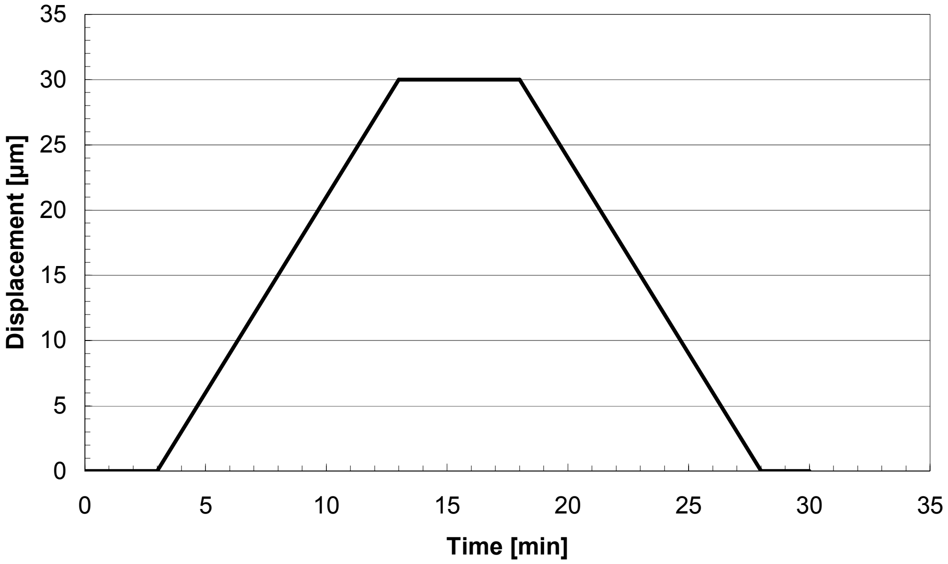


Figure 10 Control shear strain displacement profile

Examples of stress relaxation measurement are shown in appendix A, as described in Tables 2. During the test the displacement is controlled at a constant rate while force is monitored. The displacement is controlled via a servomotor with a gearbox providing accurate feedback. The load is monitored by a load cell with 100 N working range. For the high temperature work a cylindrical heater was used.

The shear stress is calculated by dividing measured force by cross-sectional area of a joint (variable A). The shear strain is calculated by dividing displacement of the solder joint by the lap joint gap; and using a correction factor for the extension of the supporting laminate. The laminate extension can be determined by measuring a part B (from Figure 3) under the conditions of interest. The length between the jaws of the ETMT is measured, and is used to correct the measurements for the distance between the jaws for the assembled samples (seen in Figure 4).

4. TEST PROCEDURE

To identify the volume effects of solder joints the following steps need to be taken referring to the sections above:

- Identify solder materials
- Select and manufacture samples
- Identify temperature and strain rates to be applied
- Apply loading regime to samples
- Measure the deformation of the laminate under the same conditions
- Analyse displacement data to determine strain rates, correcting for the contribution from the laminate.
- Evaluate the effects of volume on shear rate, creep and stress relaxation. (See Appendix A and B as examples)

Data collected by this method is ideal for use in modelling to allow the effects of decreasing joint dimensions (approaching the solder intermetallic grain size dimensions) to be taken into account.

5. ACKNOWLEDGEMENTS

The work was carried out as part of a project in the Measurements for the Processability of Materials (MPI 5.3 M4) Programme of the UK Department of Trade and Industry.

6. REFERENCES

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2) Lau, J. H. “Solder Joint Reliability – Theory and Application, Van Nostrand Reinhold, New York, NY, 1991, pp384-4388

7. APPENDIX A

Following plots show load–displacement characteristics of 3 different sizes of SnAg3.5Cu0.7 solder joints (0805, 1206 and 2512) as described in Table 1. The measurements were taken at 25°C for two different strain rates of 20 and 100 µm/min.

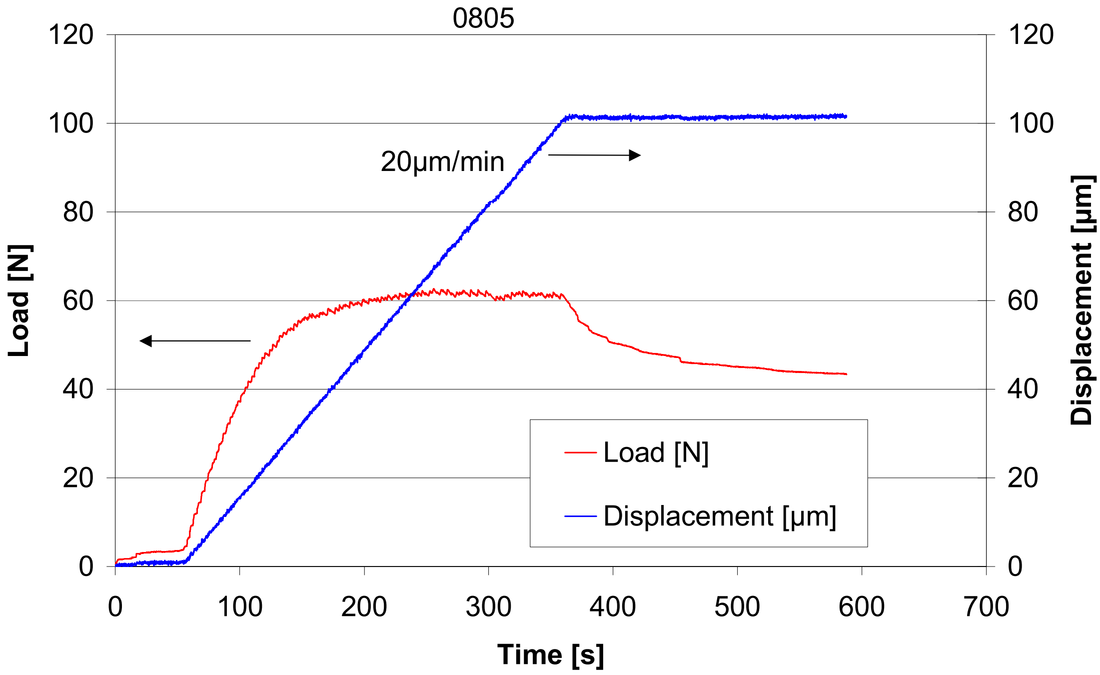


Figure 11 0805 joint at 0.003/s strain rate

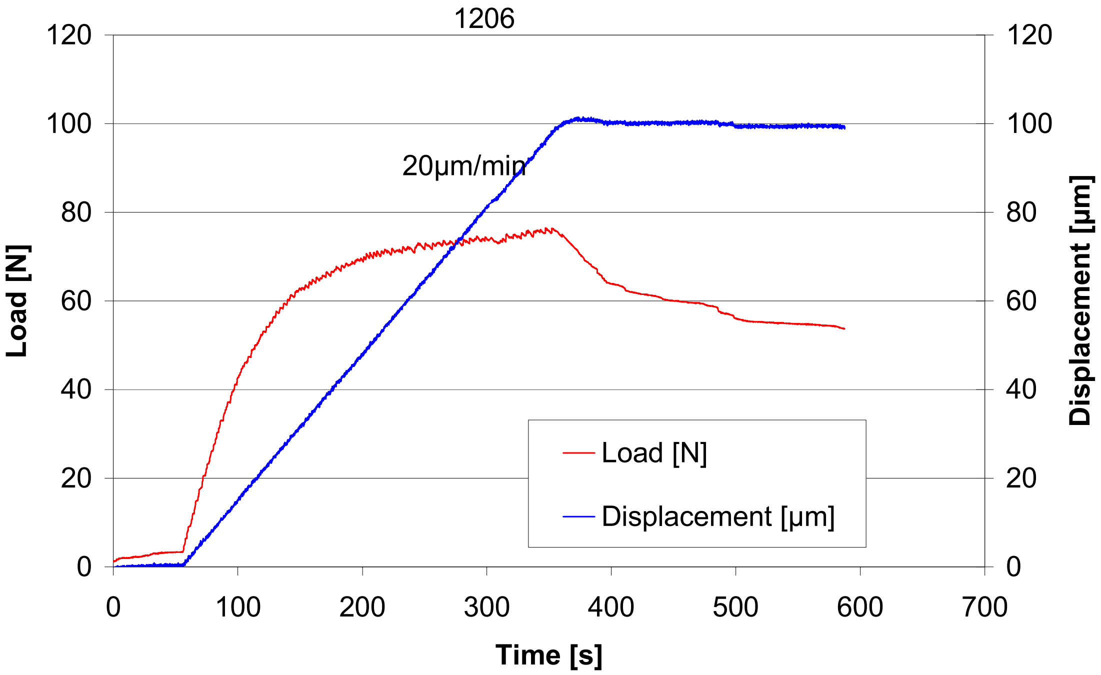


Figure 12 1206 joint at 0.003/s strain rate

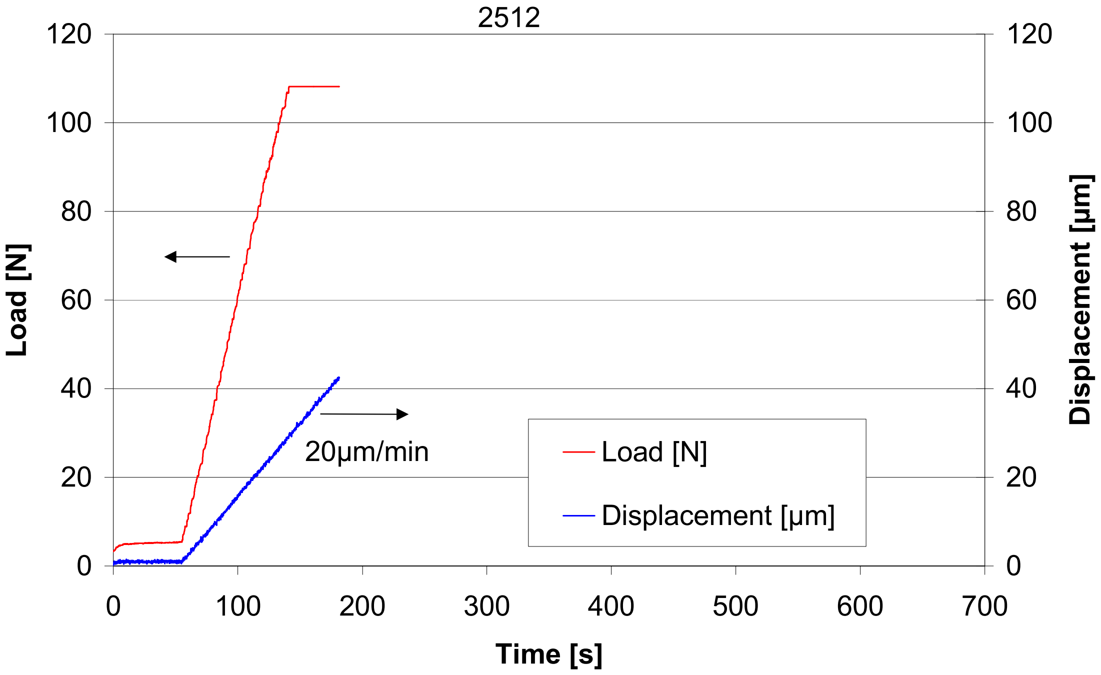


Figure 13 2512 solder joint, still in elastic region (at 20μm/min displacement rate)

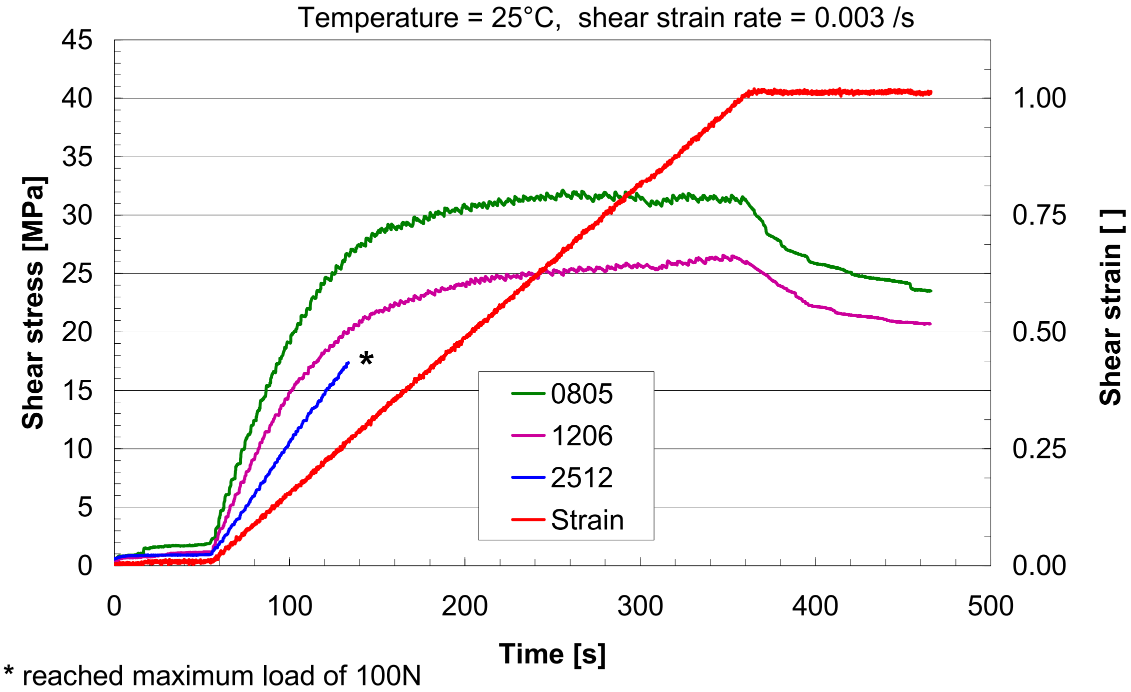


Figure 14 Comparison of stress relaxations for 0805 and 1206 solder joints at 0.003 /s strain rate

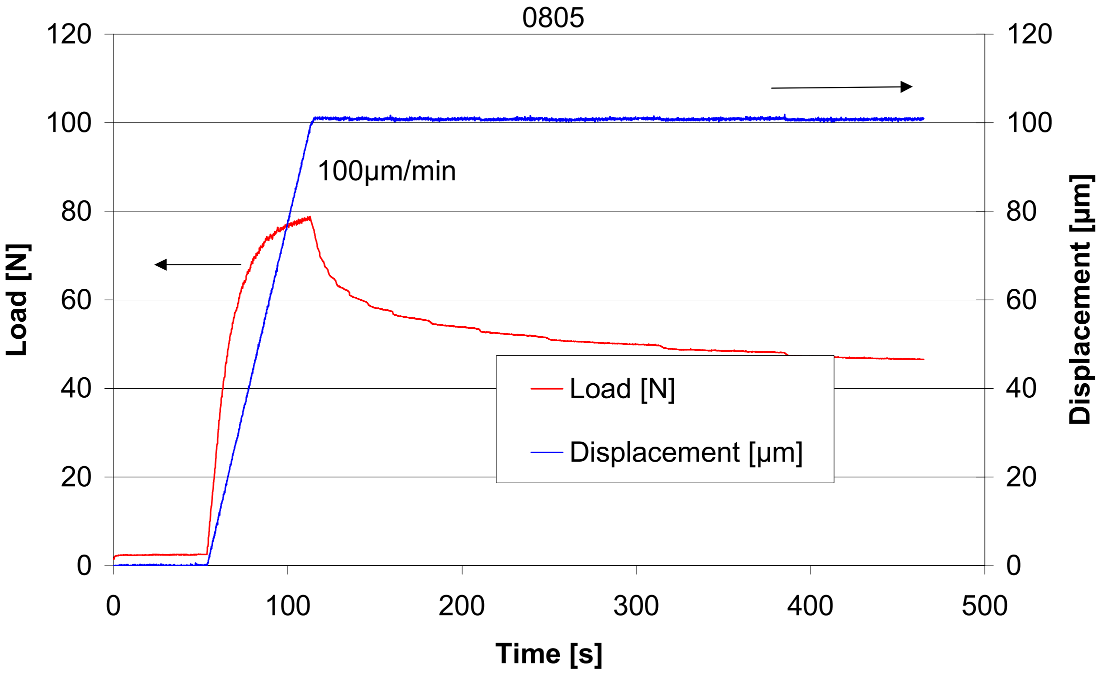


Figure 15 0805 joint at 0.016 /s strain rate

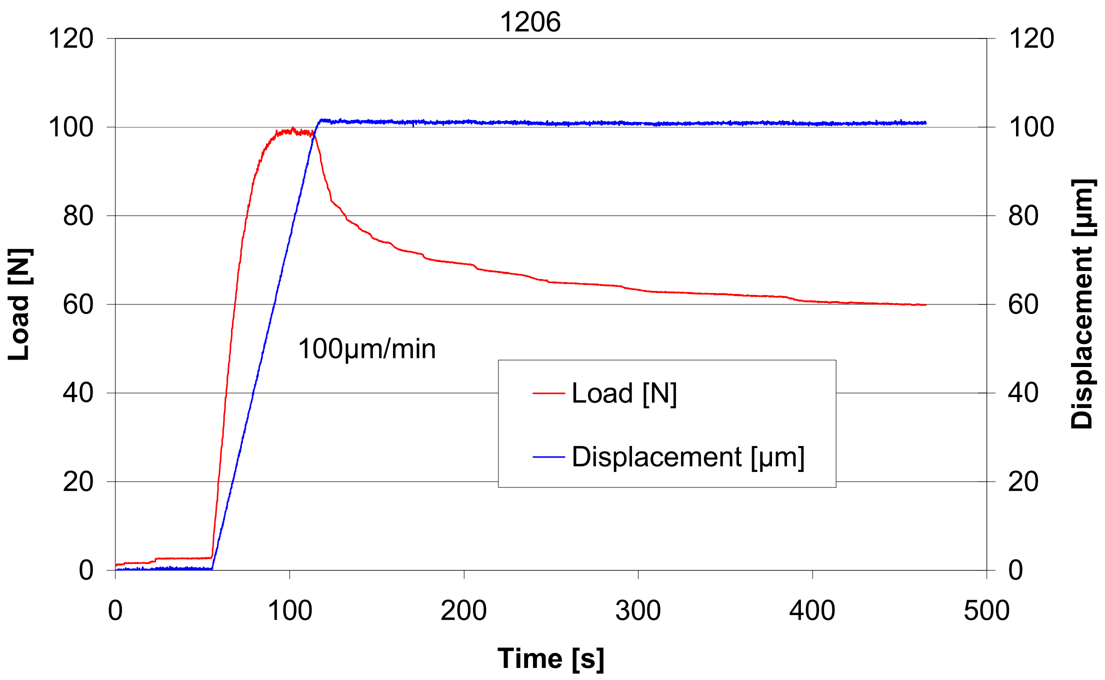


Figure 16 1206 joint at 0.016 /s strain rate

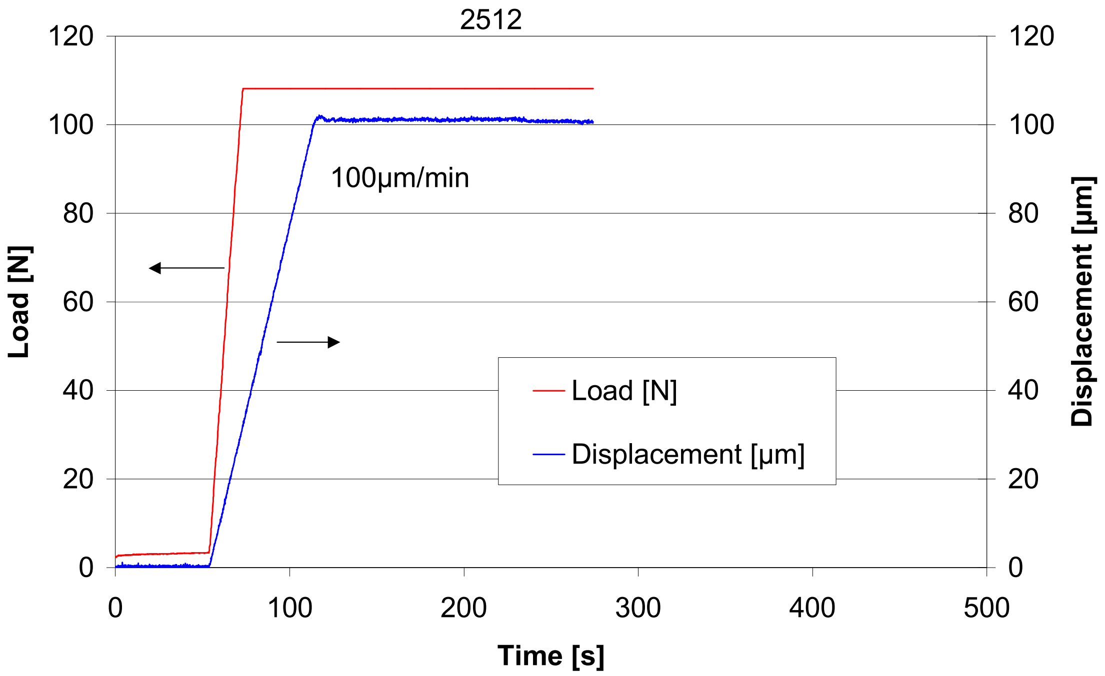
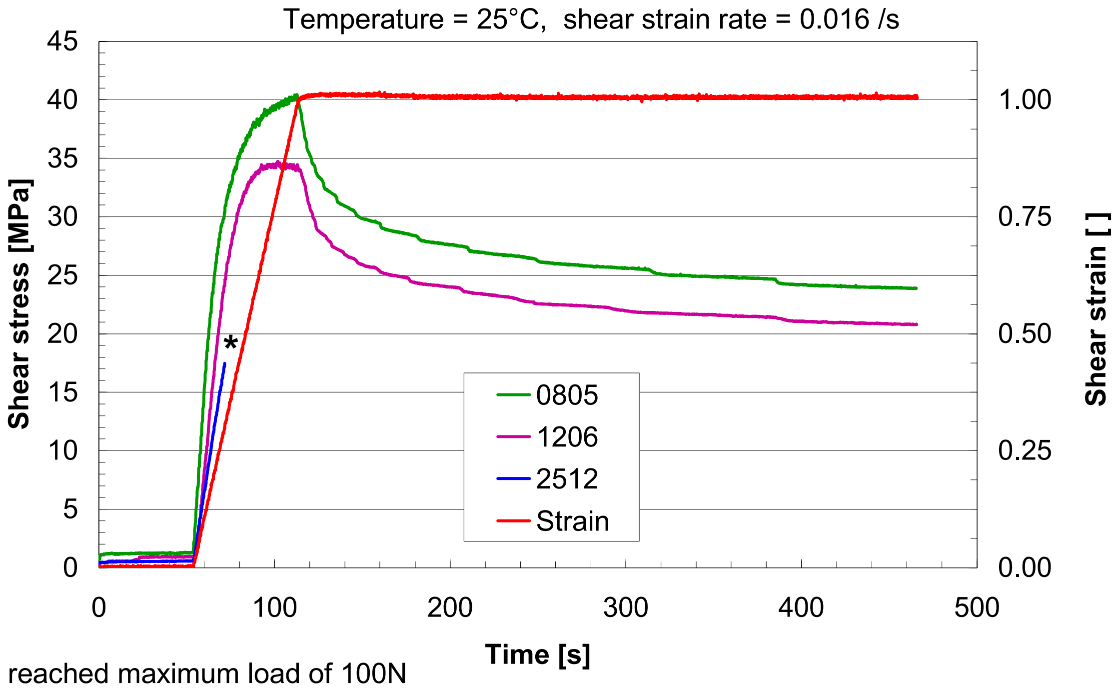


Figure 17 Solder joint is still in elastic region (2512 sample at 100µm/min displacement rate)



* reached maximum load of 100N

Figure 18 Comparison of stress relaxations for 0805 and 1206 solder joints at 0.016 /s strain rate

8. APPENDIX B

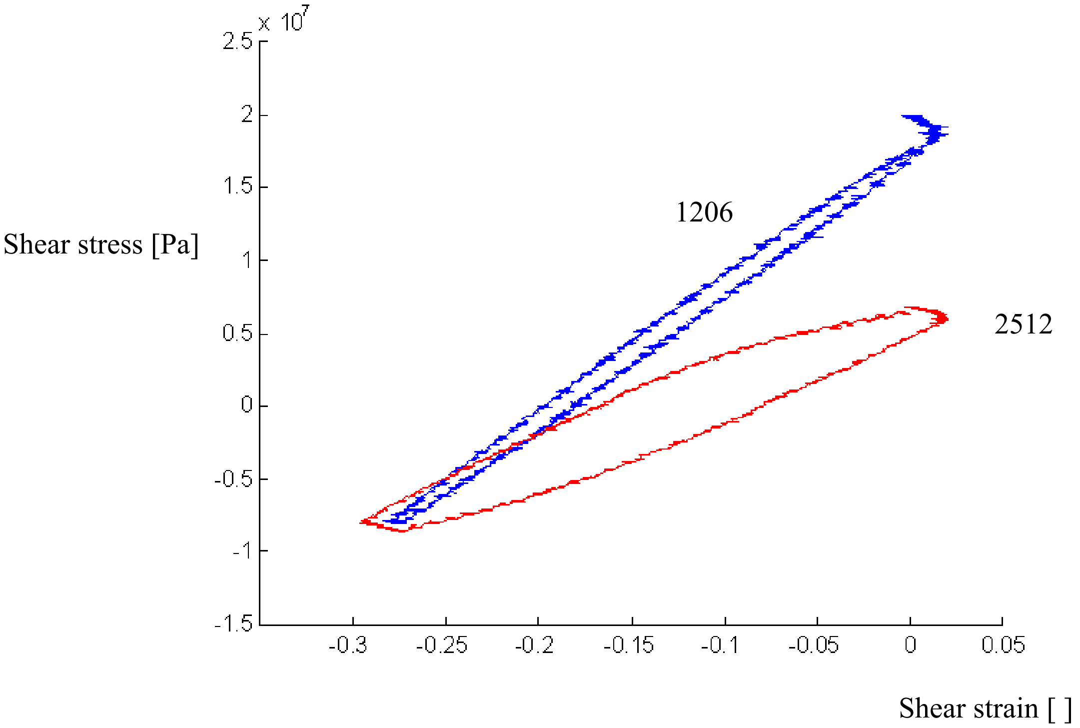


Figure 19 Stress – strain hysteresis loop at 25 °C (3µm/min displacement rate)

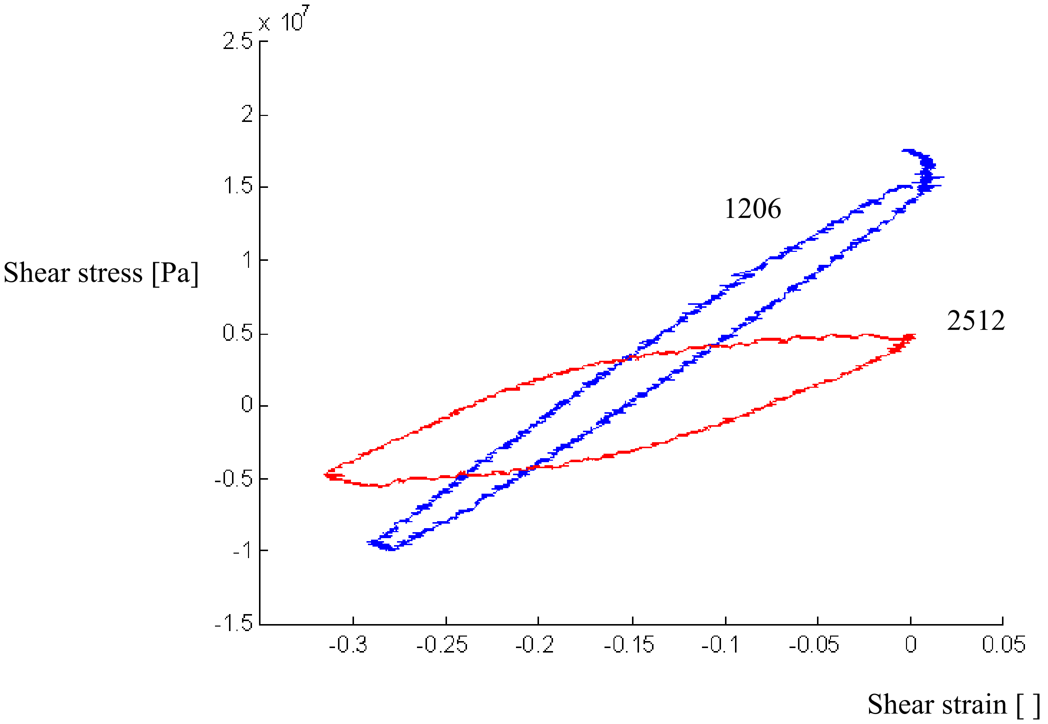


Figure 20 Stress – strain hysteresis loop at 50 °C (3µm/min displacement rate)

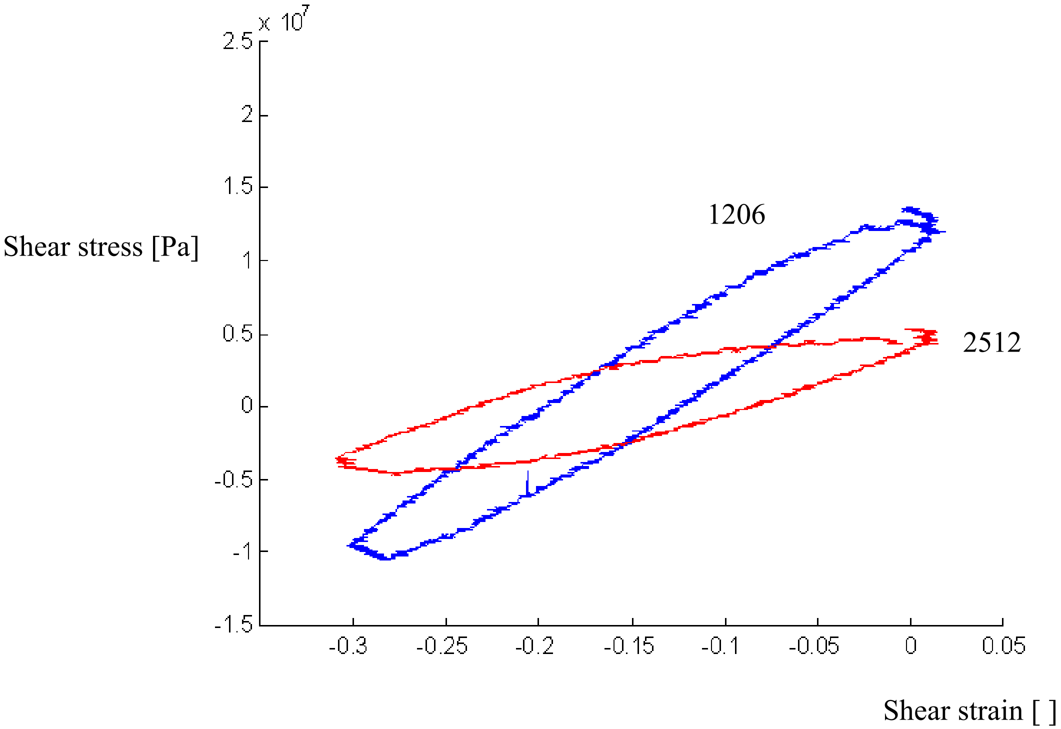


Figure 21 Stress – strain hysteresis loop at 75 °C (3µm/min displacement rate)

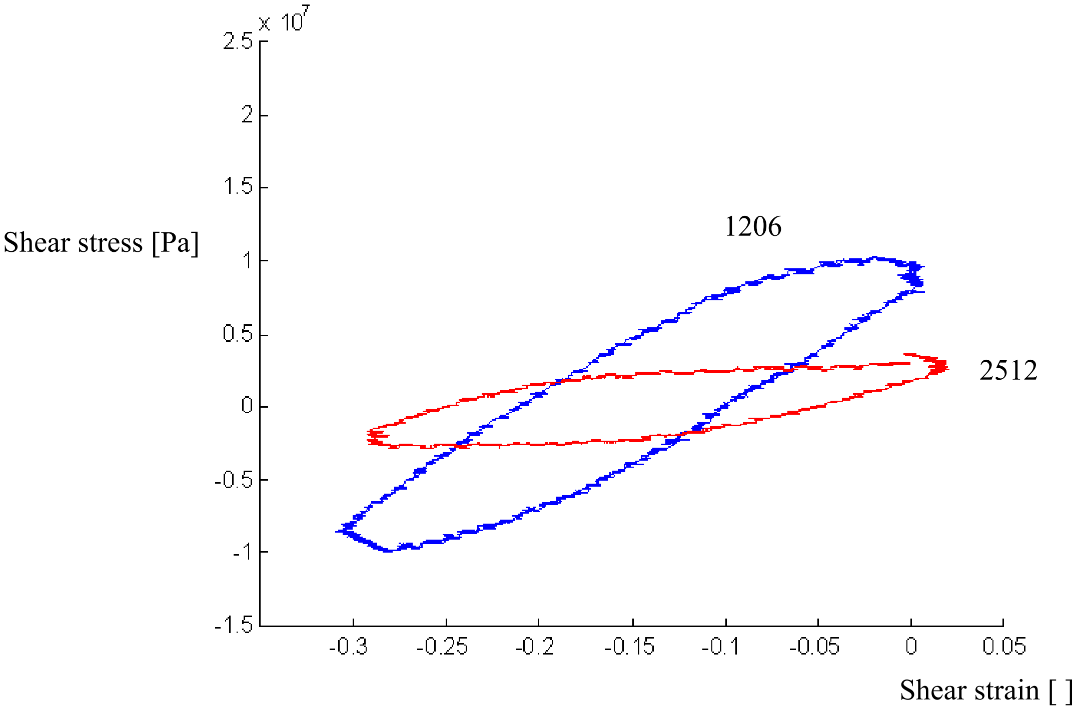


Figure 22 Stress – strain hysteresis loop at 100 °C (3µm/min displacement rate)