Optimal design and experimental investigation of the material-nanostability and deformation behaviour of Al-5.78Zn-1.45Cu-2.49 Mg, Al-5.6Zn-2.5Mg-1.6Cu and Al-Mg-0.6Si alloys under cyclic-loading for ultra-precision structural applications

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Abstract: This paper presents the design and construction of a new simple test facility for the investigation and testing of the deformation behaviour of material properties, namely plastic monolithic, inelastic, elastic and spring joints under cyclic loadings. Test samples were prepared in various machining directions (orthogonal and longitudinal) of Al-5.78Zn-1.45Cu-2.49 Mg, Al-5.6Zn-2.5Mg-1.6Cu and Al-Mg-0.6Si aluminium alloys. As a pulling force for sample deformation, an electromagnet unit was used. The test load range was between 0.2N to 200N, increased by a programmable factor of 1.1-1.4 for a train time of 900s. Two capacitive sensors and interferometers sensors mounted at different sample locations were used to test the sample deformation with and without loading. In a temperature-stable housing that offers isothermal conditions, the overall measuring machine is integrated. The calculated parameters include plastic and inelastic deformation.

Keywords: Al-5.78Zn-1.45Cu-2.49 Mg alloy; Al-5.6Zn-2.5Mg-1.6Cu alloy; Al-Mg-0.6Si alloy; Spring joints; Plastic deformation; cyclic loadings; precision structure
1. Introduction
For various ultra-precision applications, such as inertial, laser and optical applications, material stability is a critical characteristic [1-5]. A significant stability requirement is considered to be stability under short time loadings (shock, impulse, and vibration), and under medium to long time loadings without load relaxation of internal stress or imbalance [6-8]. Inertial applications, namely precision weighing scales had been considered in research. The steel mono-blocks (mechanical elements) are the principal components of these scales. In order to translate the block-deformation to the output display unit in terms of weight, these elements undergo cyclic-loading and bind to an electromagnetic coil. After the block (each cycle) is released from the load, with a quick response, it should be returned to its original dimensions. In this weighing scale, which is under consideration in this report, these facts are the drawbacks of the used steel mono-blocks. Accordingly, under high weighing frequency and high-stability, the weight measurement process requires ultra-precision. Therefore, the replacement of these elements with an alternative material which validates the above-mentioned characteristics is an essential requirement for such elements.

Many common materials are currently used for high-stability applications, such as: steels containing chromium and nitrogen (carbon steels), steels containing margin (non-carbon), bronze (mostly alloys containing beryllium) and titanium. To achieve the necessary strength, these materials are solution-treated, aged quenched. Steel, on the other hand, has a high degree of unwanted magnetic permeability. The following attractive properties are provided by some aluminum-based alloys: they are cheap, simple to produce, and have a low-modulus of elasticity that results in thicker flexures [9-12]. The key objectives of the present work are to examine the mechanical-properties of various aluminium alloys experimentally, namely Al-5.78Zn-1.45Cu-2.49 Mg, Al-5.6Zn-2.5Mg-1.6Cu and Al-Mg-0.6Si, and to choose the most suitable one to replace the high frequency steel mono blocks.

2. Experimental Setup

2.1. Specimen design
A dissimilar, 220×45×25 mm aluminium alloy samples have been design, built and produced. Two thin flexures (mid cross section of 0.15×25 mm²) with two cutting directions, i.e. longitudinal, ‘L’ and orthogonal, ‘O’ was developed to detect ultra-precision deformation of the specimens by using a CNC milling machine with diamond tools mounted on a ball bearing spindle. The specimen was placed at a 3-point, stress free, clamping-points in the milling machine. Early deformation is avoided by free cutting of the flexures at the beginning of the test. As a consequence, residual-stresses from the process of machining are held near the surface. Through heat-treatment of the samples, stress relief was achieved. For orthogonal and longitudinal cuttings, the specimen geometry is indicated in fig.1 whereas fig.2., exhibited the classification refers to the above-cuttings directions. Longitudinal and orthogonal cuttings mean that the spring cutting direction is tangential to the fibre-diameter spring at the joint spring radius and radial direction, respectively.
2.2. Deformation measurement

Ultra-precision measurement of the deformation of the specimen is considered a significant demand in this review. For this reason, the measurement of such deformation was done using two interferometers and two capacitive sensors. The capacitive sensors are located on the opposite side of the sample groove and are glue-fixed. And on the upper surface, the interferometers are mounted. Tiny steel foils were used in order to achieve magnetic fixation with retro-reflectors. In addition, the application force hook was mounted and the interferometer initialized by retro adjustment, which can be pushed freely on the floor, only magnetically held in place. The deformation was measured at the position of the sensors and the geometry was scaled to flexure deformation.

2.3. Test machine

The test machine is designed to allow loading times to be short (1 second) to long (hours). The unit consisted of four elephant feet, an aluminium frame, i.e. a clamping frame with a quadratic opening for connecting the specimen, two cylindrical bearings for interferometer collecting, and a transmitting power. With clamping and adjustment instruments, the upper plate contains the voice-coil. Ferro fluid in the air gap in between increases the binding of the voice-coil to the magnet. In addition, special care is taken to avoid thermal-deformation during measurement by coupling the voice-coil and magnetic assembly into that of the specimen. Other sections include (not shown in the figure) a force-transducer and electronic devices. Fig.3., displays the schematic test used as machine.
3. Experimental procedures

The mechanical properties of various cutting directions of Al-5.78Zn-1.45Cu-2.49 Mg, Al-5.6Zn-2.5Mg-1.6Cu and Al-Mg-0.6Si aluminium alloys (AA) have been analyzed herein. The experimental machine incorporates a temperature-stable housing for ultra-precision measurements. In addition, to achieve the same value as the surrounding temperature, the temperature of the stable housing was modified and regulated, with an error of 1 K for all tests. The outside vibration of 100 nm was also suppressed to 10 nm by isolators and to below 1 nm by digital data filtering. In addition, to mitigate temperature, seismic and electrical disruptions, data is collected during the night. The sample was put in the clamping frame to begin the experiment, and then cyclic loading and unloading began with 15 minutes of waiting time after releasing the unloading load to separate the inelastic recovery deformation from the plastic deformation after unloading. The loading force increased by a programmable factor of 1.1-1.4 in the next period. Usually, a test cycle takes a few minutes to allow the residual temperature compensation of capacitive and interferometer data to be processed. The test-conditions are as follows: the force load ranges from 0.2 N to 200 N; the interferometer, capacitive-sensor and temperature controller resolutions are 10 nm, 0.3 nm, and 0.001 K, respectively. The calculated parameters for aluminium alloy specimens are the inelastic and plastic deformations, and the time constant. The abbreviations CS and IF indicate the output of the capacitive and interferometer-sensors, respectively, for each measured deformation.

4. Results and discussions

4.1. Loading and Unloading cycle (cyclic loading)

The loading-unloading period for the Al-Mg-0.6Si and Al-5.6Zn-2.5Mg-1.6Cu AA group of alloys is shown in Figure 4 (as an example for all test phases). The load cycle begins at 1130 minutes and ends at 1167.5 minutes (i.e. with 2250 s of load application time in the downward direction), as can be seen from the figure. The unloading, however, begins at 1163.33 minutes and finishes at 1248.33 minutes. In addition, it is equally important to know that a period of up to 3000 s is required for inelastic recovery to determine the plastic deformation. Furthermore, it should be noted that the inelastic deformation is much lower than the plastic deformation and therefore the loading characteristics are within a range of up to 40 MPa in their declaration of capacity.
4.2. Inelastic and plastic deformation

As a consequence of the micro-creep in the material that arises due to the motion of the atomic layers in the spring joint during the loading process, inelastic deformation occurs. The glides return to their original location after load release. Depending on the load on the joints and the pollination duration of the last few hours, this behavior will vary. In the other side, the material atoms are further away from each other without splitting as the load rises, approaching the yield point, and there is plastic-deformation. The atomic layers are so deeply moved here that if the relief is no longer back in their original-position.

The reliance of inelastic deformation on the stress for Al-5.78Zn-1.45Cu-2.49 Mg composite with symmetrical and longitudinal cutting headings are given in Fig.5a and 5b, individually. From the figures, it can be seen that the direction of machining (orthogonal or longitudinal) negligibly affects the measure of inelastic disfigurement because of the reasonable exactness of the estimating sensors and the variation in tests properties. The base of 1 nm and the limit of 16 nm twisting were estimated under stress estimations of 10 MPa and 150 MPa, resp.
Figure 5. Inelastic deformation of Al-5.78Zn-1.45Cu-2.49 Mg aluminum alloy

Plastic deformation for both specimen groups was appeared in figures (6a and 6b). Aluminum alloy specimens with symmetrically machining direction has a plastic deformation of a little bandwidth for every load points. Then again, Fig.6b indicates aluminum alloy with longitudinal cutting course and could be insignificantly superior to that of symmetrically cutting, notwithstanding the enormous dispersing in the individual estimated values. Subsequently, the plastic disfigurement of the 7075-T7351-L AA is not as much as that of 7075-T7351-Q in the stress interval somewhere in the range of 40 and 110 MPa. This can be ascribed to the temperature impact and to the electrical floats of the electronic gadgets. The plastic distortion is in opposition to the tensile stress with two cutting headings. In the event that this understanding was considered here, just the capacitive sensors ought to be utilized something like 40 MPa, in light of the fact that the electrical float of the interferometer is excessively huge as appeared in Fig.6b. It is significant here to focus on the way that the plastic distortion of the whole estimation cycle adds the disfigurements comparative with the previous load. The accompanying model clarifies the plastic deformation between two stress points for both cutting directions. For AA 7075-T7351-L, the deformation mean qualities were 0.8 nm and 1.1 nm for 80 and 150 MPa stresses, individually. What's more, the outcome is plastic distortion of magnitude 0.3 nm. By a similar way the deformation of AA 7075-T7351-Q are: 1.1 nm at 80 MPa and 1.5 nm at 150 MPa, and the subsequent
plastic deformation is 0.4 nm. Comparative with the inelastic deformation, note that the plastic deformation is lower and consequently the diagrams are in the range up to 40 MPa in their capacity explanation.

![Plastic Deformation 7075Q](image1)

**Figure 6.** Plastic deformation of Al-5.78Zn-1.45Cu-2.49Mg aluminum alloy orthogonally machined and B) longitudinally machined

As referenced over the longitudinal cutting direction mode exhibit best outcome for estimated deformation than that of orthogonally. Consequently, just this mode utilized on the Al-Mg-0.6Si and Al-5.6Zn-2.5Mg-1.6Cu aluminum alloys.

Figure 7 indicates the inelastic deformation of Al-Mg-0.6Si aluminum alloy for the normal bending stress. The figure shows that, the inelastic deformation at the loading scope of 10 to 20 MPa can be set equivalent to zero, in light of the fact that the identified deformation for trial 1, when capacitive sensor demonstrates 0.5 nm deformation, can be deciphered as a drift. A similar explanation applies to the 0.7 nm deformation estimated by the interferometer for trail 5. Likewise, from the figure, the most extreme normal estimation of the deformation at 150 MPa was 9 nm.

Moreover, as compared to the inelastic deformation of Al-5.78Zn-1.45Cu-2.49 Mg aluminum alloy presented in figure 8, the inelastic deformation of Al-Mg-0.6Si is a bit lower. For instance, at stress value of 140 N/mm², the inelastic deformation as calculated by the capacitive sensor is equal to 10 nm, and 21 nm for the Al-Mg-0.6Si and Al-5.78Zn-1.45Cu-2.49 Mg respectively.
Figure 9 shows the inelastic deformation of Al-5.6Zn-2.5Mg-1.6Cu alloy as a component of the ordinary bending stress. As figure indicates at low loads up to 40 MPa, the distinction between the deformation estimated by CS and IF sensors are little. On the other hand, when stress level builds, the difference gets higher. It reflects that a sample in the range of Al-5.78Zn-1.45Cu-2.49Mg is a further trial is worse in all tested tensile stresses. The deviation of the two estimation strategies for the both samples is inside the tolerance range. This again indicates that the principle effect on the measurement of samples is done. The distinction in thermal treatment has clearly no effect on the inelastic deformation.

Figure 7. Inelastic deformation for Al-Mg-0.6Si aluminum alloy

Figure 8. Plastic deformation for Al-Mg-0.6Si aluminum alloy
Plastic deformation for Al-5.6Zn-2.5Mg-1.6Cu alloy specimen is presented in figure 10, from the figure it was noted that for a stress value limiting to 80 MPa, the plastic deformation is less than 0.4 nm. Then a abrupt rise in plastic deformation was noted amongst the last two points of the curve i.e. 80 and 150 MPa the corresponding increase in the average deformation of the sample is equal to 1.4-0.2 nm. The material Al-5.6Zn-2.5Mg-1.6Cu alloy compared to an even higher strength, due to the artificial aging and stretching.

5. Conclusions
This work incorporates the development of another straightforward test facility for the examination and testing of materials properties of solid spring joints for precise structures. In the test, an electromagnet was utilized to produce the pulling power important for the deformation of the unique geometry sample. The deformation and versatile recuperation of the samples in the wake of pulling power were recorded with the assistance of an interferometer, and capacitive sensor, for various aluminum alloys (Al-5.78Zn-1.45Cu-2.49 Mg, Al-5.6Zn-2.5Mg-1.6Cu and Al-Mg-0.6Si), with various machining directions (longitudinal and orthogonal).

The consequences of this work incorporate the inelastic and plastic deformation of the material, and a variety of the load of 10 MPa upto 160 MPa, at that point the naturally visible deformation after partition of the examples. The test machine carries out in a temperature stable housing. Measurement is carried...
out down to a remaining strain under $10^{-6}$.

a) Materials nanometer behavior is unlike from micrometer behavior.

b) The Al-Mg-0.6Si alloy material with tensile strength of 275 MPa shows 60% lower inelastic deformation than Al-5.78Zn-1.45Cu-2.49 Mg alloy with 435 MPa and Al-5.6Zn-2.5Mg-1.6Cu alloy with a tensile strength of 505 N/mm². Since a difference of Al-5.78Zn-1.45Cu-2.49 Mg and Al-5.6Zn-2.5Mg-1.6Cu alloys not be recognized, is near to the deduction that irrespective of inelastic deformation of the thermal post-treatment of aluminum is critical here is the alloy composition.

c) For the calculation of plastic deformation of the test materials, the deformation of 7075 L is only 20% less than in 7075Q. The Al-5.6Zn-2.5Mg-1.6Cu alloy material shows a clear difference from Al-5.78Zn-1.45Cu-2.49 Mg alloy. The lower tensile strength and lower stress are the major reasons of the toughest plastic deformation field in materials from Al-Mg-0.6Si alloy.

d) The inelastic deformation among longitudinal and orthogonal cutting direction expressed no differences to distinguish.

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