Implementation and characterization of elastic deformation in spring steel, B-Ti and CuBe used as flexure joint in a crystal bending device using digital image correlation DIC

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Abstract:

Characterization of mechanical properties of candidate materials used for flexure joints which is a beamline component in crystal bender has conducted in this study. The methodology was a combination of tensile test, strain gauge and digital image correlation (DIC) to the candidate materials steel, copper beryllium (CuBe), heat treated CuBe and heat treated beta titanium. The results from strain gauge and DIC were consistent. The important mechanical properties like elastic modulus (E modulus), 0.2% yield strength, maximum elastic stress and maximum elastic strain for candidate materials were found. In addition, inhomogeneous strain distribution in materials due to localization of strain in samples was found using DIC. Anisotropy is considered as a reason for the difference of E modulus between our measured values and the literature values.

Contents

1. Introduction

Thermo-mechanical processing is a typical method to improve the mechanical property of materials. Sample test for polycrystalline bulk samples could be done ex situ at any processing state traditionally. However, as the higher precision and quality of materials are becoming important in application and theory *in situ* tools are needed. The traditional way of sample test is not sufficient to the future requirement. *In situ* characterization of the microstructure of polycrystalline bulk sample using synchrotron radiation is one important technique, nowadays. Flexures' applications have grown leading to a more systematic treatise of the design methodologies. Flexures can be used in high precision devices as well as in ultra-clean environment. In addition, flexures-based devices also show an increasing application in accelerators facilities in mechanisms used to position with high resolutions accuracies the optical components. In our study, flexure joint is a beamline component used in crystal bender. Therefore, selection of suitable materials for flexure joint is essential. The mechanical properties of the candidate materials are worth to study. There are several methods to study the mechanical properties. The simply and typical method is tensile test. Stress strain curve obtained from tensile test of candidate materials can provide their mechanical properties such as elastic modulus (E-modulus), yield strength and ultimate tensile strength and maximum elastic strain. Apart from these parameters, the heterogeneities of the deformation field across the sample are quite important to study. This can show localization of stress in the candidate materials. To study the mechanical properties of candidate material samples for crystal bender, using Digital Image Correlation (DIC) with load frame and strain gauge together is an effective way. Tensile deformation tests of candidate materials can be performed by a load frame. Strain gauge which changes the resistance during deformation can be used to measure the elongation of samples. DIC measures the displacement and strain of samples. Stress strain curve can be plotted using the recorded stress and elongation by load frame as well as recorded strain in DIC software. In addition to E modulus and maximum elastic strain, the localization of stress generation and location of necking behavior are our interest. Not only the strain at every record time during tensile test, but also how the strain varies in the local position can be record in DIC.

Focusing of high-energy X-rays to small spot sizes on sample is a means to achieve high spatial resolution. Without a constrained area of interest in sample, scanning on large area of sample results in a longer time for experiment and result analysis. If more advanced study of sample under stress application using high-energy x-rays, DIC can also be the first feasible step to identify and narrow down the area of interest of the sample by evaluation the variation of strain of the sample. [1], [2]

2. Experimental Methods

2.1 Strain gauge

Strain gauge is a device to measure strain on an object. It usually contains an insulating flexible backing supporting a metallic foil pattern as shown in Figure 1**Error! Reference source not found.**. Before measurement, it is stick to the object being measured with suitable glue. After gluing samples should be left for drying the glue according to the user guide of the glue. In measurement, the object and the foil are deformed when being pulled or compressed. Take electrically resistive strain gauge as an example, electrical resistance changes when the strain transferred to the strain gauge from the measurement object causing the foil deformed.

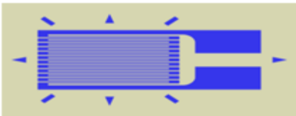


Figure 1 Foil strain gauge

The working principle of strain gauge is according to the strain / resistance relationship. The physical property of electrical conductance and its dependence on the conductor's geometry is used. When an object is pulled (i.e. tension), it will become narrower and longer that electrical resistance increases. When a conductor is compressed, it will become broader and shorter that electrical resistance decreases.

The Wheatstone bridge

The Wheatstone bridge is applied in measurement of resistance. It can be used in determination in both the absolute value of a resistance by comparison with a known resistance and relative changes in resistance. Determination of relative changes in resistance could be applied in strain gauge techniques as shown in Figure 2. $R_1 \ldots R_4$ are bridge arms. V_s is the bridge excitation voltage (supply voltage). V_o is the bridge output voltage. The relative changes of resistance in strain gauge could reach the order of magnitude of 10^{-4} to 10^{-2} that high measurement accuracy fulfilled.

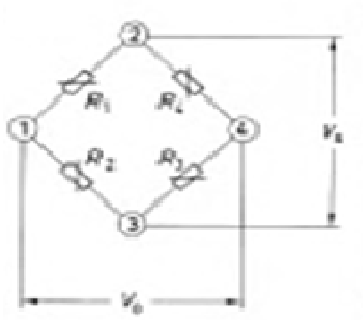


Figure 2 Wheatstone bridge circuit

$$\frac{Vo}{Vs} = \frac{\Delta R}{4R} \quad (1)$$

$$\frac{\Delta R}{R} = k\mathcal{E} \quad (2)$$

$$\frac{V_o}{V_s} = \frac{k\mathcal{E}}{4} \quad (3)$$

The strain $\mathcal{E}$ can be calculated by equation (3) which is obtained by equation (1) and (2), where K is the gauge factor. [3]

2.2 Load frame

Load frame is used in the tensile deformation test to determine Young's Modulus (E Modulus of a material). The load cell in load frame is a transducer that is used to create an electrical signal whose magnitude is directly proportional to the force. Tensile stress or compressive stress is applied to an object from load frame. Deformation in term of elongation with respect to applied load is record in load frame software DDS 32.

Stress strain relationship is unique for each material. A typical stress-strain curve is shown in **Error! Reference source not found.**.

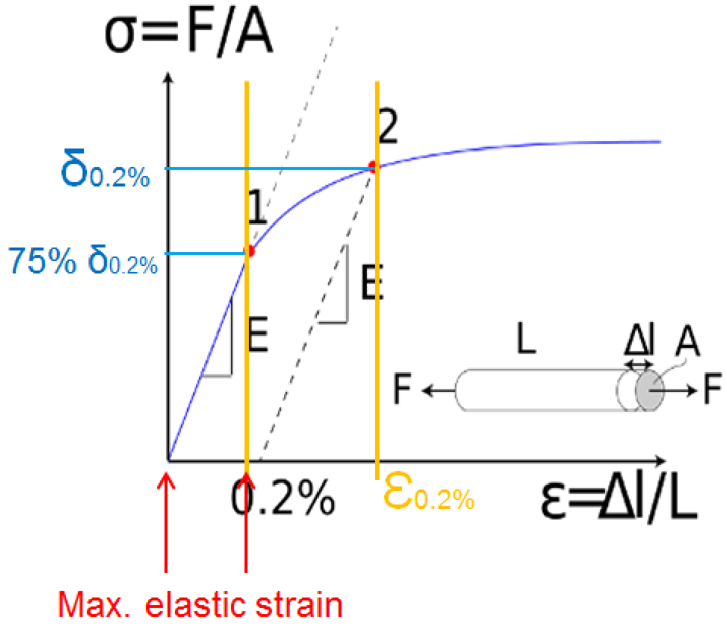


Figure 3 A typical stress strain curve

Various material properties as well as data for determine E modulus could be obtained from this curve. The y coordinate of point 2 is the 0.2% yield strength $\delta_{0.2\%}$. The 75% of $\delta_{0.2\%}$ is the y coordinates of point 1 which is the maximum elastic stress while the x coordinate of point 1 is the maximum elastic strain. 75% of $\delta_{0.2\%}$ is a useful and practical value. It has been historically used because of safety factor (i.e. 1 / 0.75 = 1.33). The E modulus can be calculated by equation (4) using the stress and strain coordinates within the range of maximum elastic strain (i.e. before point 1). [4]

$$E = \frac{\delta}{\varepsilon} \tag{4}$$

2.3 Digital images correlation DIC

DIC, which is an effective technique to map deformation in macroscopic mechanical testing, is an optical method based on the comparison of images before and after deformation. It is widely applied in various areas of science and engineering such as measurement of displacement, strain and flow. Using a CCD camera as the DIC camera, images of the sample during the tensile test can be acquired. The greyscale images are divided into a grid of interrogation cells. A cross-correlation algorithm is required to detect movement of reference markers between cells by searching for areas by matching greyscale values from each image. Computer software is used to cross correlate images and extracting the deformation of the reference grid.

3. Sample description

Tensile deformation test were carried out on 4 candidate materials for the crystal bender as described in Table 1. Deformation test using combined methodology of strain gauge and DIC have been performed.

Table 1 Samples description

Sample	Specification	Heat treatment	Dimension (mm)
Austenite spring steel (steel)	EN 1.4301	No heat treatment	30 x 6.95 x 0.1
Copper Beryllium Alloy 25 (CuBe)	ASM 4530	No heat treatment	30 x 6.95 x 0.1
Copper Beryllium Alloy 25 (CuBe - HT)	ASM 4530	Tempered at 315 °C for 8 hours	30 x 6.95 x 0.1
Beta Titanium (Ti - HT)	ASM 4914	Tempered at 540 °C for 8 hours	30 x 6.95 x 0.1
Remarks	HT: Heat treatment		

4. Experiment Setup

Experimental setup is shown in Figure 4. Samples were sanded by sand paper and cleaned by acetone before sticking strain gauge on the sample. To conduct DIC experiment, suitable size of white specular markers was sprayed on the samples with a black background as shown in Figure 5. The finished sample was then used in the deformation test. The pulling speed was 0.8 um/s and the applied strain gauge voltage was 2 V. The change of resistance from strain gauge is determined by Wheatstone bridge, the output voltage of the bridge is further amplified. The data from Wheatstone bridge, load cell and DIC is recorded by digital oscilloscope.

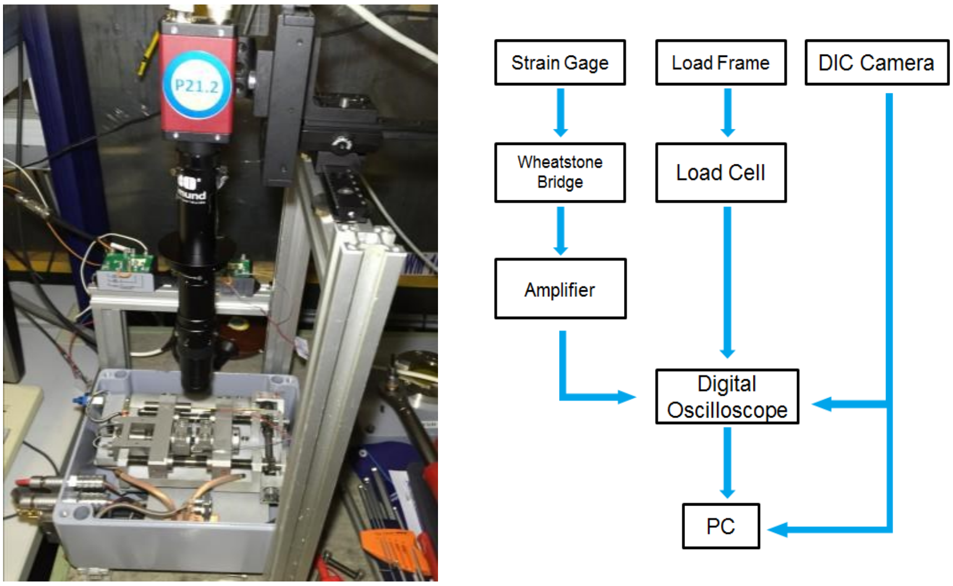


Figure 4 Experimental setup: (a) photo of the setup (left); (b) flow chart of the setup (right)

[2]

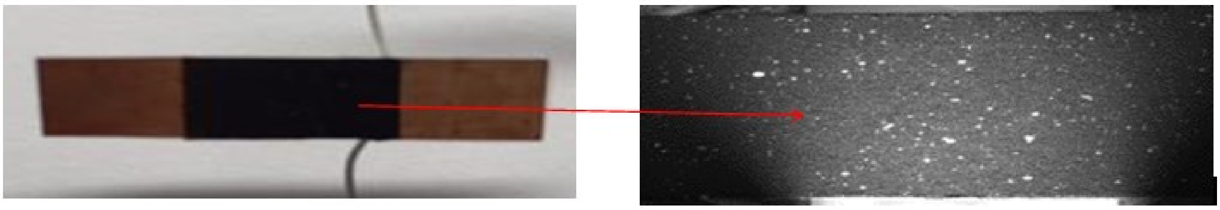


Figure 5 Specular markers for DIC

Experimentally used apparatus are described in the following table:

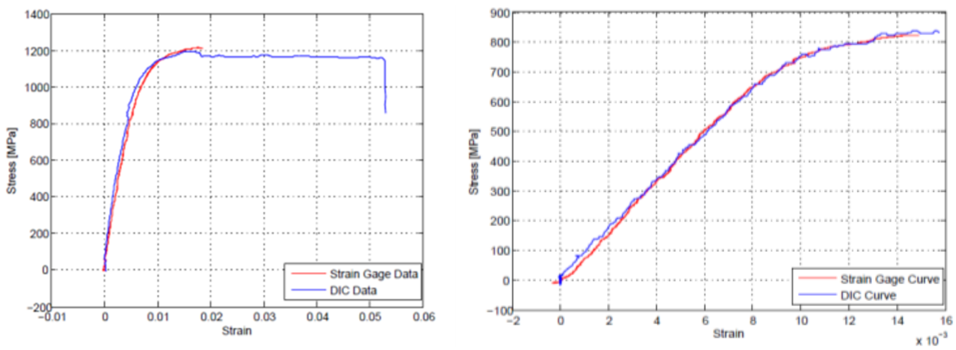
Table 2 Experiment apparatus

Apparatus	Descriptions
DIC Camera	Mante CCD 504-B
Load Frame	Kammrath & Weiss
Load Cell	5KN load cell
Strain gauge	HBM 1-LY15, Maximum voltage input is 4V, gauge factor K = 2.08

5. Result and Discussion

5.1 Stress Strain curve

The stress strain curves for steel, CuBe, CuBe(HT) and Ti(HT) are shown in Figure 6. Mechanical properties can be obtained in these curves. Curves obtained by strain gauge are consistent with curves obtained by DIC using Matlab-based DIC code from E.M.C Jones, University of Illinois, April 22, 2015 Version 4 [5].



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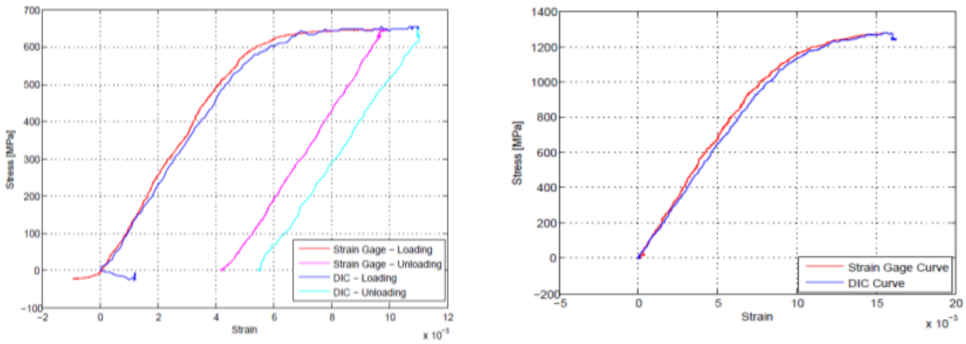

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Figure 6 Stress strain curve for samples (a) steel, (b)Ti(HT), (c) CuBe, (d) CuBe(HT)

The E modulus, 0.2% Yield Strength, maximum elastic stress and maximum elastic strain are summarized in Table 3. They are obtained by Matlab [11]. Ti (HT) shows a highest maximum elastic strain followed by CuBe (HT). The most suitable candidate material for flexure joint should be with high stiffness and maximum elastic strain. Therefore CuBe (HT) is the most suitable candidate which has high elastic modulus and maximum elastic strain.

Table 3 Result of candidate materials for flexure joint in crystal bender

Sample	E modulus (GPa)	0.2% Yield Strength	Maximum Elastic stress (MPa)	Maximum Elastic strain (%)
Steel	200 , 173	965 , 1106	827	0.46
CuBe	131 , 119	620-800, 634	475	0.40
CuBe - HT	131 , 129	1130-1420 , 1177	883	0.71
Ti - HT	82 , 80	1172 , 794	596	0.74
Remark	Literature value, DIC Experimental value HT: Heat treated			

[6]

The deviation between experimental and literature result is less than 10%. The deviation could be result from friction of load cell and pixel scale calculation in DIC. In addition, clamping of sample and light source for DIC may also influence the experiment result which is different from literature. Besides, the deviation may also be result from anisotropy.

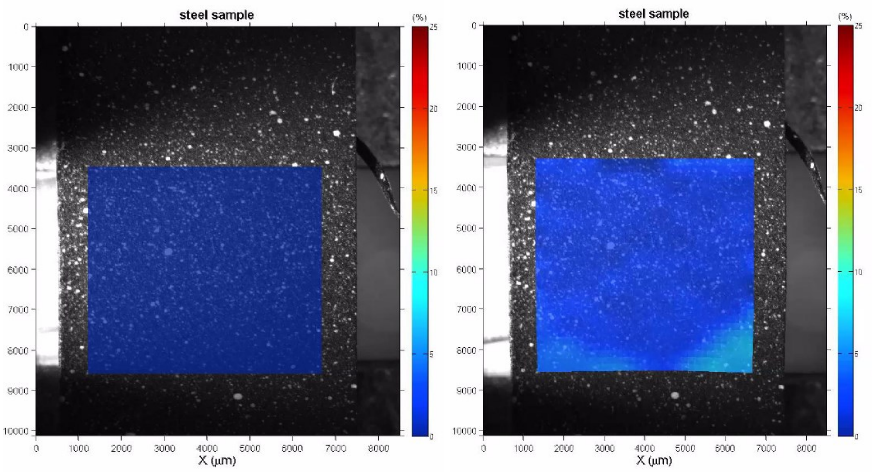
5.2 Anisotropy

Our measured E moduli for candidate materials are different from the values from literature. Anisotropy is a possible cause. A study conducted by Toyota Research Institute revealed there is a 28% difference of E modulus of steel in different orientation of crystal structure. E modulus was the highest in (111) orientation while it is the lowest in (100) orientation. E modulus is orientation dependent. Take our steel sample as an example and compared with the result in Toyota Research Institute. The E modulus of our steel sample is within the range of this result.

Atoms slip when sample is pulled. The dislocation moves in the slip plane along slip direction. Slip is preferred to occur in the direction with high atom density. Slip systems depend on crystal structure. The plastic deformation of samples being pulled during experiment is much smaller than being rolled during manufacturing. 0.2% yield could not lead to texture evolution in our experiment. Stronger plastic deformation during manufacturing leads to texture evolution. Therefore plastic anisotropy of materials appears in manufacturing which ultimately determined the E modulus of the material. For more in deep study, instead of macroscopic strain mapping, microscopic strain mapping could be applied to study the strain distribution in sample. [7] - [10]

5.3 Localization of strain

Full field strain distribution over a wide range of strain is measured in DIC. Inhomogeneous strain distribution in materials is revealed. This is a phenomenon of localization of strain. Figure 7 shows the strain distribution in steel sample in the tensile deformation test. The strain is represented by pixel intensity. Before load application, the intensity of pixels in the selected area of the first image is the same showing that no elongation in the sample. The second image shows increment in pixel intensity. The sample is being pulled and it is within the elastic strain limit. Strain distribution at this stage is still even. As the elongation increases, the strain is less even. The red region on the third image shows a high pixel intensity which is an indication of localization of strain. The last picture shows the sample cracks in the region of localization of strain. Inhomogeneous deformation is typical in deformation test. Localization of strain in sample appears in larger strain. In the early stage of elongation before 0.2% yield strain, localization of strain is not obvious. Therefore, the effect of localization of strain on experiment result is NOT significant. [11]



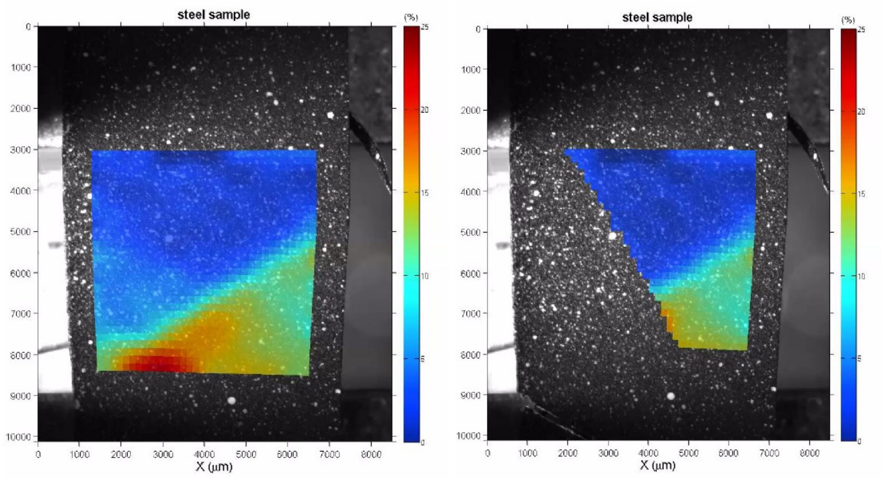


Figure 7 DIC images of steel

6. Conclusions

Stress strain curve is obtained in tensile deformation test by implementation of DIC. The accuracy of DIC is validated by simultaneously using strain gauge to measure the strain in the test. The most suitable candidate material for flexure joint should be with high E modulus and maximum elastic strain. Therefore CuBe (HT) is the most suitable candidate which has high elastic modulus and maximum elastic strain.

Improvement:

The followings can be done to improve the experiment:

Use a homogenous illumination light source to reduce the shadow for a more accurate analysis.

Sample geometry should be changed to dog bone shape for a better clamping.

More computer power is needed for a faster 2D and 3D DIC analysis

Future Prospection:

Use X-ray and DIC to study the texture of sample.

7. References

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