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Strain-Hardening Effects during Plastic Buckling of Axially Compressed Aluminium Tubes

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Abstract: **The paper investigates the effects of strain-hardening in aluminium (6063) circular tubes undergoing plastic buckling due to axial compression under quasi-static and dynamic loads. Experimentation includes the study of change in modes of deformation behavior and buckling for sets of annealed and as received tubes. Systematic studies were conducted to determine the effects of strain-hardening and strain rate. Quasi-static tests were conducted on as received (VHN-75) and annealed (VHN-35) tubes to characterize the deformation pattern and load-deflection behaviour. On a set of annealed tubes interrupted loading tests were conducted on intermittently annealed specimens to observe the effects of strain hardening. All the quasi-static test cases have been repeated under dynamic loading conditions for different velocity ranges.**

***Keywords*— Strain-hardening effects, buckling, energy absorption capacity, impact test.**

I. INTRODUCTION

Aluminium alloys are widely in use for automotive parts, machinery, design structures, and aircraft parts owing to their low weight, greater strength and absorption capacity during impact. Design and production of light and crashworthy structural parts in aluminium entail development of alloys and manufacturing processes, structural design and the measure of its crashworthiness. Energy absorption capacity of materials is used in various transportation system has led to increased interest in thin walled high strength sections. The energy absorption capabilities of such components are important in improving the crashworthiness without increasing the weight. Strain-hardening is the ability of the material to plastically deform. This means that as a material of is compressed, due to plastic deformation strain hardening increases. The hardening in a material can be nullified by annealing process. Also, the strain-hardening in a material can varied by thee methods of interrupted loading and intermittently annealing processes. A material's strength is dependent on its microstructure. The engineering processes to which a material is subjected can alter this microstructure.

II. MATERIAL PROPERTIES AND DIMENSIONAL SPECIFICATION

The tubes as received, had an average vicker's hardness value of 75 VHN. A set of tubes were annealed by heating them to a temperature of 360oC. Due to the effect of annealing the average vicker's average number reduced to 35 VHN. Annealing improves the ductility property of material by making it softer. The following table shows the material properties of aluminium alloy. The specimens were machined on a lathe to a length of 140mm each. The edges were smoothened by using a file. The methodology of the project consisted of experimental work and finite element analysis. The experimentation work consisted of quasi static and dynamic tests.

Table. 1 Material properties and dimensional specifications

Property	Value	Dimensions (mm)
Density	2700 kg/m^3	Do = 50 Di = 48.4 L = 140
Modulus of Elasticity	69 GPa	
Yield stress	276 MPa	
Ultimate stress	310 MPa	

Table. 2 Vicker's hardness number

Hardness Number (VHN)	Value
Vicker's Hardness Number (as received)	75 VHN
Vicker's Hardness Number (Annealed)	35 VHN

III. QUASI-STATIC AND DYNAMIC TESTS

Quasi-static tests were carried out on a universal testing machine (UTM). The maximum capacity of the UTM is 400kN. The dynamic tests were carried out on drop weight testing machine. The impactor mass was fixed to 63.5kg for this experimentation work. The dynamic tests were carried out for different drop heights depending on the tubes energy absorption capacity calculated from the quasi-static tests.

Figure. 1 Universal testing machine (UTM)

Figure. 2 Drop weight testing machine

The tests were carried out for a set of as received and annealed tubes. Annealing is a process were the material is heated up to its recrystallisation temperature. By the process of annealing the material's ductility is improved but there is a reduction in its hardness. For a set of as received tube and annealed tubes both quasi-static and dynamic tests were carried out under different loading condition i.e. complete compression and interrupted loading. The interrupted loading tests reveal the strain-hardening effects at different stages of deformation.

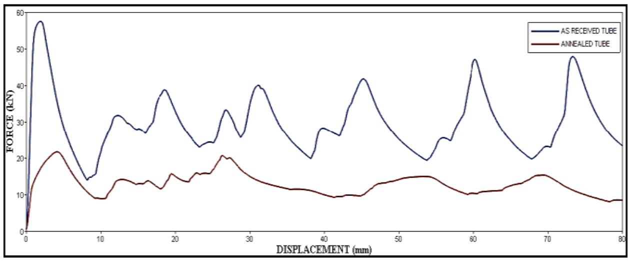

Figure.3 Load-displacement response under quasi-static tests for as received and annealed tubes

The above Figure. 3 represents load-displacement response under quasi-static loading condition for as received and annealed tubes. The annealed tubes show a lower load carrying capacity. Annealing nullifies the strain-hardening effects. The test results have been plotted up to a displacement of 80mm. The energy absorption capacity for as received tube was 2.3 times more than that of annealed tube. Annealed tube under quasi-static loading condition were under non-axis symmetric buckling under going a transition from circular lobed mode to triangular lobed mode. Hence for the formation of one-fold undertakes more displacement than usual in the case of annealed specimens.

Table. 3 Comparison of test results under quasi-static loading condition

Test	Energy absorbed (Joules)	Maximum force (kN)
Annealed	**1034.144**	**21.76**
As received	**2373.404**	**57.64**

The test specimen for the above condition of experimentation is shown in the below figures. As received specimen is undergoing a complete axisymmetric buckling mode.

Figure. 4 Quasi-static test specimens for as received tube

For annealed tube, there was a change in mode of deformation for circular to triangular lobe mode as shown in Figure. 5.

Figure. 5 Quasi-static test specimens for annealed tube

Similarly, tests were carried out under dynamic loading condition. The load-deflection response was plotted for as received and annealed specimen. The drop height was set by calculating the energy absorbed during the quasi-static analysis under same parameters. The height is calculated using the formula:

E=mgh

Where, E = Energy absorbed during impact under quasi-static loading (Joules); m = mass of the impactor (63.5 kg);

g = acceleration due to gravity (9.81 m/s2); h = drop height for dynamic testing (m). Thereby, from the above data the calculated height for as received and annealed tubes was 3 m and 2 m respectively.

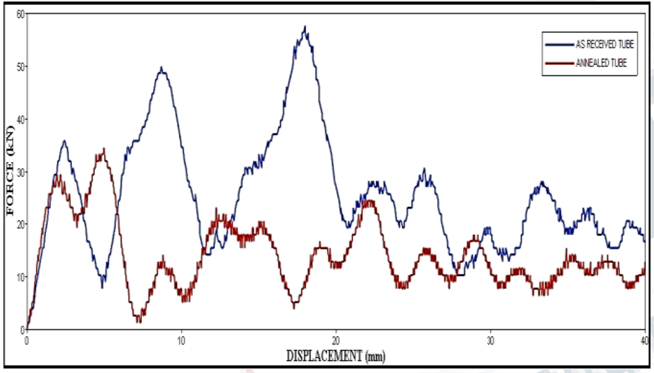

Figure. 6 Comparison of load-displacement response under dynamic tests for as received and annealed tubes

The above figure represents the load-displacement response between as received and annealed tubes under dynamic loading. There is a substantial decrease in load carrying and energy absorption capacity for annealed tube. The conclusion which can be drawn from this experimentation is the load carrying capacity decreases as the material becomes more ductile or softer. The energy absorption capacity for as received tube was 1.8 times more than that of annealed tube. In the case of as received tubes, the maximum force as shown in Figure. 6, is displayed at the second lobe mode formation. This might be caused due to the maladjustment the impactor or due to bouncing of the specimen during impact. The results of the above tests are given in Table. 4.

Table. 4 Comparison of test results under dynamic loading condition

Test	Energy absorbed(J)	Maximum force(kN)
Annealed	**560.95**	**34.71**
As received	**1016.32**	**57.45**

Figure. 7 Dynamic test specimens for as received tube

For annealed tubes, the deformation mode observed was triangular or non-axisymmetric mode of buckling. As triangular lobe mode is formed due to folding of the specimen, the deformation length of every fold is more.

Figure. 8 Dynamic test specimens for annealed tube

IV. INTERRUPTED LOADING UNDER QUASI-STATIC AND DYNAMIC TESTS

In this condition of testing the loading is interrupted after every fold is formed, i.e. after every fold the specimen is unloaded and reloaded again from the same point of deformation. The tests were carried under quasi-static and dynamic loading conditions. After the completion of one-fold, the deformed length is measured and the corresponding load deflection response is plotted and energy absorbed for completion of one-fold is calculated. Interrupting the loading increases the strain-hardening at the critical points of deformation by making it stronger. Hence deformation per fold decreases in this type of loading condition. The tests should be conducted under constant deformation rate.

The test results of interrupted loading were compared with the results of continuous impact under dynamic loading. The tests results were plotted under a load-displacement curve.

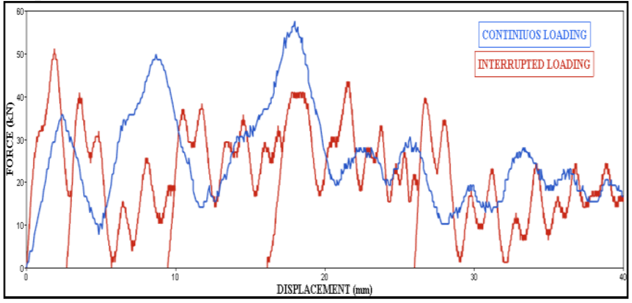

Figure. 9 Dynamic loading tests for continuous and interrupted loading of as received tubes

The results of interrupted loading have been plotted for five folds. The folds have been combined from the point of unloading. The total energy absorbed during interrupted loading is given as the summation of energy absorbed for all the folds which is equal to 917.34 kN, whereas for continuous or sudden impact, the energy absorbed is 1016.32 kN. The results have been plotted up to a displacement of 45 mm. The following table represents the results of the above tests.

Table. 5 Comparison of dynamic test results for continuous and interrupted loading of as received tubes

Test (Loading Type)	Energy absorbed (J)	Maximum Force (kN)
Continuous	**1016.32**	**57.45**
Interrupted	**917.34**	**51.37**

There is a small difference in energy absorption capacity between the two loading conditions. Hence unloading and reloading doesn't seem to affect the load carrying capacity of the specimen. The only conclusion which can be drawn from the above experimentation is with regard to strain-hardening. The observation can be made based on the deformation behaviour of the specimen.

Figure. 10 Dynamic test specimens under interrupted loading of as received tubes

It is observed that the specimen is undergoing a change in deformation mode. The crack as shown in Figure. 10 is the result of exceedance strain value above the fracture point. As the fracture strain is exceeded in the specimen, a fine crack is developed.

Similarly, interrupted loading test were also carried out for annealed tubes. The corresponding results were plotted on a load-displacement curve.

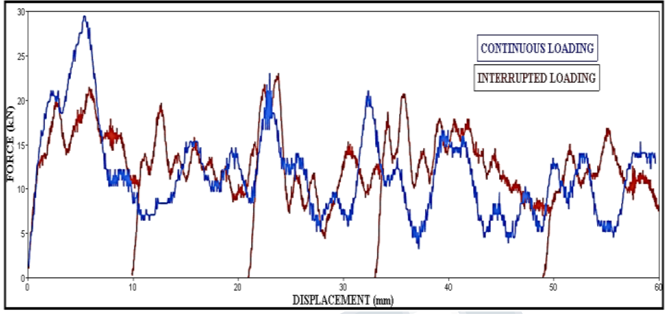

Figure. 11 Dynamic loading tests for continuous and interrupted loading of annealed tubes

The above graph is being plotted up to a displacement of 60mm. As with regard to energy absorption capacity, for interrupted loading it was found to be 792.08 kN and for continuous or sudden impact the energy absorbed was 698.03kN. Hence it can be concluded that similar to as received tubes, loading and unloading doesn't seem to affect on energy absorption capacity and maximum load which a material can withstand.

Table. 6 Comparison of dynamic test results for continuous and interrupted loading of annealed tubes

Test (Loading Type)	Energy absorbed (J)	Maximum Force (kN)
Continuous	**698.03**	**29.31**
Interrupted	**792.08**	**22.94**

The variation in maximum force can be noted from visual observation of the deformed specimen. It might occur due to global buckling of the specimen due to sudden impact.

Figure. 12 Dynamic test specimens under interrupted loading of annealed tubes

At critical points in compression i.e. at points were strain-hardening is maximum, the material will be plastically deformed. Hence it can be explained as once a material is loaded, it deforms elastically to a point were maximum yield stress is achieved. Once a material reaches its yielding point, it starts to plastically deform and a fold is formed. After the completion of one-fold, the material again buckles elastically under axial loading. Therefore, this point in the deformation can be noted as the part were strain-hardening is maximum. If the specimen is annealed at these points, the strain hardening effects nullifies. Hence, annealing at these critical points helps in nullifying the strain hardening effect which incurred due to the previous fold. Quasi-static tests were conducted on specimens which were intermittently annealed. The test results were compared with test conducted under complete compression of tube under quasi-static loading.

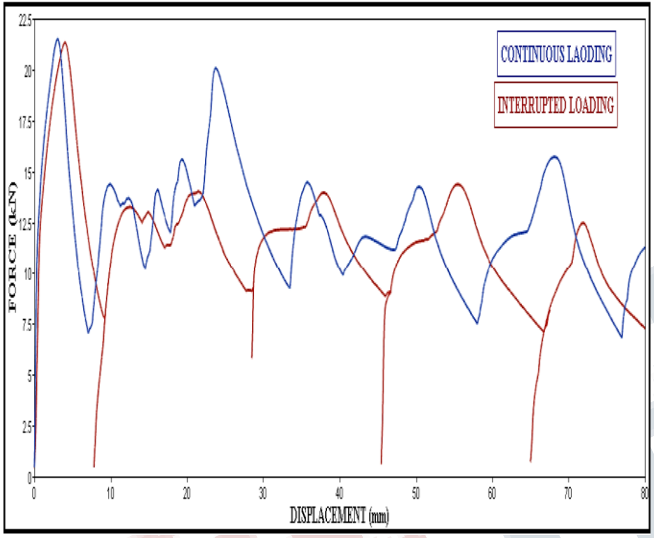

Figure. 13 Quasi-static tests for continuous and interrupted loading of intermittently annealed tubes

Both the test specimens undergo a transition from circular lobed mode to triangular lobed mode. Under complete compression, the transition occurred after the first fold. The tube is undergoing a non-axisymmetric buckling. As the material is undergoing a triangular lobed mode deformation, the material is more strain hardened after the third fold under complete compression. Under interrupted loading of intermittently annealed tubes, the material strain hardening properties decreases as annealing makes the material more ductile. The changes incurred due to intermittent annealing is change in deformation length for every fold. This observation can be made from the deformation behaviour of the specimen.

If a transition is occurred in the deformation mode of the tubes, the material take can undertake more load to complete one-fold. This property is affected as every fold is formed as annealing helps to reduce strain hardening effects on the specimen.

Figure. 14 Quasi-static test specimens for intermittently annealed interrupted loading

The results related to maximum force and energy absorption capacity were calculated for the two conditions. The results have been plotted up to a displacement of 80 mm.

Test (Loading Type)	Energy absorbed (J)	Maximum Force (kN)
Continuous	**991.97**	**21.76**
Interrupted	**955.72**	**21.39**

Table. 7 Comparison of Quasi-static test results for continuous and interrupted loading of intermittently annealed tubes

From the above test results, it can be concluded that, intermittent annealing does not affect the material's energy absorption capacity. The affects observed were only with regard to deformation behaviour with changes in deformation modes hence with intermittent annealing, a transition incurred in modes and the deformation length for every fold.

V. CONCLUSIONS

The mode of deformation of a circular tube under axial compression depends on its geometry. This means, a relatively thicker tube can deform in axisymmetric and thinner tubes fold in lobe mode. For any given tube the mean collapse load at which the folds are initiated is higher for axisymmetric buckling. The annealed tubes show a better deformation behaviour then as received tubes for both quasi-static and dynamic loading conditions due to improved ductility.

Unloading and reloading at any stage does not seem to affect the load-deflection characteristics or the deformation pattern of tube. The effect of intermittently annealing of tubes nullifies the strain-hardening effects which occurred due to the previous folds, which in turn modifies the load carrying capacity.

The test conducted on the tubes with a radius to thickness ratio of 15.62. The experimentation conducted on the thinner tubes either buckle in axisymmetric or lobed modes, whereas thicker tubes buckle in axisymmetric mode. However, under intermittent annealing formation of lobe modes and continue into unstable buckling mode. A crack is generated if a material exceeds it fracture strain value. This observation was made in interrupted loading of as received tubes.

Energy absorption capacity is more under dynamic than quasi-static tests under continuous loading condition. The energy absorbed during dynamic loading was approximately 1.5 times more than that during quasi-static loading. However, the need for more accurate and detailed representations of the load-deflection characteristics which reveal the occurrence and extent of instabilities in the deformation behaviour or account on effects of friction poses formidable problems. Dynamic approaches would seem to be inappropriate and the role of material strain hardening which cannot be ignored on account of different loading speeds.

The conclusion which can be drawn from the experimentation is that, annealed tubes are more ductile when compared to as received tubes. Hence a ductile material is softer which in turn affects its load carrying capacity and energy absorption capacity. As received tubes are much more strain-hardened when compared to annealed tubes. This helps in withstanding more load during the impact. Strain hardening alters the material properties including yielding point. Due to this improvement, the material can withstand loads for a longer time without undergoing fracture or failure.

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