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Effect of CT Specimen Geometry to Fracture Properties of Aluminium Alloy Using Simulation Analysis

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Abstract: Aluminum alloys are the alloys in which aluminium is present as the predominant metal. Due to its strength and fracture, aluminium alloys are widely used in aviation, aerospace, energy, transportation, and automotive industries. This study was conducted to identify the mechanical properties of aluminium alloys in simulation analysis and compare the data obtained with the previous research. The variation of plastic behaviour on different types of the specimen was conducted to study which specimen will give a better result in terms of its strength and chemical composition contains in aluminium alloys. There were several samples made by Al7075, Al7075-T6 and Al6061-T6 used and three different loads were applied to start from 2500 N, 3750 N, and 5000 N. As the load applied to the specimens increased, the stress will also increase for the specimens to withstand the load applied. There is a linear relationship between stress-load, stress-deformation, and stress-strain graphs. Yield strength can be obtained from the stress-strain graph. Based on the results, 0.187 W CT specimen shows the strongest tensile strength when compared with other specimens tested. In term of material properties, all of the specimens indicates the highest results of yield strength in Al6061-T6 compared to other two materials. These results were affected by the chemical composition of aluminium alloys, the specimen configuration, and the plastic zone size.

Keywords: CT Specimen, Plastic Deformation, Tension Loading, Yield Strength, Aluminium Alloys, Ansys Software

1. Introduction

Aluminium is one of the most widely used metallic materials for today's high-technology engineering applications such as aviation, aerospace, energy, transportation and automotive [1]. In the aerospace, aircraft and automotive industry the lightweight design is of paramount importance.

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Therefore, in these industries materials with low density and high mechanical properties are used such as aluminium alloys [2]. Many structural steels and aluminium alloys generally exhibit significant increases in fracture toughness, characterized by the J-integral, over the first few mm of stable crack extension (∆a), often accompanied by large increases in background plastic deformation [3]. Aluminium alloys are the alloys in which aluminium is used as the main metal. Typical alloy elements are copper, magnesium, manganese, silicon, tin and zinc. For this study, aluminium alloys Al7075, Al7075-T6 and Al6061-T6 were used to identify the effect of compact specimen (CT) geometry to fracture properties of aluminium alloy. Aluminium alloy AA7075 is an aluminium alloys with zinc as the primary component. It comes from many well mechanical properties and indicate good ductility, high strength, toughness and good resistance to fatigue. Due to its high strength to weight ratio, its resistance to environmental effects, for example corrosion and other advantages such as machinability, its high level of usage will sustain its status for a long time with continuing improvement and developments [1].

Based on the previous researches [4], the study about mixed-mode fracture toughness versus thickness and yield strength in aluminium alloys has stated that minimum thickness required in the CT sample to dominate the plane strain conditions for different alloys based on standard ASTM E1820. According to the research effect of microstructural through-thickness non-uniformity and crack size on fatigue crack propagation and fracture of rolled Al7075 alloy by Ali O. Ayhan, this research is more to measure the thickness of microstructure with fatigue crack propagation of aluminium alloy. There are lack of fatigue crack growth (FCG) along some portions of crack front and deflection of fracture propagation from its original plane. According to [5], the researcher had proposed an approach which includes a way to quantify certain derivatives by following the super-convergent patch recovery method principle in order to guarantee the domain independent property. This study conducted due to the domain-independent property is not assured when a cracked body undergoes a large elastic-plastic deformation. From this research, it was found that second integral plays an important role in finite strain elastic–plastic problems. For the J-integral evaluation, the inclusion of the second integral is needed. It cannot be used as the crack parameter in elastic-plastic issues of finite strain without the second integral. When the structure is subject to the cyclic load applied and undergoing crack propagation, this problem may be more pronounced.

Another research by [6] had been conducted to evaluate material properties and fracture simulation of cryorolled 7075 Al alloy. In this study, in order to predict the fracture behaviour of specimen, strain energy rate, stress distribution around the crack tip, crack propagation and plastic zone size has been evaluated in XFEM simulation for both Bulk and ultrafine-grained (UFG). From this research, the size of plastic zone around the crack tip was bigger in UFG compared to bulk form in which shows the significant improvement in the fracture toughness due to formation of UFG in cryolling process. By these research gap, the objectives of the study are highlighted. There are different of mechanical properties of Aluminium Alloy Al7075 between the four types of CT specimen that will be used in this experiment which are 0.24W CT specimen, 0.187W CT specimen, K_{Ic} CT specimen and Disk-Shaped CT specimen. This study is conducted to identify whether the results of mechanical properties of different aluminium alloys by using simulation analysis are same as the previous research. From this comparison, we are able to know which materials are the best in terms of its geometry to fracture properties of aluminium alloys.

2. Materials and Simulation Methods

2.1 Parameter of materials

In this study, there were four different types of compact tension (CT) specimen tested in Ansys. The loads had been applied to these specimens starting from 2500 N, 3750N, and 5000 N. The specimens that drawn in Solidworks were exported in Ansys software. The aluminium alloys used in this area of study were Al7075, Al7075-T6, and Al6061-T6. Table 1 shows the parameters setting in Ansys.

Table 1: Parameters setting in Ansys software

Parameter	Value	
Young's modulus (E)	Al6061-T6	68.9 GPa
	Al7075-T6	70 GPa
	Al7075	71.7 GPa
Poisson's ratio	0.33	
Load	2500 N, 3750 N, and 5000 N	

2.2 Simulation Methods

The further process is by conducting the CT specimens. CT specimen is a type of standard notch specimen in accordance to ASTM and ISO standard. It is extensively used in the area of fracture mechanics to obtain the mechanical properties of ductile materials. The area of monitoring the fracture properties was conducted in Ansys software as in Ansys, it can help to produces the more suitable mesh for precise and effective multi-physics solutions. After meshing, the properties of materials obtained in ANSYS will be analysed and compared with the previous research. The flow for this process are as illustrated in Figure 1. In Ansys, there will be two boundary conditions applied in each specimens, known as force and fixed support. The force was set at the upper hole while the fixed support at the lower hole. As the different loads of 2500 N, 3750 N, and 5000 N applied, the specimens will have a crack growth at the notch end. The specimens experienced an elastic-plastic deformation at the yield point. In this study, the maximum yield point is at 5000 N of load.

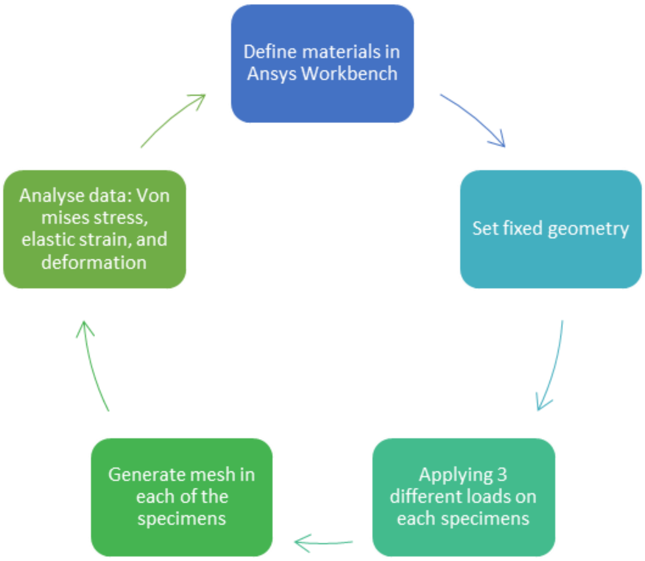


Figure 1: The flow process in Ansys

2.3 Preparation of specimens

The configuration of CT specimens are according to standard ASTM E-1820. These specimens were drawn in Solidworks at first before being exported into Ansys for further analysis. There were different geometries at the end notch in each specimens. Figure 2 illustrated the geometry of each specimens tested.

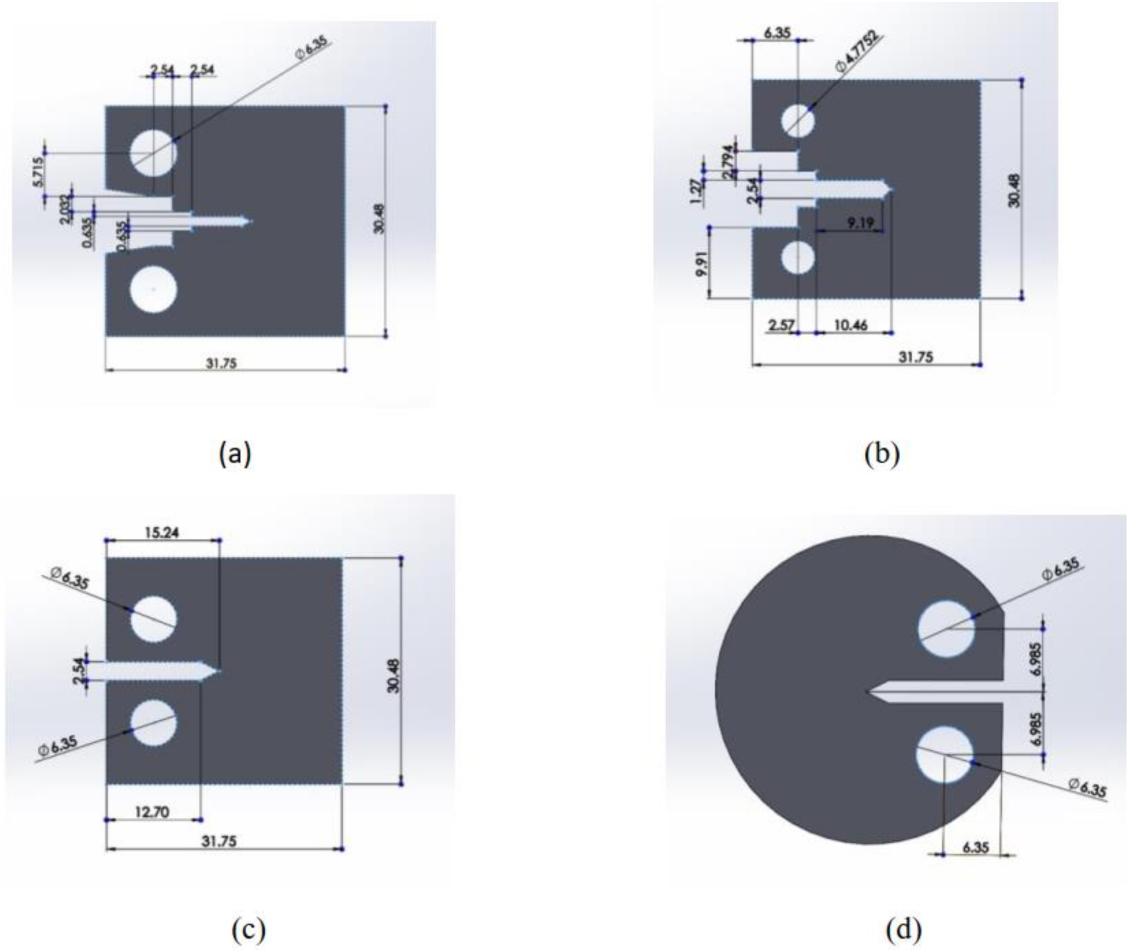


Figure 2: The configuration of CT specimens for (a) 0.24 W, (b) 0.187 W, (c) K_{1c}, (d) DCT

3. Results and Discussion

3.1 Results

The objective of this study was to study the mechanical properties of aluminium alloys and compared the properties of data obtained with the previous research. The selected model were three square specimens and one round specimen. The comparison was carried out by comparing the relations between stress-load, stress-strain and stress-deformation, with the previous study. The four types of CT specimen were produced by conducting the structural analysis in Ansys. A whole process analysis was conducted to evaluate the strength of aluminium alloy with different materials and loads. The load applied by 2500 N, 3750 N and 5000 N. The comparison properties of data is done to determine the strength and behaviour of aluminium alloy on CT specimen. The comparison is more focusing on the deformation of specimen, yield strength and elastic strain. Table 2 shows the tensile results of aluminium alloys for all CT specimens with the respective loads applied.

Table 2: Tensile results of aluminium alloys for all CT specimens

		Strain			Deformation, mm		
Specimen	**Load, N**	**Al7075**	**Al7075T6**	**Al6061T6**	**Al7075**	**Al7075T6**	**Al6061T6**
0.24 W	2500	0.008489	0.008695	0.008834	0.099413	0.10183	0.10345
	3750	0.012733	0.013043	0.013251	0.14912	0.15274	0.15518
	5000	0.016978	0.01739	0.017668	0.19883	0.20366	0.20691
0.187 W	2500	0.00855	0.008758	0.008897	0.10462	0.10716	0.10887
	3750	0.012825	0.013136	0.013346	0.15693	0.16074	0.16331

	5000	0.0171	0.017515	0.017795	0.20924	0.21433	0.21775
K_{1c}	2500	0.00892	0.009137	0.009283	0.080111	0.082057	0.083367
	3750	0.01338	0.013705	0.013924	0.12017	0.12308	0.12505
	5000	0.01784	0.018273	0.018565	0.16022	0.16411	0.16673
DCT	2500	0.005511	0.005645	0.005735	0.005627	0.077549	0.005856
	3750	0.008266	0.008467	0.008602	0.008441	0.008646	0.008784
	5000	0.011022	0.01129	0.01147	0.011254	0.011527	0.011711

3.1.1 Von Mises Stress (Equivalent stress)

Von Mises stress can be defined as the value used to predict whether the materials will yield or fracture. It is most commonly used on ductile materials such as metals. In this study, three different types of aluminium alloys has been tested according to their own chemical compositions of alloy. These alloys were Al7075, Al7075-T6, and Al6061-T6. The chemical composition for the aluminium alloys are as illustrated in Table 3. As the body is in an initial state of equilibrium, the body will deforms in accordance with the load applied, until it reaches a new state of mechanical equilibrium. The inner body forces were caused by a gravity, whereas the surface forces was the forces that applied to the body as a result of contact with other bodies. The relations between the external forces are called as stress while, the deformation of the body are called as strain. Thus, this relations of external forces and deformation are called as stress-strain relations. These relations represents the material properties that compose the body of specimens. The stress contours along the notch of each specimens for all materials are as shown in Table 4.

Table 3: Chemical composition of Al7075 [7], Al7075-T6 and Al6061-T6 [8]

	Zn	**Mg**	**Cu**	**Fe**	**Si**	**Mn**	**Cr**	**Ti**	**Al**
Al7075	5.5	2.5	1.6	0.5	0.4	0.3	0.15	0.2	Remaining
Al7075T6	5.4	2.5	1.6	0.4	0.35	0.1	0.23	0.021	Remaining
Al6061T6	0.09	1	0.3	0.45	0.6	0.11	0.24	0.041	Remaining

From the previous research, it has been evaluated that the yield strength for Al7075-T6 is 512 MPa and for Al6061-T6 is 285 MPa [4]. When compared with the yield strength obtained at 5000 N for the three materials, all of the specimen having a yield strength beyond the range of 512 MPa and 285 MPa. This is proven that the all of the specimens has undergo plastic deformation before fracture.

Table 4: Stress contours along the notch of all materials

Specimen	**Load, N**	**Stress, σ (MPa) (Al7075, Al7075-T6 and Al6061-T6)**
0.24 W	2500	470.33
	3750	705.49
	5000	940.65
0.187 W	2500	509.78
	3750	764.67
	5000	1019.6
K_{1c}	2500	484.89
	3750	727.33

	5000	969.78
DCT	2500	274.71
	3750	412.07
	5000	549.42

3.1.2 Deformation of Specimens

Deformation can be refers as the modification of the shape or size of a specimen due to an applied force. There were two types of deformation which were elastic and plastic. In an elastic deformation, the object will return to its original shape when the force is removed. For the plastic deformation, the object will not return to its original shape even after the force is removed. For this case study, a directional deformation at x-axis has been investigated for all specimens. This is due to during tensile test, the specimen will be clamped at the upper and lower holes. In Ansys software, the upper hole has been set as applied force, while the lower hole was set as fixed support. The plastic deformation will be evaluated at the notch of each specimens, in which gave the direction of x-axis. In this study, when three different loads applied, all of the specimen shows the highest deformation in Al6061-T6. In general, it can be seen that when the load applied is increased, the deformation of each specimens will also increase.

Figure 3 shows the graph stress against load for three different materials with different CT specimens that were done in Ansys simulation. These different coloured lines represents the different type of specimen configuration. From the various line types, it can be seen that 0.187 W specimen appeared to be the highest strength with the value of 1019.6 MPa when compared to the other specimens. There was a slightly difference in the strength between the two dotted lines which are blue and grey in which represents for 0.24 W specimen and K_{1c} specimen, respectively. As illustrated in the figure, the yellow dotted line which represents DCT specimen, seems to be the lowest strength with the value of 549.42 MPa. From this graph, it can be concluded that as the load applied increase, the part of the specimen begins to stress and thus, increased the strength of the specimen.

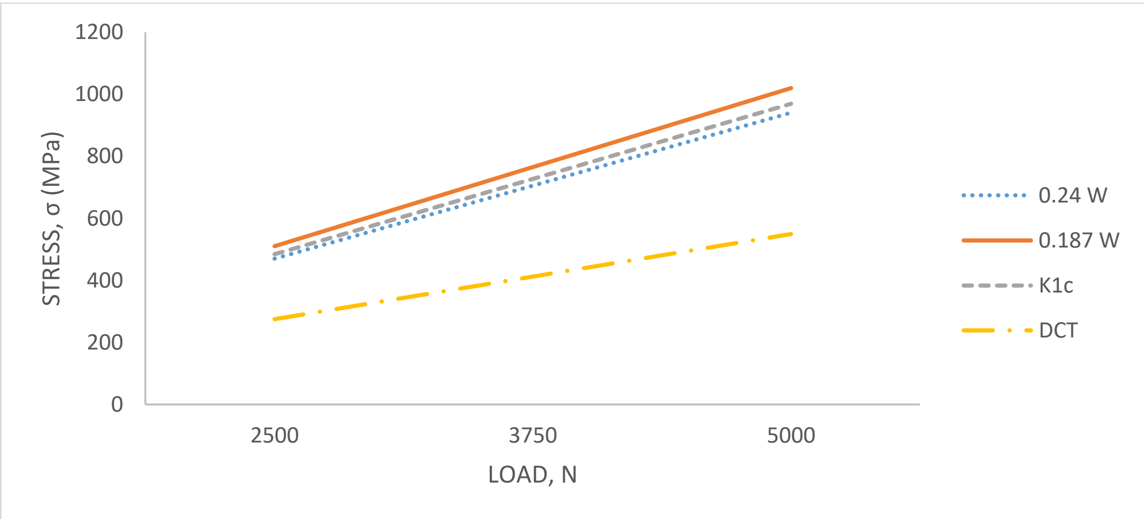
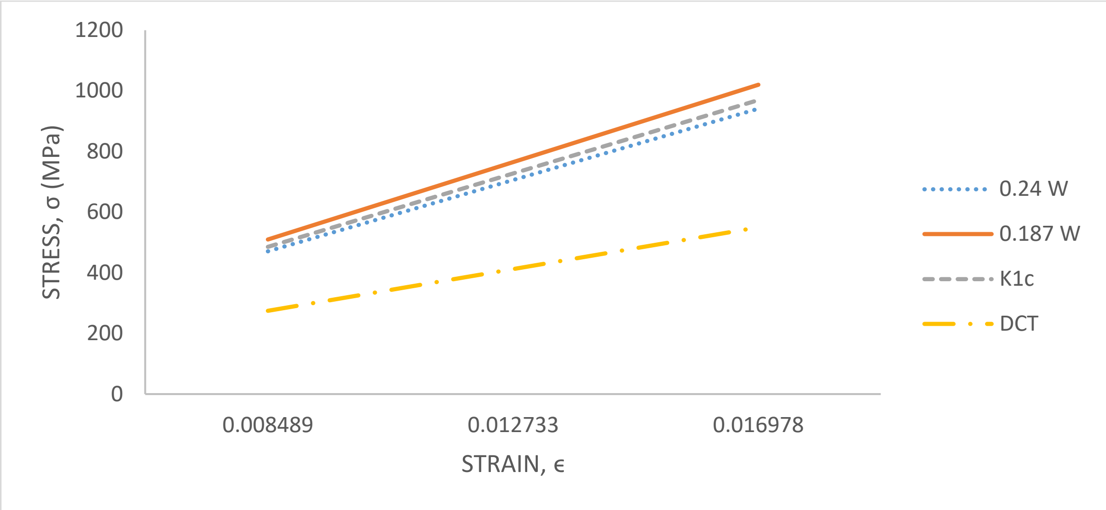


Figure 3: Graph Stress vs Load

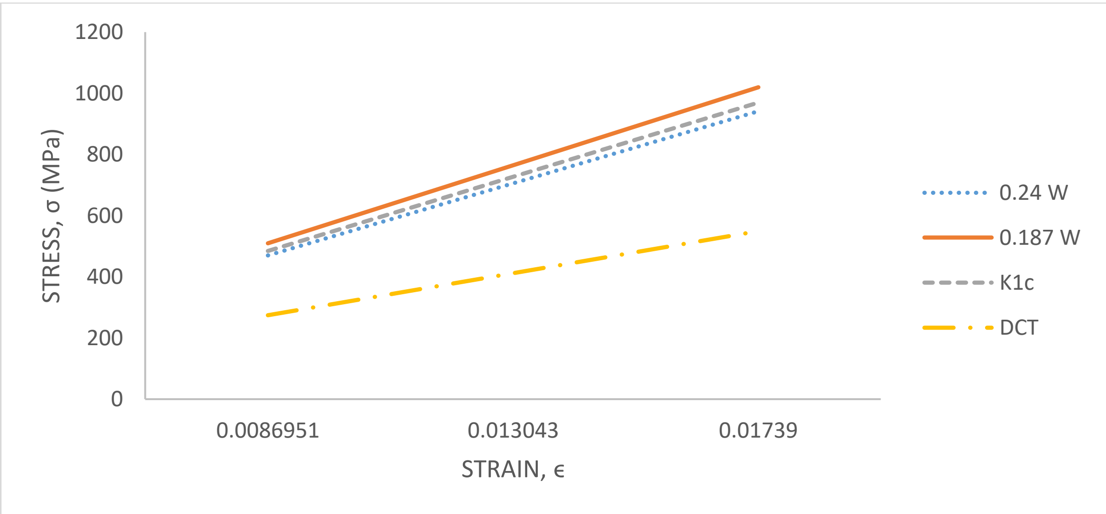
3.1.3 Equivalent Elastic Strain

The relations between stress against strain for each specimen with different materials and loads applied are as shown in Figure 4. The pattern of the graph were almost the same. This is due to the aluminium alloys are both in the same class but with different series. The yield point can be seen in these stress-strain graph, which indicates the limit of elastic behaviour and the beginning of the plastic behaviour. The yield strength, which also known as yield stress is the stress at which a material begins to deform plastically. Meanwhile, for the yield point is where nonlinear deformation occurs, which has both combination of elastic and plastic. The material will elongate elastically before entering the yield point and will return to its original shape when the applied force is eliminated.

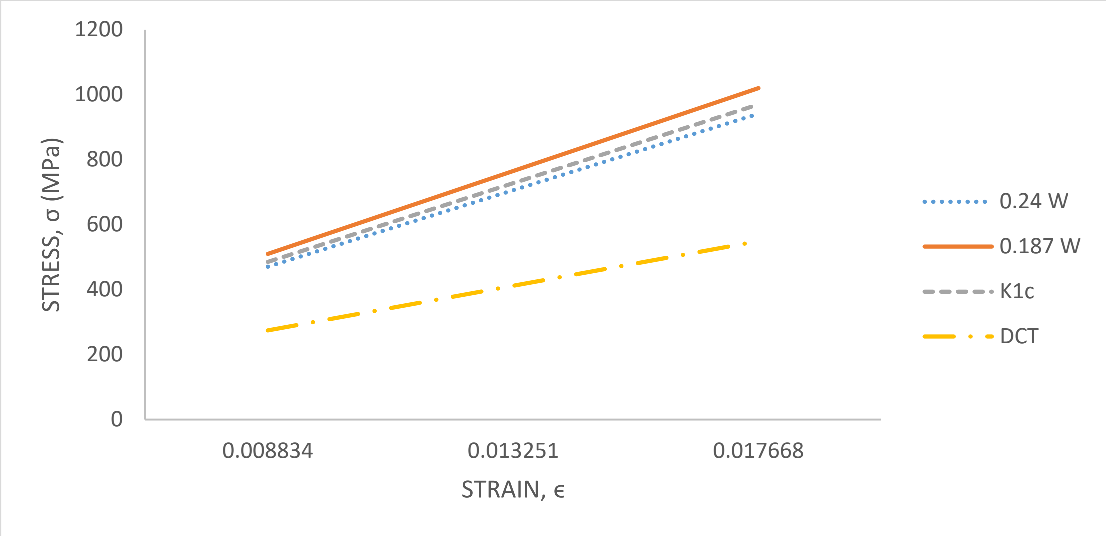
From Figure 4, 0.187 W specimen shows the highest yield strength of 1019.6 MPa, while DCT specimen shows the lowest yield strength of 549.42 MPa. Meanwhile, there is a slightly difference between the values of yield strength for 0.24 W specimen and K_{1c} specimen with the value of 940.65 MPa and 969.78 MPa, respectively. From these three graphs, it can be seen that 0.187 W specimen indicates the highest yield strength for all materials with the applied load of 2000 N, 3750 N, and 5000 N. The value for the highest yield strength is shown at the maximum line of the graph. DCT specimen shows the lowest yield strength for each materials with loads applied. This is because the configuration of DCT specimen has a round shape, and are quite differ when compared to other specimens. 0.187 W specimen shows the near line with 0.24 W specimen and K_{1c} specimen due to their configuration are almost the same in which they have a square shape. The yield strength of each specimens were evaluated at the yield point, in which can be seen at the end line of the stress-strain graph. This means that the yield strength was count at the maximum load, 5000 N for each specimen with different materials. From the graph stress-strain, it can be said that the highest yield strength for each specimen is shown in Al6061-T6.



(a)



(b)



(c)

Figure 4: Graph stress vs strain for (a) Al7075, (b) Al7075-T6, (c) Al6061-T6

3.2 Discussions

Based on the stress-strain graph, it can be concluded that all of the CT specimens shows the highest deformation at the end notch in Al6061-T6 compared to Al7075 and Al7075-T6. This is because these specimens had undergo plastic deformation at the notch end. Regarding to all of the CT specimens tested, 0.187 W specimen seem to have the highest deformation at the notch end. This is due to the angle at the end notch of this specimen is quite higher with the value of $\alpha = 90°$. Disk-shaped CT (DCT) specimen tends to have a lowest deformation since the angle at the notch end is 52.79°. However, for the other two specimens which are 0.24 W and K_{1c}, there is a slightly different between the values of yield strength due to the angle of at the notch end for this two specimens were same with the value of $\alpha = 53.13°$. In this study, it can be identified that there is a linear relationship between the notch angle with the deformation of specimen because as the angle at the notch end of the specimen increased, the yield strength will also increased.

According to previous research that had conducted a tensile test on compact tension (CT) based on ASTM-E1820, it has been discussed that when the angle is increased from $\alpha = 15°$ to $\alpha = 60°$, the amount of mixed-mode fracture toughness will also incresed. As the angle at the notch of specimen increased, the yield strength will also increased and thus, the deformation of the specimen will become higher [4]. This statement had proven that there is a correlation between the angle at the notch end with the yield strength and the deformation of specimen. Plastic zone size also affect the deformation of specimens. This is because the size of plastic zone is depending on either plane-stress or plane-strain condition. In plane-stress, this zone is thin enough and make the stresses through the thickness of the specimen are approximately constant. Previous study had stated that the damage growth of specimen involved remarkable plastic deformation and correlated failure mechanism at the final failure (notch end). This study also mentioned that when the damage reached a point at which the surface become unstable, the local separation (fracture) will quickly occurs [9].

All of CT specimens had undergo plastic deformation before fracture. After applying the loads, specimens will be pulled in an opposite directions and there will be a small necking at the notch end as a results from the tension loading. This situation happened because the specimens tends to withstand the fracture. When the stress is gradually increased and it is beyond the elastic limit, the specimen will undergoes a plastic deformation. At this point, a permanent distortion occurred as it exceed the yield strength and cause it to elongate before fracture. Based on the previous research by Torabi and Campagnolo (2016), a study had conducted on elastic-plastic fracture analysis of notched Al7075-T6. This research has confirmed that the plastic behaviour of ductile material can be interpreted by using stress-strain curve. In spite of strain to failure in which large for ductile materials, the ultimate strength is the main parameter to understand the plastic behaviour. If the strain at the ultimate point is only a small fraction, the necking of specimen occurs quickly with a small plastic deformations and progresses slowly through large plastic deformations until it fracture. On the other hand, the researchers also indicated that plastic deformation will not occur on a small-scale yielding because in this small yielding failure, there was no clear on non-linear portion in the load-displacement curve [10].

At the end of the notch of CT specimens, there were a plastic zone occurred due to the tension loading. In simulation analysis, the plastic zone take place after the load being applied to the specimen. The size of plastic zone depends on the radius of the geometry of notch. The end notch of each specimen will experience an opening due to its geometry of radius. In this state, there were small elongation at the notch opening. Previous study had investigated the fracture process zone from the notch and plastic zone size on CT specimen. This research stated that the plastic zone is increasing proportionally with the radius of notch. This happened because as the radius at the notch is increasing, the size of plastic zone will become bigger, and thus increased the strength and stiffness of materials [11].

4. Conclusion

For this research, three-dimensional (3-D) model of specimen was modelled in Solidworks and being analysed in ANSYS software to study the mechanical properties of different aluminium alloys by using simulation method for CT specimen. Then, the results obtained will be compared with the previous research. The specimen used in this research is compact tension (CT) specimen. Based on the data obtained, the main objective of this research are achieved. The output parameters considered for this research were deformation of specimens, maximum von mises stress and equivalent elastic strain. From the plotted graphs, it can be concluded that there is a correlation between stress-strain, stress-load, and stress-deformation. The deformation at the notch shows that the specimens experienced a ductile crack growth as the loads were increasingly applied. A permanent distortion occurred when the stress was beyond the yield point. At this point, the elastic behaviour were limited before the specimens continued to elongate and experienced plastic deformation before fracture. However, before entering the yield point, the specimens deformed elastically and returns to its original shape even after the load had been removed. The deformation of specimens were affected by its configuration, geometry at notch, and chemical composition of Al alloys. At the end of this research, it can be concluded that 0.187 W CT specimen shows the best specimen that can be used to study the fracture properties of ductile material because it has a highest yield strength compared to others (0.24 W, K_{1c}, and DCT). In terms of strength, all of the CT specimens shows the highest yield strength in Al6061-T6 when compared to Al7075 and Al7075-T6.

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