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Effect of Loading Rate on Fracture Behaviour and Shear Lips Formation of Al6061 Alloy

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Abstract: Aluminium alloys are widely used in many engineering industries due to their mechanical and material properties. It is used in many applications, especially automotive parts, like automobile cylinder heads, engine blocks, and chassis. It is important to obtain the behaviour of fracture of this material. Several materials testing has been conducted on aluminium 6061 alloy to fulfil the requirement in industries. However, the effect of specimen thickness on shear lip ratio and plastic zone size on fracture specimens for aluminium 6061 under the three-point bending test is hardly studied. Also, the fracture behaviour of this material has only sometimes been clarified. The objective of this paper is to study the effect of the thickness of the sample as well as the loading rate on the formation of shear lips for aluminium 6061. To find out whether shear lips occur on the fracture surface of aluminium 6061, a three-point bending test was performed on a Single Edge Notched Bending (SENB) specimen. Analysis has been made to determine the shear lips ratio dependence on specimen thickness and loading rate. Based on the result of the analysis, the shear lips ratio decreases as the specimen's thickness increases. Besides that, the shear lips ratio decreases as the loading rates increases. A high loading rate and specimen thickness resulted in low plasticity behaviour because the stress states are in plane strain conditions where the formation of shear lips is minimum. From the three-point bending test, a good agreement of data gains from the dependency of shear lips ratio on specimen thickness and loading rates. Overall, aluminium 6061 is fractured in a ductile manner with significant shear lips formation.

Keywords: Al6061, three-point bending, shear lips, loading rates, thickness

1. Introduction

Aluminium alloys are often employed in the engineering sectors related to transportation, building, and other commercial uses. Different parts of the automotive car body are manufactured using other aluminium alloys. The car body, lighting frames, different engine parts and many more are some examples of applications of aluminium alloys. They possess excellent mechanical properties, which allow them to be machined rapidly and economically [1].

6061 aluminium alloy (Al6061) is famous for its requirements of medium to high strength, good toughness, and excellent corrosion resistance. It is also a lightweight alloy with high strength relative to its weight [2]. Al6061 is a hardened aluminium alloy that contains magnesium and silicon elements of significant alloys. Aluminium 6061 is one of the most versatile heat-treated alloys, which contains magnesium and silicon as major elements [3]. 6061-T6511 aluminium is furnished in the T6511 temper process of heat treatment. The metal is solution heat-treated, undergone stress relief, and artificial ageing to produce this temper [4]. Although 6061 alloys are more workable and better for welding than other alloys, they have a different high strength and stress resistance than 7075 [5]. For instance, 6061 aluminium alloy contains more miniature zinc than its 7075 counterparts.

The aluminium 6061 alloy has the highest elasticity and strength with excellent machinability. Hence, it is believed that large plastic deformation will occur at the crack tip of the fractured body. However, the size of plastic deformation

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*Corresponding author: mazhar@uthm.edu.my at the crack tip, known as shear lips formation, depends on the thickness of the specimen. The loading rates also affect shear lips formation [6]. Hence, investigating the shear lips formation on different thicknesses and loading rates of fracture bodies is beneficial in identifying the material's ductility.

Understanding the fracture behaviour of Al6061 alloy under dynamic loading rates is essential. The objective of this paper is to study the effect of the thickness of the sample as well as the loading rate on the formation of shear lips for aluminium 6061. At the end of the study, enough literature will help to understand the fracture behaviour of the Al6061 alloy under dynamic loading rates. This research will provide enough data to understand the application of Al6061 for the automobile body structure application.

2. Materials and Methods

Al6061 is the material that was utilised in this investigation. table 1 contains a list of the chemical compositions. To conduct the three-point bending test, 12 SENB specimens were prepared in four groups with different dimensions, 10x10x50 mm^3, 10x15x50 mm^3, 10x20x50 mm^3, and 10x25x50 mm^3. Each group consists of three specimens to conduct the test under three different loading rates, as shown in table 2. Pre-notch was made in single edge notch bending (SENB) specimen with a notch length (a) reaching 0.45 ~ 0.55 of specimen width (W). The specimens were prepared as per ASTM E399 using Computerised Numerical Control (CNC) Wire-Cut Electric Discharge Machine (EDM).

Table 1 - Chemical composition of Al6061 [6]

Element	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Wt.%	0.66	0.2	0.32	0.06	1.08	0.14	0.04	0.03	Remainder

Table 2 - The specimen's geometries and testing conditions

S. No:	Specimen Dimension (mm)	Thickness, B (mm)	Loading Rate (mm/s)
1	10 x 10 x 50	10	20
2			40
3			60
4	10 x 15 x 50	15	20
5			40
6			60
7	10 x 20 x 50	20	20
8			40
9			60
10	10 x 25 x 50	25	20
11			40
12			60

A three-point bending test was conducted in the lab's air conditioning. The three-point bending test configuration is shown in Fig. 1. For this investigation, three different loading rates of 20, 40, and 60 mm/min were applied to each set of specimens. In order to perform the three-point bending test, the universal testing machine (UTM) was used. The optical microscope (OM) was used to observe the fracture surface and measure the size of the shear lips. The average area of the shear lips on both sides was divided by the specimen thickness to estimate the shear lips ratio. The formula for the shear lips ratio's calculation is shown below in equation (1).

$$Shear\ lips\ ratio = \frac{\sum A_{average}}{Thickness} \times 100\% \qquad (1)$$

Where, $A_{average} = \frac{left\ shear\ lips\ area + right\ shear\ lips\ area}{2}$ and Thickness = Thickness of specimen (B).

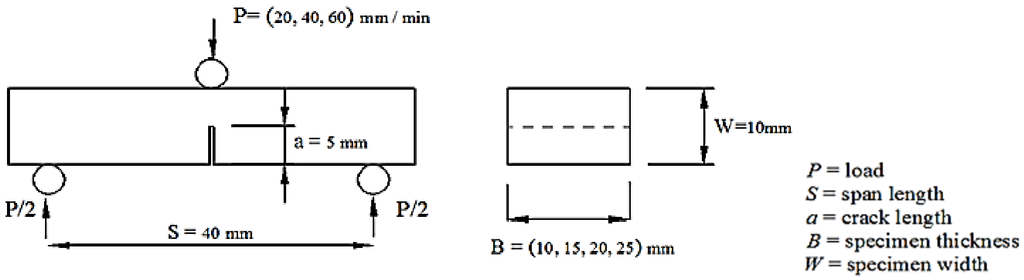


Fig. 1 - Three-point bending test configuration

3. Results and Discussion

The fracture properties of the maximum load (P_{max}) and shear lips ratio were determined after performing the three-point bending test on an Al6061 alloy specimen at three different loading rates of 20 mm/min, 40 mm/min, and 60 mm/min. In the meantime, the effect of loading rate and specimen thickness on the fracture behaviour of Al6061 alloy was investigated. The results were obtained as listed in table 3.

Table 3 - Results of tests and calculations

Load rate, mm/min	Thickness, mm	Shear lips ratio (SLR), %	P_{max}, N
20	10	38.345	2423.44
	15	27.910	3735.31
	20	18.605	5167.81
	25	15.540	6468.13
40	10	35.294	2552.50
	15	24.688	3827.50
	20	17.648	5271.88
	25	14.564	7096.25
60	10	32.446	2724.06
	15	22.392	3812.81
	20	17.192	5343.13
	25	13.316	7092.81

3.1 Effect of Specimen's Thickness on Maximum Load

The maximum loads, P_{max} of Al6061 alloy, were measured and shown in table 3. It was found that the P_{max} of Al6061 alloy increased by increasing the thickness of the specimen. The result in table 3 shows that the thickness of 25 mm was the highest peak compared to 20 mm, 15 mm, and 10 mm. Fig. 2 represents the relationship between load and displacement at a load rate of 20 mm/min. The explanation is that increasing the thickness of the specimen leads to expanding the section area and therefore needs higher energy to fracture it. M. A. Daud et al. found that the P_{max} of AZ61 magnesium alloy was raised at the increasing thickness of the specimen [7].

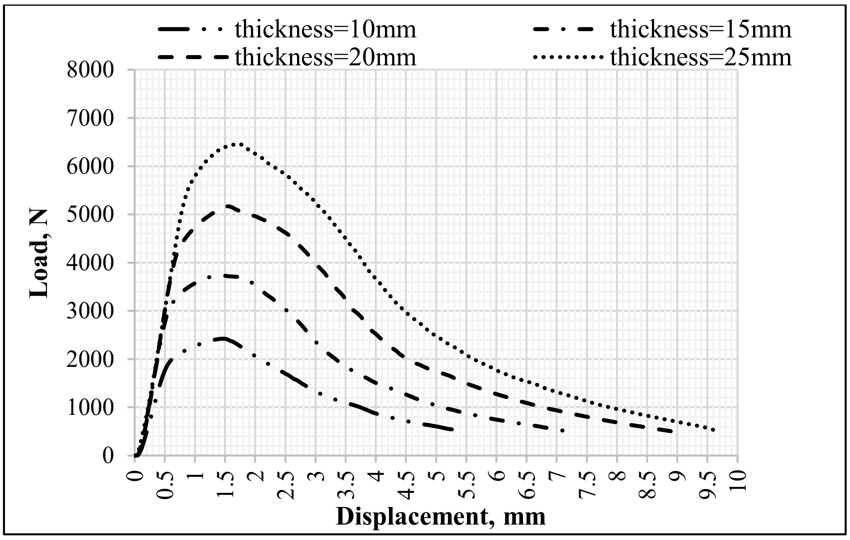


Fig. 2 - Graph of load vs displacement for 20 mm/min loading rate

3.2 Effect Loading Rate on Maximum Load

Fig. 3 represents the relationship between load and displacement at 20 mm/min, 40 mm/min and 60 mm/min load rates for 10 mm specimen thickness. The maximum loads (P_{max}) of Al6061 alloy were also measured from the curves and shown in table 3. The P_{max} of Al6061 alloy increased at an increasing loading rate. Similar findings were reported by Joyce, who found that for A106 steel, P_{max} at a high loading rate was larger than P_{max} at a static loading rate [8]. Li et al. noted that twining increased at a high loading rate in another investigation [9].

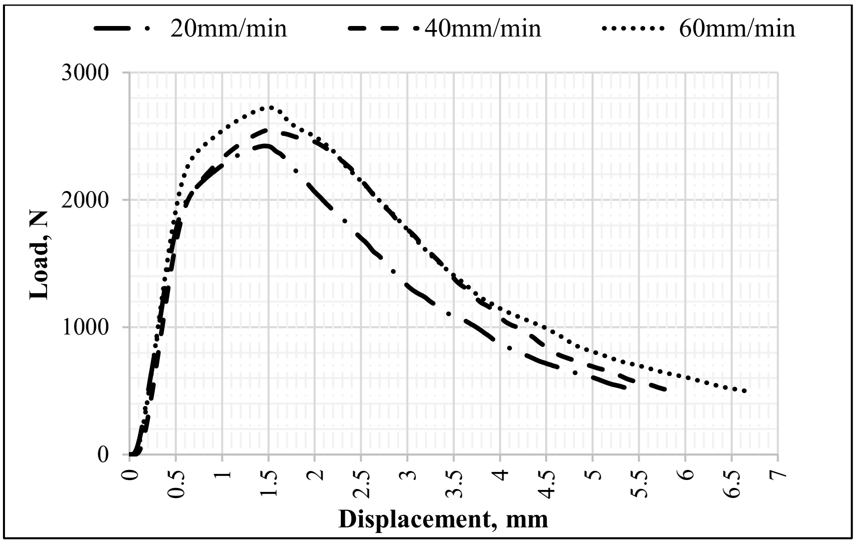


Fig. 3 - Graph of load vs displacement for 10 mm specimen thickness

3.3 Effect Loading Rate on Shear Lips Ratio

As shown in Fig. 4, the shear lips ratio dropped as the loading rates grew. A high loading rate results in low plasticity behaviour because it has the shortest time to undergo plastic deformation [5]. The Aluminium 6061 specimens were in-plane stress condition as they had a ductile manner and underwent plastic deformation. Latif et al. investigated the shear lip formation at different loading rates for magnesium alloys and found out the shear lips ratio decreased as the loading rates increased [10].

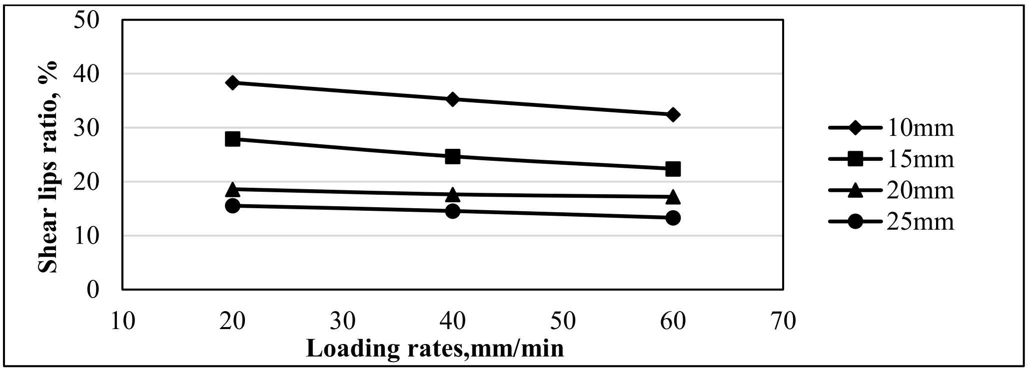


Fig. 4 - Graph of shear lips ratio vs loading rates

3.4 Effect of Specimen's Thickness on Shear Lips Ratio

As shown in Fig. 5, the relationship between the thickness of the specimen and the shear lip ratio has been plotted. This indicates that as the thickness increases, the shear lips ratio decreases. This means that any increase in the thickness of the specimen leads to reduced plasticity behaviour of the metal in fracture. Daud et al. investigated the shear lip formation at different thicknesses for AZ61 magnesium alloys and found that the shear lip ratio decreased when the thickness of the sample increased [7].

3.5 Fracture Surface Observation

Fig. 6 represents the overview of the fracture surface of Al6061 alloy specimens. As shown in Fig. 6, the increase in thickness of the specimen leads to a decrease in shear lips ratio when comparing the thickness of sample 10 mm and the thickness of sample 25 mm, as the minimum and maximum thickness in this investigation, respectively. Also, when comparing the different loading rates on the specimen, the loading rate increases, leading to a decrease in the shear lips ratio. Fig. 7 shows the samples tested under a 20 mm/min load rate. The results showed that the surface of the sample thickness of 10 mm was relatively rough, with many ductile dimples relative to other samples of higher thickness. It is clear that the greater the thickness of the sample, the closer to an elasticity state at the fracture. This supports the results obtained by calculating the shear lips ratio for each sample.

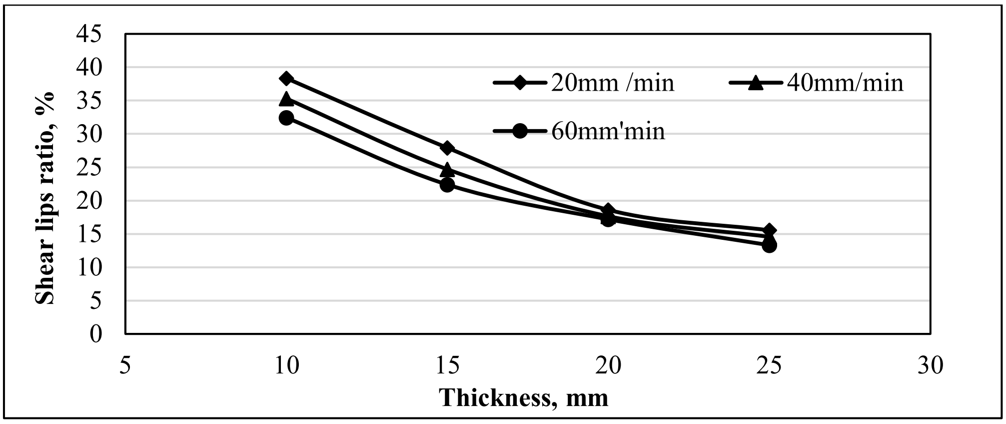
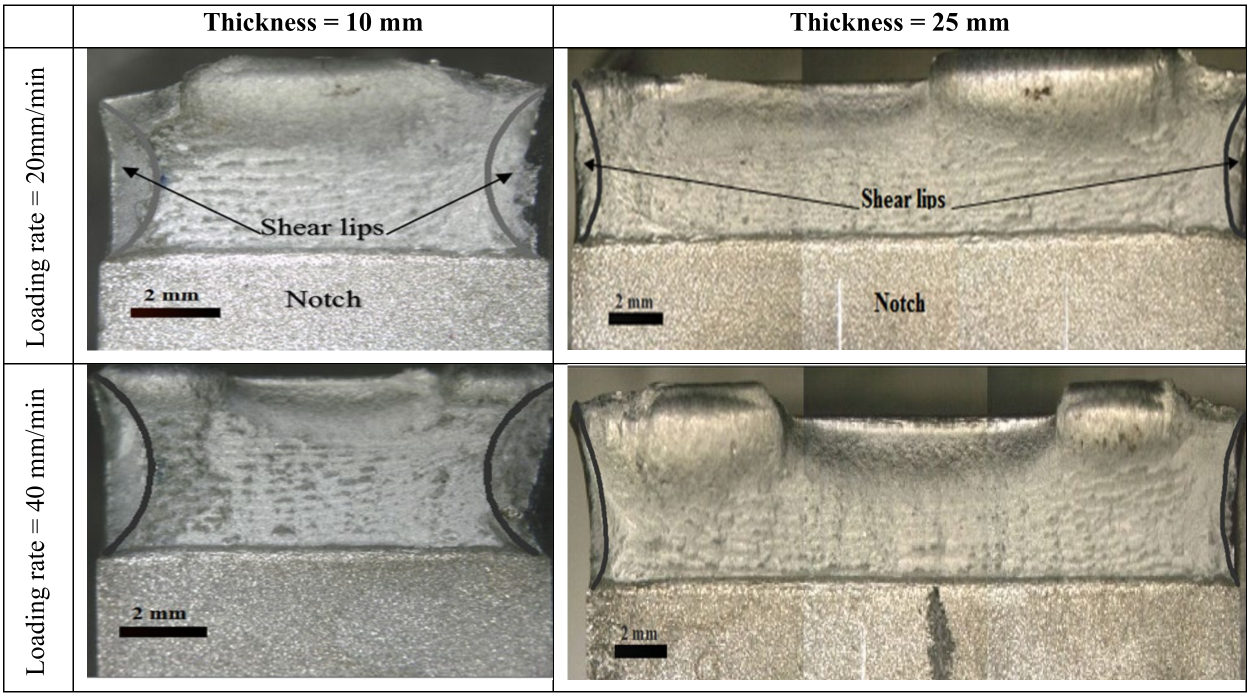


Fig. 5 - Graph of shear lips ratio vs thickness



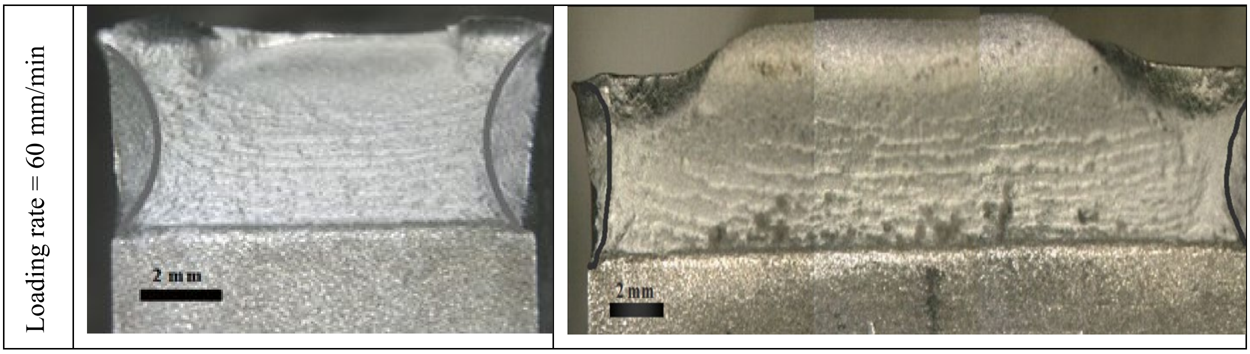
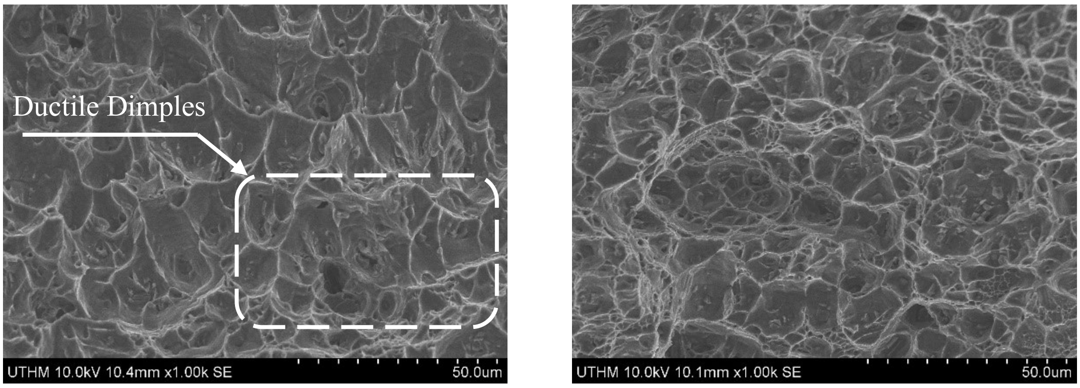
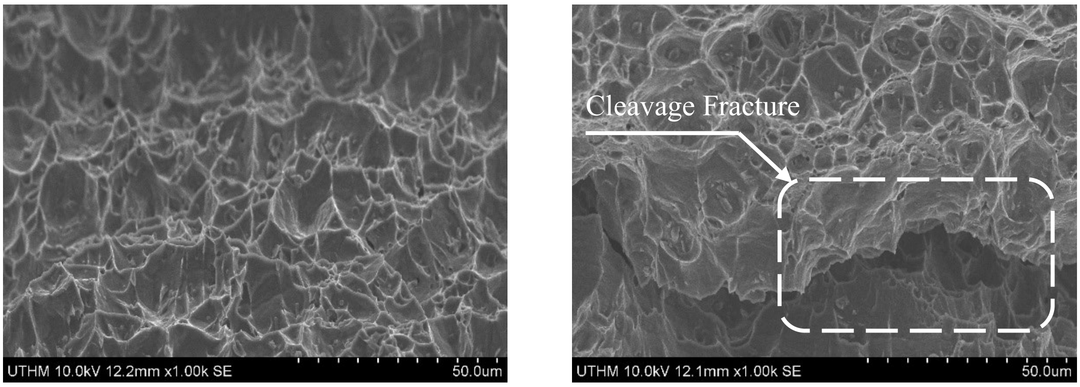


Fig. 6 - Overview of the fracture surface of Al6061

Fig. 7 represents the fracture surface of specimens with a thickness of 10 mm, 15 mm, 20 mm, and 25 mm, fractured using a 20 mm/min loading rate, observed by scanning electron microscopy (SEM). The fracture surface of 10 mm thickness in Fig.7 (a) is compared to the fracture surface of the 25 mm thickness sample in Fig. 7 (d). Different fracture pattern was found on both fracture surfaces. The 10 mm thickness specimen indicated slightly higher ductile fracture behaviour than the 25mm thickness at a 20 mm/min loading rate. Daud et al. compared the fracture surface of the 8 mm thickness sample to the 2 mm fracture surface of the AZ61 magnesium alloy. The fracture surface of an 8 mm thick sample was dominated by a cleavage fracture surface connected to a river pattern. This demonstrates that there was little plastic deformation, and the sample failed in a brittle way. The sample fracture is confirmed by a tiny ratio of shear lip area under plane strain circumstances [7].



(a) Thickness = 10 mm (b) Thickness = 15 mm



(c) Thickness = 20 mm (d) Thickness = 25 mm

Fig. 7 - Using a 20 mm/min loading rate, a fracture surface was seen using SEM in the centre of the tested samples

4. Conclusion

Bending tests have been conducted with a three-point bending configuration, where the effect of loading rate and thickness of specimens were investigated. All the data indicate that the behaviour of the fracture of the aluminium under all the parameters was a fracture in ductile mode. It was found that there was a relationship between the shear lips ratio and the thickness of the specimen. The increase in thickness of the sample led to a decrease in the shear lips ratio. Also, the rise in load rates led to a reduction in the shear lips ratio. In all cases, the shear lips ratio was higher than 10%. The aluminium 6061 underwent a plastic deformation condition before fracture.

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