Critical J-Integral of Thin Aluminium Sheets Employing a Modified Single Edge Plate Specimen

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ABSTRACT

A new kind of specimen geometry, modified single-edge crack specimen - is designed to determine fracture toughness (critical J-Integral) of a crack in thin plates of aluminum alloy 6061-T6, such that the line joining the centers of the load-points passes through the crack-tip. In this specimen geometry, high stress concentration at the crack-tip is generated with minimum chances of buckling of any part of the specimen. An experimental-cum-numerical methodology is developed in which the critical load is obtained from an experiment, and the stress field is determined in the specimen, through a finite element analysis. The stress field yields the critical J- Integral (J_c). The fracture toughness of thin aluminum 6061-T6 sheets is found to be much higher than the plane strain toughness.

Keywords - **Fracture toughness, J- Integral, modified single edge crack specimen, thin plates.**

I. INTRODUCTION

Thin sheets of metals have wide applications such as in aircrafts, pressure vessels, ship building, bridges, ground vehicles, etc. The fracture toughness of thin sheets in Mode I is known to be substantially higher than the plane strain toughness of thick sheets and, therefore, its value is more relevant for many applications. In thick plates of ductile materials, where there is a large plastic zone near the crack tip, their fracture toughness is often characterized with the critical J-integral (J_{Ic}). However, it is difficult to determine the fracture toughness of thin sheets as their specimen tends to buckle during testing.

There are several techniques available in the literature to determine fracture toughness (i.e. J_c) of thin plates. Several studies have been made on double edge notched tensile (DENT) specimen to determine fracture toughness of thin plates.

Investigations have been developed for both sub critical crack extension and final fracture of thin walled geometries. In [1,2] experiments are conducted to study the effect of thickness on the critical values of J integral and CTOD (J_c and δ_c) of aluminum thin plates of 1-6 mm thickness using double edge notched tension (DENT) specimens. The work required to fracture the ligament of DENT specimen is partitioned in two components, the first component is called the essential work of fracture and second component as non-essential work of fracture caused due to necking. Their research showed that with increase in thickness J_c and δ_c increases linearly for thinner specimens and nonlinearly for larger thicknesses. They attended almost same results by testing sixteen different alloys of aluminum, brass, stainless steel, bronze, Zinc and lead [3]. Investigations are done on the fracture toughness of thin DENT specimens made up of copper foils with thickness ranging from 0.02 to 1 mm using an improved digital speckle correlation method (DSCM). The results showed that J_c increases with increasing thickness upto 0.3 mm and there after it decreases for both specimens, prepared in rolling and transverse directions [4]. A brief overview of the existing methods for simulating stable crack extension and failure, including the research in fatigue and fracture of thin- walled structures over the past decades [5].

In a DENT specimens used by several investigators, the tensile load in the un-cracked ligament is high and it tends to make the specimen fail in localised yielding and thus stress concentration due to the crack tip is subdued which leads to necking formation at crack tip and, thereby, it suppresses the crack propagation. Consequently, it becomes difficult to isolate the fracture toughness from such a test.

Over the years, J integral is determined using a single edge notched compact tension (CT) specimen applying combined bending and tension load [6-8]. In [6], the J-Integral is evaluated for single edge notched (SEN) specimen under bending and tension, both in terms of loads and displacements and as the original path independent integral. An expression for determining J-Integral from the load displacement record of SEN specimen is given and the result is compared with other analytical expressions and with FE calculations [7]. In the middle-cracked tension specimens of different geometry, experimental data on steady state tearing (SST) are examined with the use of global parameters characterizing the mechanical behavior of a moving crack tip embedded into a fully developed moving neck [8]. If a compact tension specimen is employed, guide plates, one on the side of each face of the specimen, are required to avoid buckling of the thin specimen [9]. This makes the technique cumbersome and there is always a doubt on the role of friction between guides and the specimen.

The aim of the present study is to develop a simple and effective specimen geometry to determine the fracture toughness (i.e critical J-Integral (J_c)) of thin sheets of aluminum 6061-T6. A single-edge crack specimen is modified in such a way that the line joining the centers of the loading points passes through the crack-tip. This maintains high stress concentration at the crack-tip with reduced chances of buckling along the crack front. In this experimental-cum-numerical technique, the critical load was obtained from experiment. The numerical analysis determined the stress field in the specimen by employing the nonlinear stress-strain behavior of monotonic loading of the specimen material. This stress field is used to determine critical J-Integral.

II. SPECIMEN
Thin sheet of thickness ranging from 0.7 to 2.0 mm is the prevalent and extensively used vehicle construction material. This investigation is focused on evaluating critical J-Integral (J_c) of thin plates of aluminum alloy 6061-T6. As per the availability of material in the market, the specimen thicknesses were chosen as 1.0 mm and 1.6 mm.

Tensile test of these materials were conducted to determine elastic-plastic properties as per ASTM-E8 [10]. The specimens were tested under plane stress conditions using a 100 KN Universal Testing Machine. The cross-head speed was chosen to be very slow, 0.1 mm/min. Fig. 1 shows the stress-strain behavior of 1.6 mm thick sheet of aluminum alloy 6061-T6. The stress-strain behavior of 1.0 mm thick sheet of aluminum alloy 6061-T6 was similar.
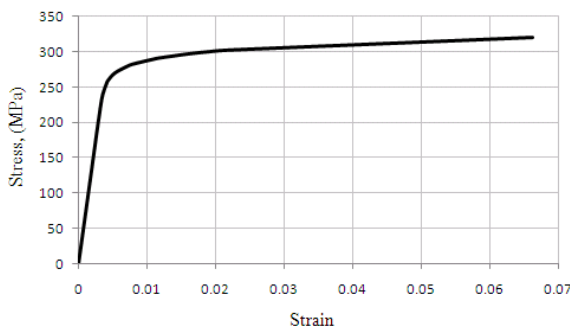

Figure 1: Stress-strain curve of aluminum 6061-T6 with thickness of 1.6 mm

The material behavior was found to follow Ramberg-Osgood relation, as given in equation (1):

$$\frac{\varepsilon}{\varepsilon_o} = \frac{\sigma}{\sigma_o} + \alpha \left(\frac{\sigma}{\sigma_o}\right)^n \qquad (1)$$

where α is a coefficient and n is an exponent of the power hardening material, σ_o and ε_o are the flow stress and flow strain, respectively. α and n are found by fitting the curve of the Ramberg-Osgood equation on the original stress-strain

curve [11] and they are listed in Table 1 along with other experimentally obtained material properties.

While designing the specimen of the thin aluminum alloy sheets, a very approximate estimation was made. The plastic zone size (r_p) was estimated using the following Irwin's formula [12] for plane stress (2):

$$r_p = \frac{1}{\pi}\left(\frac{K_c^2}{\sigma_{ys}^2}\right) \qquad (2)$$

where K_c is the critical stress intensity factor and σ_{ys} is the yield stress. When available value of toughness of aluminum alloy is used for plane stain as K_{Ic} = 25 Mpa√m, r_p was found to be 2.6 mm. The actual plastic zone size is much larger as the toughness of the thin sheets, determined through this investigation, was found to be much greater than plane strain toughness. Thus the specimens of this study were definitely loaded in plane stress.

Table 1: Mechanical properties of aluminum alloy 6061-T6 specimens tested as per ASTM-E8

Sheet thickness	Young's modulus (GPa)	Yield stress (MPa)	Ultimate strength (MPa)	n	α
1.6 mm thick	69.8 ± 1.5	277.6 ± 8.3	319.8 ± 16.2	22	67.73x10⁻⁶
1.0 mm thick	70.4 ± 1.5	267 ± 5.3	294.9 ± 2	32.19	52.39x10⁻³

Preliminary experiments were conducted on symmetric DENT specimens made from the aluminum alloy 6061-T6. It was found that the tensile load in the un-cracked ligament was high and the specimen failed predominantly in yielding. In fact, the necking was found to form on the entire length of the un-cracked ligament of the specimen. The stress concentration due to the crack tip was not high enough for the crack to grow before the material yielded. Consequently, it became difficult to isolate the fracture toughness from such a test. Thus DENT specimen geometry was found to be inappropriate for fracture toughness testing of thin sheet aluminum alloy 6061-T6.

A new single edge crack specimen geometry was developed to suppress yielding of un-cracked ligament and enhance the chances of failure through fracture growth. In a DENT specimen, the un-cracked ligament is primarily subjected to tensile stresses caused by the external load. On the other hand, in a single-notch specimen, there is a superposition of two loads, bending moment because the specimen is not symmetric and tensile due to external pulling load. The bending moment develops high stress concentration at the crack tip but at the same time high compressive stresses are usually generated in the region far away from the crack tip. These compressive stresses may

cause the buckling of the thin specimen which should not be allowed so as to facilitate two dimensional analysis of the specimen. However, the tensile load suppresses the compressive stresses. In a conventional single-edge specimen, load P is applied at the mid-thickness; d = W/2, as shown in Fig. 2.
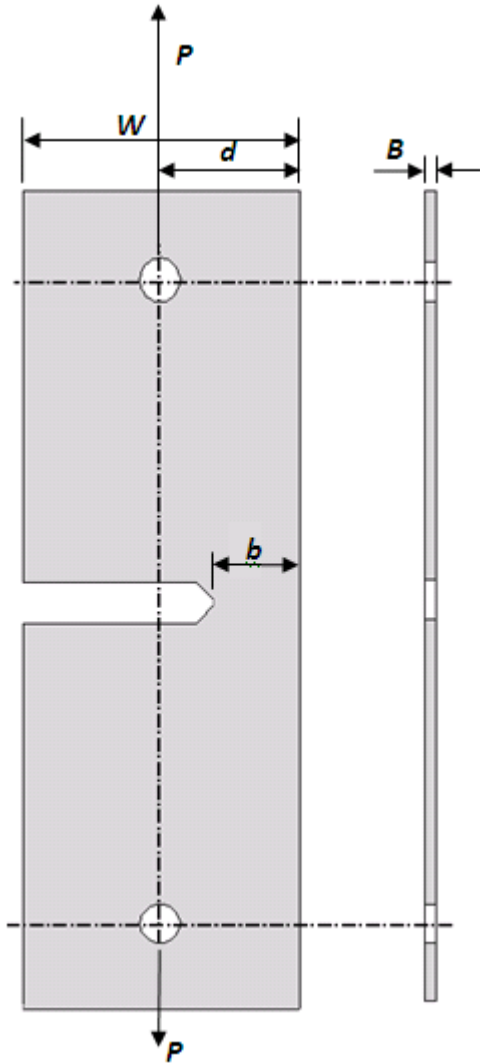

Figure 2: Modified single-edge crack specimen

However, it was felt that the conventional single-edge specimen might not be appropriate specimen configuration. The load distance, d, should be chosen appropriately. Thus, preliminary numerical simulations were carried out to determine distance d of the load point: The case d = b was chosen because, high compressive stresses were not generated in the specimen and the specimen was unlikely to buckle. However, during experiment, close attention was paid to assure that buckling was not taking place.

        Fig. 3 presents the geometry of the specimen. The specimens of size 190 mm × 60 mm, were cut on a conventional milling machine.
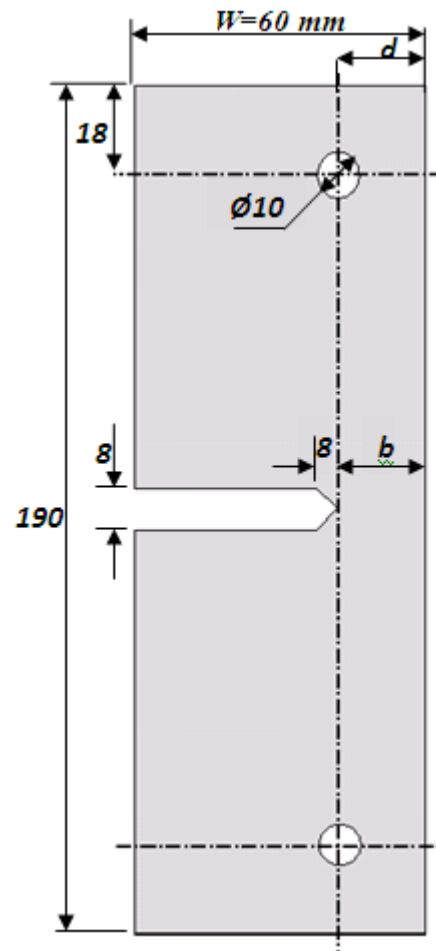

Figure 3: Geometry of Modified Single-edge crack specimen.

To minimize the distortion of the specimen plate while preparing the dimensions, five specimen plates were bonded together using double stick tapes, to make a reasonable thick stack. The crack dimensions (Figure 3) of the specimens are achieved by cutting a slot from the milled stack of specimens, with the help of a wire-EDM machine. The tip of the crack, prepared through a wire-EDM machine, was not sharp enough. It was required to be extended to obtain a sharp initial pre-crack. A suitable fixture was developed to hold a fresh razor blade and apply a reasonable large force to make crack tip very sharp. The crack was extended by about 2 mm. The radius of curvature at crack tip was monitored through a shadow-graph (LEICA) and was found to be of the order of 12μm. Pardoen T et al. (1999) also used the similar technique to sharpen a crack. The single-edge crack, cut in the specimens were such that the propagation of the crack was perpendicular to the rolling direction; that is, the tensile load was applied along the rolling direction during testing. Experimental tests were performed by varying the un-cracked ligament length, b, for both kinds of the aluminum alloy sheets.

III. EXPERIMENTAL-CUM NUMERICAL TECHNIQUE

Experimental tests were performed on the modified single-edge crack specimens, by pulling the specimen in a 10-ton Universal Testing Machine at the very slow speed of 0.1 mm/min as shown in Fig. 4. The detection of crack initiation was done by closely monitoring the crack-tip with the help of magnifying glass and simultaneously observing the run-time load-displacement curve. It was found that the crack grew suddenly and the load started dropping at the same time. Thus, the load-displacement curve yields the critical load. The critical load obtained from experiments was used as loading boundary conditions in a nonlinear numerical analysis to obtain stress-strain fields.

In this study, a two-dimensional, plane stress, numerical analysis of the modified single-edge crack specimen was done using software package ANSYS 10.0. PLANE82 element was used for this fracture mechanics analysis. PLANE82 is an 8-noded element and is able to account for plasticity, creep, swelling, stress stiffening, large deflection and large strain. Because of the symmetry of the specimen with respect to the crack plane, only half specimen was modeled for the analysis.
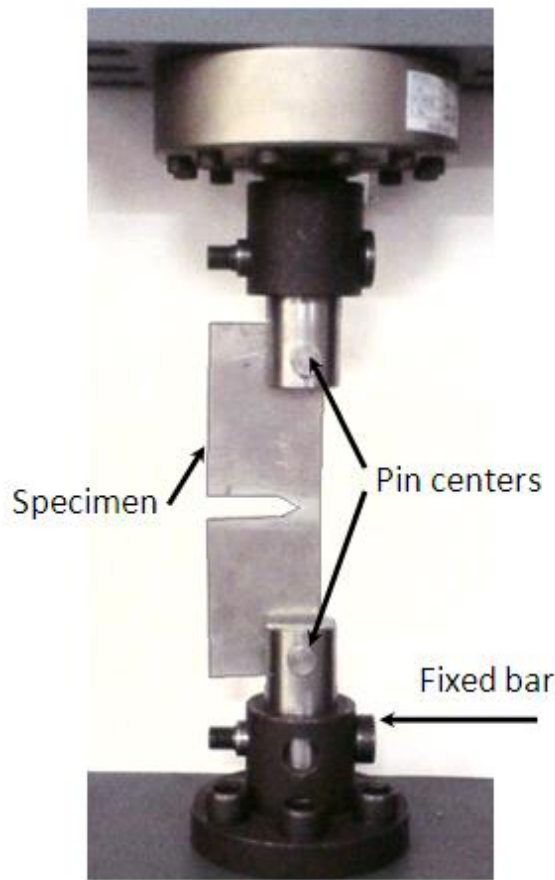

Figure 4: A Photograph of the Experimental set-up with a specimen loaded in a UTM.

The crack-tip was modeled by converting the quadrilateral iso-parametric element (PLANE82) in to a special element with mid-side nodes moved to the quarter points, called quarter-point element[13]. The load on the specimen was applied on a mass-less element at the pin center of the hole which gets equally distributed on all the nodes along the circumference of the hole by defining a rigid-region.

In the numerical analysis, the material non-linearity was accounted for by inputting the experimental stress-strain data of the material, presented in section 2. However, only monotonically increasing loading was considered to determine J-Integral. The results obtained from the converged nonlinear analysis were used to calculate the fracture parameter, J-Integral, by a subroutine written in ANSYS's scripting language.

IV. RESULTS AND DISCUSSION

Five specimens were tested for each thickness 'B' (1.0 mm and 1.6 mm) and the un-cracked ligament length 'b' (10 mm, 16 mm & 20 mm). It was found that in the thin plate of aluminum alloy 6061-T6, significant plastic deformation took place prior the crack growth at the region close to the crack-tip. A dimple was formed prior to the crack growth on each face of the specimen as shown in Fig. 5 (a). The 'V' formed by the tangents to the upper and lower edges of the dimple at the crack-tip had an included angle of $64^{o} \pm 7^{o}$. At the critical load the crack grew suddenly along one of the two edges of the dimple as shown in Fig. 5 (b), and the load on the specimen started dropping. If the crack initiated along the upper edge of the dimple on the front surface, the crack moved inside the material at an angle in such a way that it comes out along the lower edge of the dimple on the rear surface.
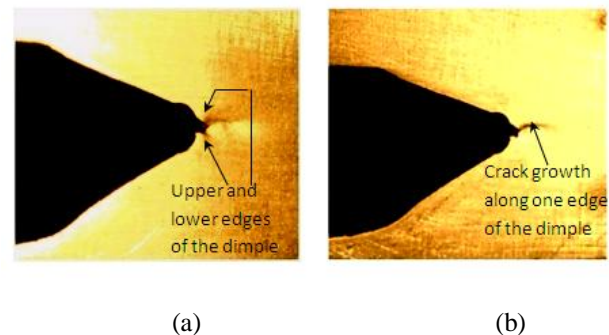

(a)   (b)

Figure 5: A Photograph of the specimen just before crack initiation (a); and after crack initiation (b).

Table 2 shows the average critical load obtained from the experiments on all five specimens of each size. Fig. 6 shows a typical experimental load vs. load-point displacement plots for a 1.6 mm thick specimen with un-cracked ligament length b = 16 mm.

Table 2: Experimental observations of the critical load of all specimen geometries

Specimen thickness B (mm)	Un-cracked ligament length b (mm)	Critical load for five samples of each specimen (N)				
1.6	10	3001	2799	2947	2900	2893
1.6	16	3912	4010	3925	3921	3607
1.6	20	4733	4655	4475	4669	4620
1.0	10	1748	1780	1862	1693	1862
1.0	16	2300	2336	2374	2186	2155
1.0	20	2727	2773	3006	2763	2716

The J-Integral, computed by the sub-routine was found to be independent of the paths   except when the path chosen was close to crack tip or the free surface of the specimen.
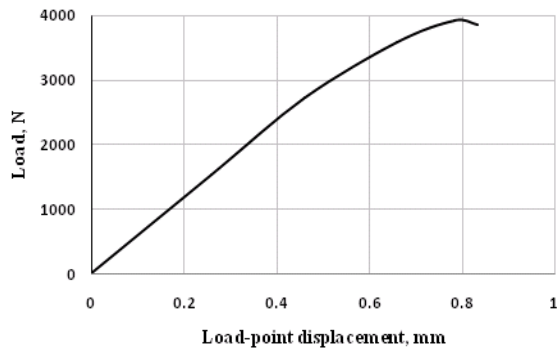

Figure 6: Load versus the load-point deflection curve for specimen with B = 1.6 mm and b = 16 mm.

Fig. 7 presents the critical J-Integral for 1.6 mm and 1.0 mm thick sheets of aluminum alloy 6061-T6 with varying un-cracked ligament. The J_c values obtained for thickness of 1.6 mm with varying un-cracked ligament length b were found to be consistent with b as 10, 16 and 20 mm. Pardoen T. et al. (1999) have observed that the fracture toughness does not depend much on the ligament length for DENT geometry. The average value of J_c obtained for B = 1.6 mm was 121 kJ/m^2.
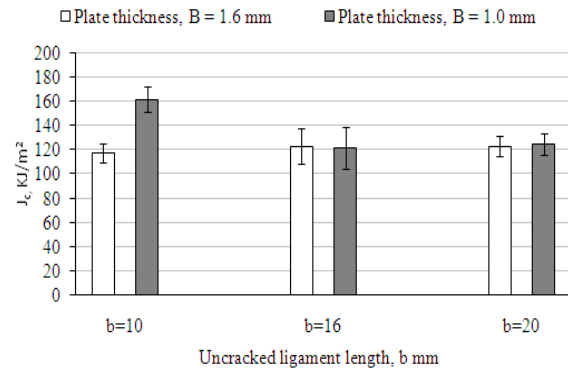

Figure 7: Variation of J_c with varying b for B = 1.6 mm and B = 1.0 mm.

In case of the thinner aluminum alloy 6061-T6 sheets of 1.0 mm thickness, J_c ($\approx$ 120 kJ/m^2) determined for the specimen of higher un-cracked ligament b (16 mm and 20 mm) was same as J_c of thicker specimen of 1.6 mm thickness. However, the J_c of smallest b = 10 mm, was found to be 160 KJ/m^2 which is significantly higher. The reason for this difference is still not understood. The experiment was carefully monitored to check whether buckling close to the free edge was taking place. No visible sign of buckling was observed. It needs further exploration to identify the reasons for higher value of J_c for b=10 mm cases of 1.0 mm thick aluminum sheet.

The investigators of this study are not aware of any study that has obtained J_c of thin sheets of aluminum alloy 6061-T6. However, data on aluminum alloy 7075-T6 is available (Zerbst U. et al. 2009).

Fig. 8 shows the J_c obtained in this study on the results of aluminum alloy 7075-T6. The higher value of J_c for B= 1.0 mm and b= 10 mm is not included in J_c of thin sheets. It is worth noting here that J_{Ic} of plane strain specimens of aluminum alloy 6061-T6 is much smaller, about 12 KJ/m^2 only. It is thus important to develop a technique to determine toughness of thin sheets.
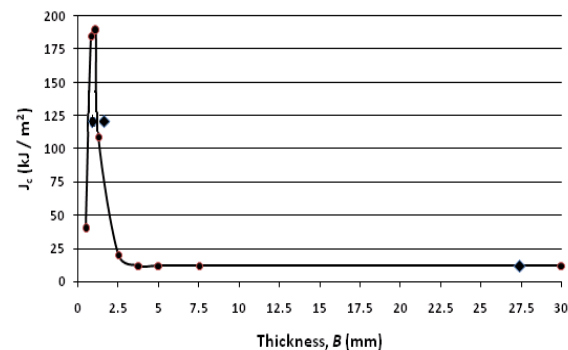

Figure 8: Variation of fracture toughness with respect to thickness as observed by Zerbst U. et al. for aluminum 7075-T6 and by this study for aluminum 6061-T6.

V. CONCLUSIONS

A modified single-edge crack specimen was designed to evaluate the fracture toughness (J_c) of crack thin sheets made of aluminium alloy: 6061-T6 with thicknesses 'B' of 1.6 mm and 1.0 mm. The geometry developed in this study is such that the line joining the centers of the loading points passes through the crack-tip (i.e d=b). This maintains high stress concentration at the crack-tip with reduced buckling along the crack front. The crack-tip was sharpened by applying controlled force on the fresh razor blade. The stress-strain curves of the specimen material aluminium 6061-T6 showed power hardening material behavior with strain hardening. An experimental-cum-numerical technique was used in which data (critical loads) was extracted from experiments and then the data was used to perform numerical analysis which was post-processed to evaluate the fracture toughness (J_c). Experiments were performed by pulling the specimens in a 10-ton Universal Testing Machine at a speed of 0.1 mm/min. The detection of crack initiation was done by closely monitoring the growth of the crack-tip and the run-time load-displacement curve. In this study, it was found that the crack-tip grows suddenly and the load on the specimen starts dropping. The critical load thus obtained from the experiments was used as loading boundary conditions in numerical analysis to obtain stress-strain field in the specimen by employing the nonlinear stress-strain behavior of monotonic loading of the specimen material. This field is further used to determine critical J-Integral (J_c) with the help of a ANSYS.

The average value of critical J-Integral (J_c) obtained from the experimental-cum-numerical technique for thickness 'B' of 1.6 mm was 121kJ/m^2. The values are found to be consistent for un-cracked ligament lengths 'b' of 10, 16 and 20 mm for the modified single-edge crack specimen used in this study. The fracture toughness values were found to be less consistent with respect to varying 'b' for thickness of 1.0 mm, as compared to 1.6 mm. The average value of J_c was found to be 135.9 kJ/m^2 for 1.0 mm thick plate.

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