Influence of Fracture in Sheet Metal Cutting

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Abstract

Sheet metal cutting employs less force as compared to shear force for cutting if cutting process is initiated by a crack. As the cutting process starts from the crack at the edge of the sheet metal, the fracture mechanics dominates and helps in sheet cutting operation by utilizing low energy. The present study substantiates this theory. Metal sheets of aluminium, zinc and mild steel of thicknesses 0.5mm, 1mm and 1.5 mm were cut by scissors using hand force. The cutting process is in tear mode as the cutting was done by scissors. The force of cutting overcomes the fracture toughness of the material. The cutting force requirement and the fracture toughness increase as the line of cut is shifted away from the free edge of the sheet. The increase of force is attributed to counter the higher surface energy forces of the higher surface area to be separated as point of cut moves away from free edge; the surface energy is due to the atomic bonding. In cutting, the off cut curls because of the point of cut or crack lies in the plastic zone. The thin sheets of 0.5 mm have higher stress intensity factor and is tougher than thick sheets of 1 and 1.5 mm. Beyond 20mm distance from the free edge toughness increases at higher rate.
Keyword: Fracture Toughness, Sheet Metal Cutting, Stress Intensity Factor, Fracture Mechanics

Introduction

Sheet metal cutting process is widely used in industry but got less attention for the investigation of the mechanism of cutting. The research in this area has revealed that it is not the shear force but the fracture mechanics that dominates and helps in the cutting operation using low energy as the cutting process starts from the edge of the sheet metal. With simple calculations it can be ascertained that the amount of force required to cut a width of a thin piece of sheet metal in one go by a blade in shear mode is much higher than if the sheet metal is cut from the edge in tear mode as will be presented in this paper.

The shearing process in sheet cutting is considered to involve plastic indentation, formation and propagation of localization zones, void nucleation, growth and coalescence, and crack initiation and propagation [1].

In sheet cutting, the force required is the sum of force to cope with fracture toughness and the force required for plastic bending [1]. A pointed tool when used to pierce through a clamped sheet cut a triangular piece as a tongue which curled that is cutting resulted in simultaneous bending of the cut part [1]. The cutting process starts with the elastoplastic flow of material at the cutting line followed by the fracture [1,2].Researchers are trying to simulate the sheet cutting process and trying to form mathematical models based on different damage models.The damage models have been proposed by Husson, Ayada, Oyane, Rice and Tracey, Mclintock, Cockroft/Latham, Lemaitre, Gurson/Needleman and Tvergaard [3,4]. Based on the damage evolution model proposed by Le Maitre the experimental results on blanking process agree well with the simulation model [2]. The cutting process involves a large number of nonlinearities with large displacements and large deformations; further nonlinearities are due to material behavior such as plasticity and damage. To address this, a large time increment simulation model using elastoplastic damage model has been proposed [5]. The large displacement case of guillotining and slitting sheet metal has been dealt with by finite element based on a mixed Arbitrary Lagrangian -Eulerian formulation [6]. In guillotine or scissors like cutting, the total work performed is composed of two components i.e., (i) work of separating the surfaces that is related to fracture toughness of the material and (ii) work of friction of blade against the work material [7,8,9].

Experimental setup

Figure 1 shows the experimental setup which is quite simple. A pair of scissors was used to cut by manual force thin sheets of Aluminum, Zinc and, Mild Steel each with thicknesses of 0.5mm, 1.0mm and 1.5mm. One hand of the scissors was clamped in a vice while on the other hand the force was applied by hand to cut the sheets. The measurement of the force was simplified by using a calibrated weight balance. The surface of the weight balance was pressed through a spring which was compressed by the downwards moving hand of the scissors as a result of downward applied force.

The force at the point of cut was calculated by the moment equation. For a particular length of cut the force changes from low to high because as the cutting point moves forward more force is required according to moment equation. The sheets were cut for 3cm and 6cm distances and the average of the high and low value of force was taken as the cutting force.

In one set of experiments, the sheet was cut at distances of l0mm, 20mm and 30mm from the free edge

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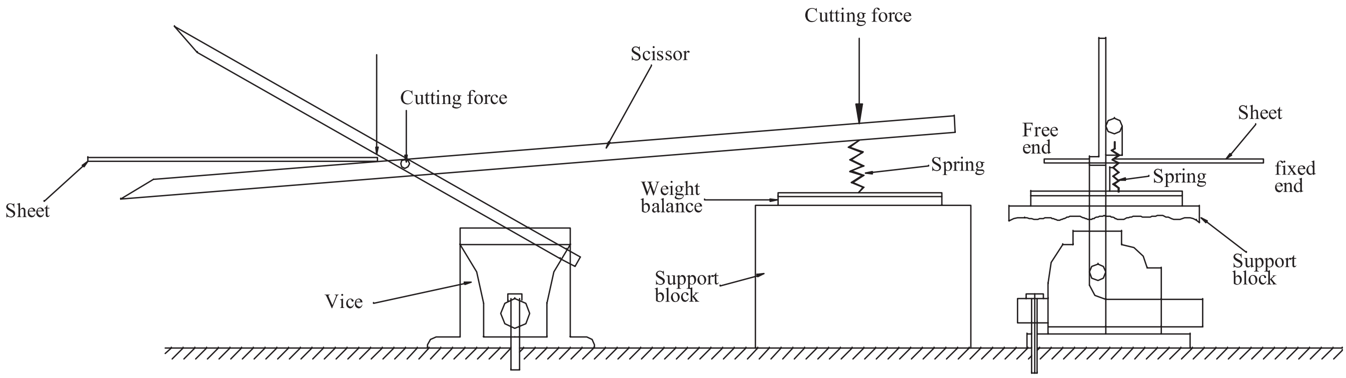

Fig. 1. Experimental set up

of the sheet. During cutting off, the cut of the sheet deflects and curls into coil. The applied force is consumed in cutting, overcoming friction and bending the offcut. The deflection and angle of off-cut or scrap is noted for cut lengths of 30mm and 60mm for the force applied at different cutting distances from the free edge. With continuous cutting, the off cut forms a coil of nearly the same diameter.

Results and discussion

The variation of cutting force with respect to distance of the free edge from the line of cut is plotted in Figure 2 for different metallic sheets of varying thicknesses. The results show that the cutting force increases as the line of cut becomes far from the free edge of the sheet. For aluminum sheet of l mm and 1.5 mm thicknesses and for zinc and mild steel sheets of 1.5 mm thickness the force increases at a higher rate as compared to the thin sheet of 0.5 mm thickness. It appears that for thin sheets the dominating factor is the fracture mechanics which requires less force and as the thickness increases elastoplastic and fracture mechanics both contribute to the separation of sheet as a result of cutting. It is estimated that at a distance of 30 mm from the free edge the force required is 30% and 25% of the force required for pure shear cutting for 1.5 mm steel and aluminum sheets respectively.The force applied is consumed in cutting, overcoming friction at the cutting surface and bending the off cut. The work done in bending is negligible in comparison to work consumed in cutting and friction of the plates as shown in Figures 3 & 4 [7]. Hence, the higher force requirement as the distance of line of cut is increased from the free edge of the sheet is due to the larger area of surface being separated as a result of cutting and the cutting force has to encounter larger inter atomic forces in the larger area being separated [7,8,9].

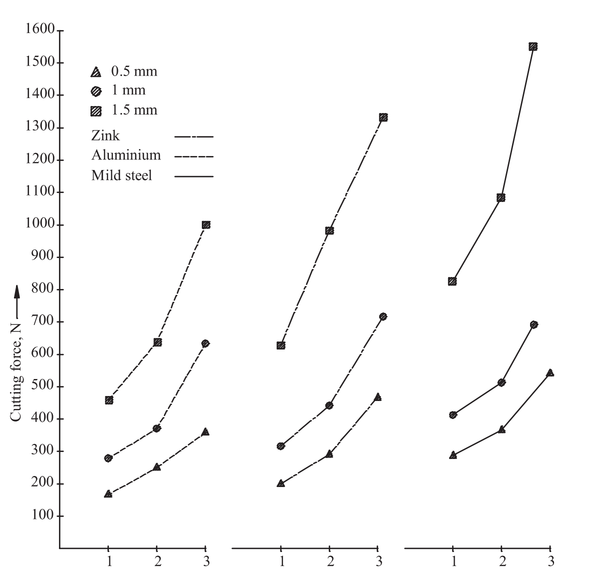

Fig. 2. Variation of cutting force with distance from free edge for various sheets

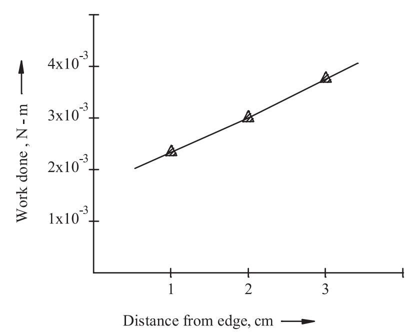

Fig. 3. Work done in bending for MS sheet 0.5mm thickness

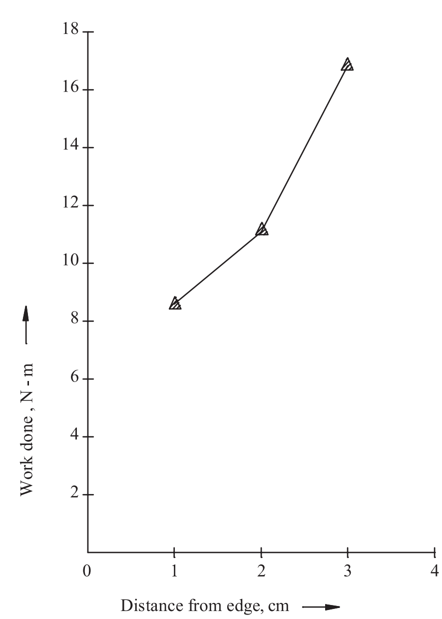

Fig. 4. Work done in cutting and friction for MS sheet 0.5mm thickness (Distance of cut 3cm)

Figure 5 shows the variation of force with thickness of sheet for various cutting line distances from the free edge for the aluminum, zinc and mild steel sheets. The force increases with the increase in thickness and the rate of increase increases with the increase in cutting distance from the free edge.

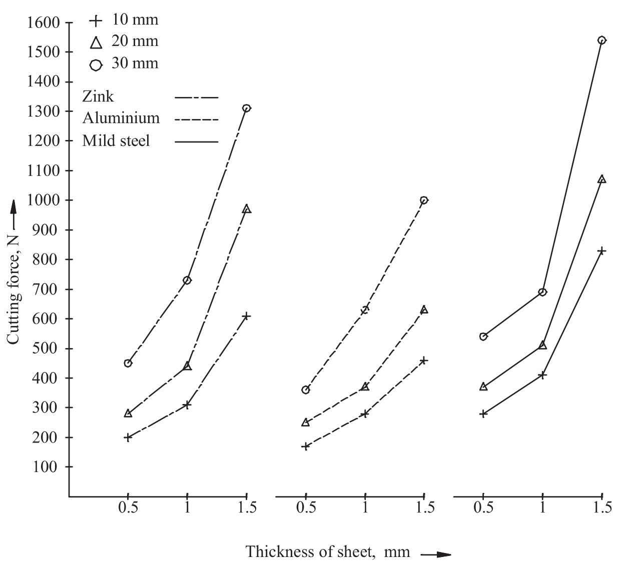

Fig. 5. Variation of cutting force with thickness of sheet

As mentioned above, when a sheet is cut the off cut bends plastically and curls. This phenomenon is commonly observed in chip curling and sheet metal cutting as reported here and elsewhere [1]. Why the off cut bends and curl is better explained by the Irwins crack tip model [10] of fracture mechanics. According to Irwin, infinite stress is developed at the crack tip that is at the cutting point of the scissors and the ductile material will undergo plastic deformation. A plastic zone is created ahead of the crack tip and a notional crack tip ahead of physical crack tip lies at a distance r_y. A plastic zone of $2r_y$ diameter is formed ahead of the physical crack tip as shown in Figure 6.

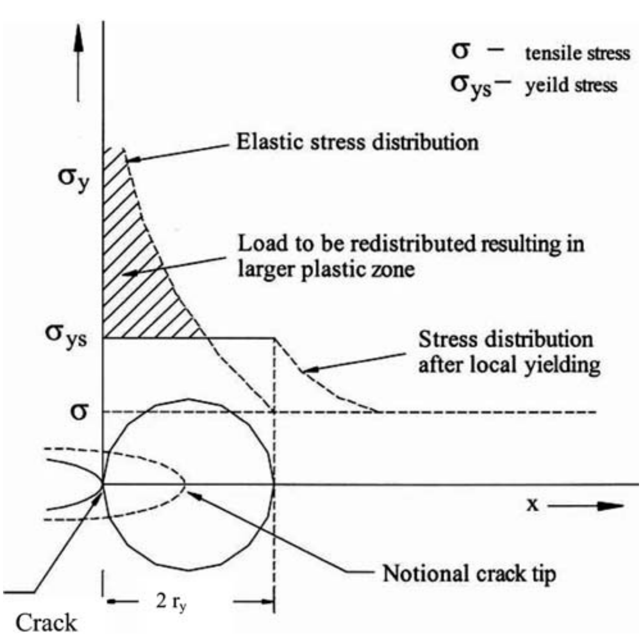

Fig. 6. Irwin model (Plastic zone size)

. The value of r_y is given by the following equation,

$$r_y = \frac{1}{2\pi}\left[\frac{K}{\sigma_{ys}}\right]^2 \quad (1)$$

Where K is the stress intensity factor under Mode I and σ_{ys} is the yield stress.

The occurrence of the plasticity makes the crack behave as if it were longer than its physical size and its propagation takes place at less force applied. In the sheet metal cutting process the off cut forms curls substantiate that the tip of cut lies in the plastic zone which extends up to a distance $2r_y$. Figures 7 shows the plastic deflection of the off cut from the horizontal line for the distances of line of cut from the free edge of different sheets of metals of different thicknesses. The

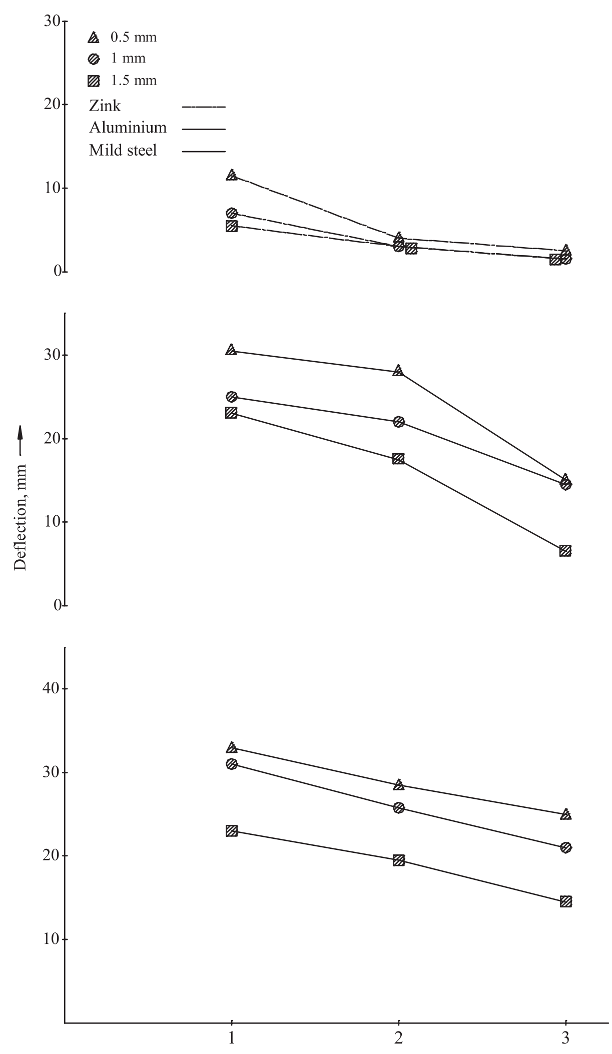

Fig. 7. Deflection from horizontal of the off cuts of various sheets

trend is different for different metals, may be because the crack propagated differently in different materials. As pointed above the work in bending is very small compared to the work in cutting and it depends on the generosity of cutting force how much it spends itself for the bending. When the distance from the free edge is small the force of separation of surface is small and is generous to bend the off cut, hence higher deflection is obtained and the curls of small diameters are formed. However as the distance of line of cut is increased from the free edge the force required for separation of the surface increases and correspondingly the deflection decreases to the limit just to separate the part to advance the cutting tip or crack. The nature of decrease of the deflection is different for different sheet materials and thicknesses. For zinc sheet there is little variation in deflection at distances of 20 mm and 30 mm for the three thicknesses of the sheet, however, at a l0 mm distance for the thin sheet the deflection is higher than that of sheets above 1 mm thickness. A similar phenomenon was observed in aluminum sheets less than 1 mm at a far away distance of 30 mm from free edge. In case of mild steel sheets this phenomenon was not observed, as for all thicknesses the defection of the off cut decreased with the increase of distance of line of cut from the free edge of the sheet. In contrast to zinc and aluminum, in steel sheets, moving of the line of cut from the free edge results in more distinctive deflection of off cuts.

As pointed above, the off cuts or the scrap curls and forms continuous coils. Figure 8 shows the curl loop diameter of off cuts for various sheet thickness of aluminum, mild steel and zinc sheets for the cut line distances of l0 mm,20mm and 30mm from the free edge. The plot shows that for thick sheets loop diameter increases linearly with the line of cut distance from the free edge whereas thin sheets show a scatter from the line which indicates that the cutting mode tends to stabilize as the sheet becomes thicker.

The fracture toughness in sheet metal cutting or guillotining is the ratio of external work to cross sectional area of the cut [7]. For a cutting distance of 30 mm the values of fracture toughness are plotted against the cutting distances from the free edge of various sheets in Figure 9. From the results it is concluded that

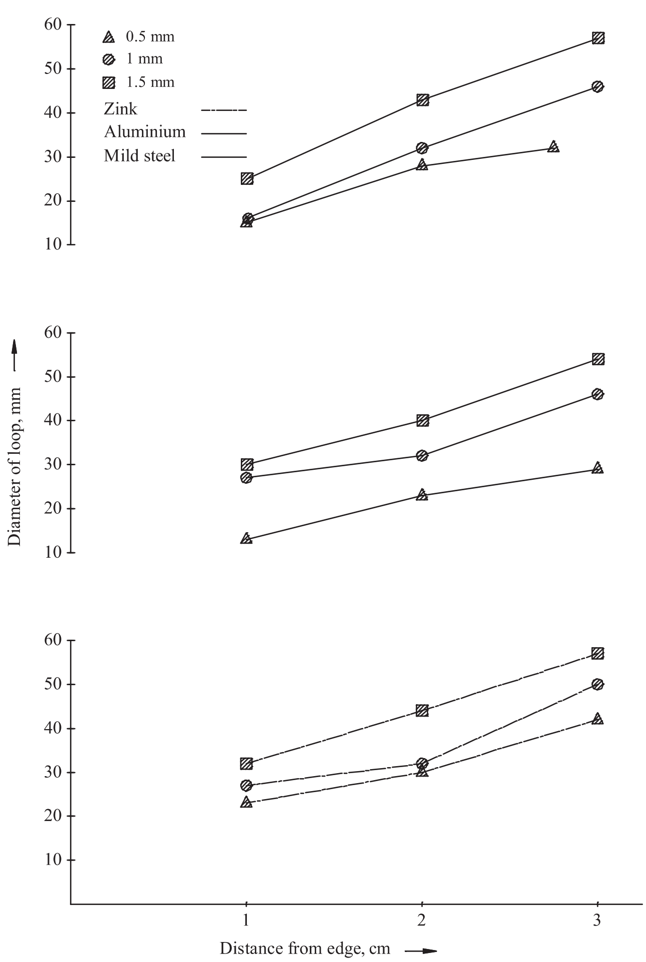

Fig. 8. Loop size of the off cuts of various sheets

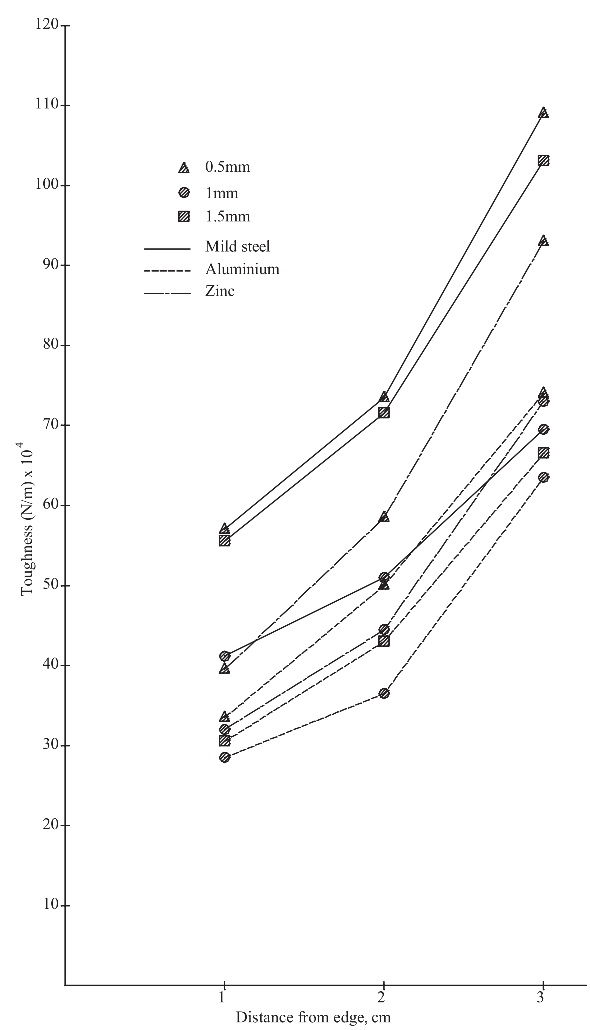

Fig. 9. Fracture toughness for various sheets related to cut distance from free edge

for all three metals the toughness increases with the increase of the cutting distance from the free edge: Also from 20 mm to 30 mm distance the increase in toughness is higher than that from l0 mm to 20 mm which shows that not only the toughness increases with the increase of cutting distance from the free edge but the rate of increase in toughness also increases. For the same thickness, steel is tougher than zinc and zinc is tougher than aluminum. Surprisingly, for all three types of metals, the thin sheet (0.5 mm) was the toughest as compared to the other thick sheets. This needs to be further investigated, however, Atkins & Mai pointed out that in thin sheets there is resistance to crack growth [7] which may lead to higher toughness.

The critical stress intensity factor K_c is related to toughness, R , by the relation [7]

$$K_c^2 = ER \tag{2}$$

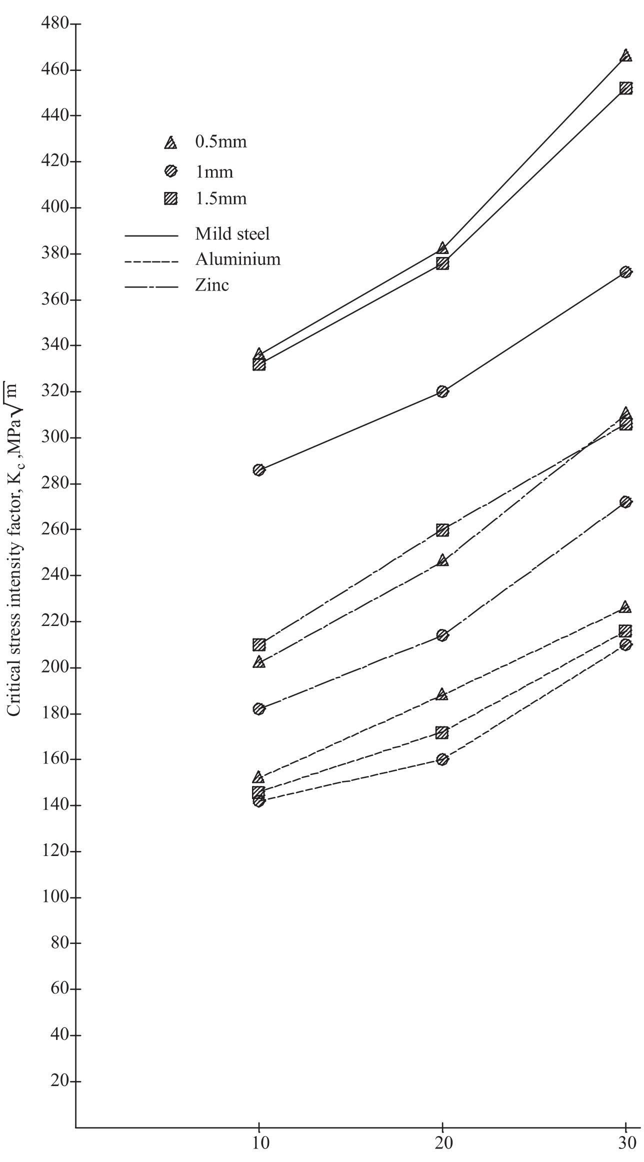

Fig.10. Critical stress intensity factor for various sheets related to cut distance from free edge

where E is the Young modulus of elasticity of the material. Using this relation K_c is calculated for sheets for cutting at different distances from the free edge and plotted in Figure l0. The value of K_c increased as the distance of line of cut increased from the free edge for all three sheet metals The thin sheets have higher K_c values compared to thick sheets. K_c values for different thicknesses of steel and aluminum sheets behaved differently; for 1 mm steel sheet K_c values are significantly lower and increase at low rate up to 20 mm distance from free edge and then increase at a higher rate. However, values of K, for 0.5 mm and 1.5 mm are close and the rate on increase in K, value is nearly the same for any distance from the free edge.

Conclusions

1. In sheet metal cutting the requirement of cutting force increases as its distance of the line of cut increases from the free edge of the sheet. The reason is, higher the surface area to be separated higher is the force requirement; as with the increase of surface area, the inter atomic bonding also increases.
2. If cutting starts from a point then the fracture mechanics helps to reduce the force requirement and the cutting point acts as a crack which lies in the plastic zone and propagates at reduced force requirement.
3. Thin sheets and thick sheets behave differently for crack propagation and thin sheets are tougher.
4. The curling of off cuts is due to crack lies in the plastic zone.
5. Fracture toughness increases with the increase in distance of cutting point from the free edge. Beyond 20 mm distance, toughness increases at a higher rate.
6. Thin sheets have higher stress intensity factor. Variation of the stress intensity factor for steel and aluminum with distance from the free edge is markedly different.

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