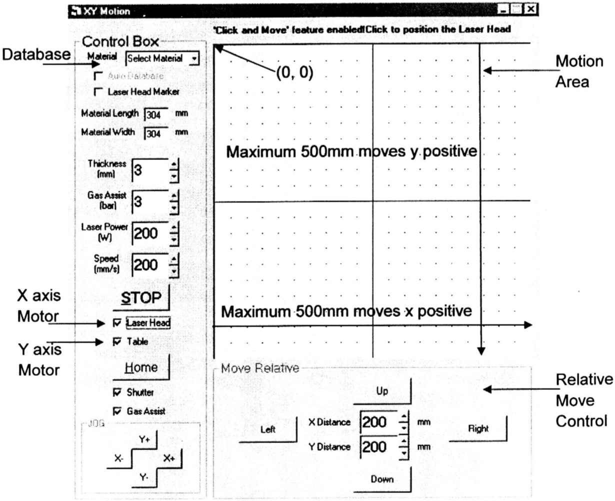
CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 CO_2 Laser Cutting Program

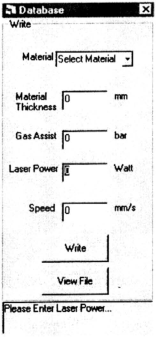
The CO_2 Laser Program is written using the programming tools discussed in the previous chapter. This program aims to provide simple to use Graphical User Interface (GUI) and to some extent, the user friendliness of the program provides a powerful tool to the user to change any parameter in real time cutting process. Some of the main functions of the program are shown below:

4.1.1 The XY Motion Form



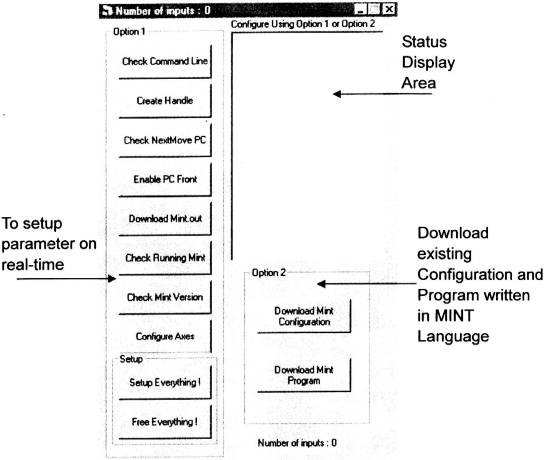
This is the main form of the entire program. It contains Click and Move features so as to allow the user to position the laser head by single-click of the left mouse button. Users are encouraged to double-click the Motion Area to have a Virtual Material display. Pressing Shift + Left Click zooms to the Virtual Material. For safety, the user must home the axis to establish a reference point. The entire motion button will be disabled while motion is in progress.

4.1.2 Database Entry



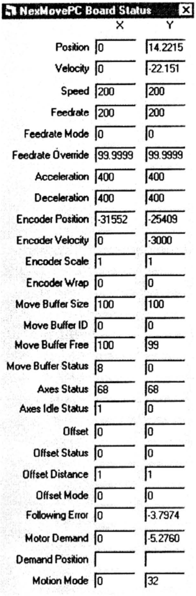
This database aims to provide a facility to store the optimum cutting parameters for all possible range. The database will be written by the program to a simple text file. Once executed, the program reads through the database for available cutting parameters and displays it as a suggestion to the user for the optimum cutting parameters.

4.1.3 System Setup



This form enables the user to setup the initial parameter to communicate to NextMovePC whenever possible. There are two options in this form. Option 1 provides the manual configuration for debugging purposes. Option 2 allows the user to download a prewritten MINT configuration and program file to the Dual Port RAM and executes it at once.

4.1.4 System Status

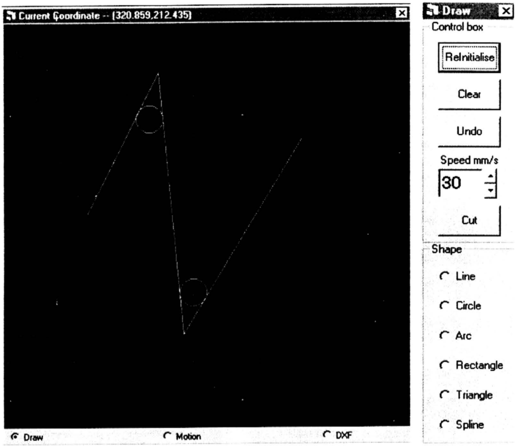


NexMovePC Board Status

	X	Y
Position	0	14.2215
Velocity	0	-22.151
Speed	200	200
Feedrate	200	200
Feedrate Mode	0	0
Feedrate Override	99.9999	99.9999
Acceleration	400	400
Deceleration	400	400
Encoder Position	-31552	-25409
Encoder Velocity	0	-3000
Encoder Scale	1	1
Encoder Wrap	0	0
Move Buffer Size	100	100
Move Buffer ID	0	0
Move Buffer Free	100	99
Move Buffer Status	8	0
Axes Status	68	68
Axes Idle Status	1	0
Offset	0	0
Offset Status	0	0
Offset Distance	1	1
Offset Mode	0	0
Following Error	0	-3.7974
Motor Demand	0	-5.2760
Demand Position		
Motion Mode	0	32

In order to monitor the NextMovePC Board status, this form is created to read the parameters from the board at intervals of 1ms.

4.1.5 Drawing Area



This is actually the CAD portion of the program where the user can draw multiple connected lines, Arc and Circle. By pressing the Cut Button the cut path is where the user draws. Another powerful tool is the integration of the DXF converter to the program. The successfully written CAM part is the multiple corners drawn by the user but is limited to 100 moves only at one load due to the physical constraint of the memory. The moves are stored in Arrays.

4.2 Rounded Corner Method

Interpolated motion is used in two orthogonal axes, for example an XY table. In interpolated moves, the axis speed and acceleration refer not to individual axis speed, but to the path along which motion is in progress. Interpolated moves are positional moves and so use a trapezoidal motion profile. Individual moves can be joined together to give a continuous path velocity. When contouring is turned on, consecutive moves are blended together so that the axes do not decelerate to a stop at the vector boundaries. In the case of sharp corner, a good solution to avoid abrupt stop on one axis is to insert an arc between the two vectors [69].

4.2.1 Geometrical Analysis

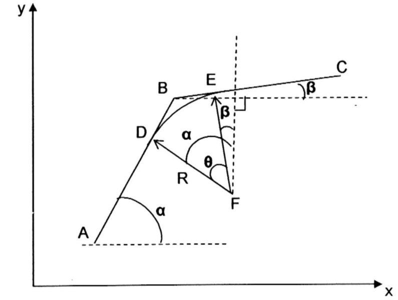


Figure 4.2.1.1: Geometrical Analysis on a blended arc on sharp corner.

The original vector move is from point A to point B followed by a move from point B to point C. To avoid step changes in velocity while these moves are contoured we apply a fillet of radius R to the moves. This results in three elements to the total moves:

- A relative vector from point A to point D
- A circle move of angle θ with center point at F (point D to point E)
- A relative vector from point E to point C

We therefore need to calculate the vector changes DB and BE, the relative position of point F(with respect to point D) and angle θ.

$$\alpha = \tan^{-1}(\frac{yB - yA}{xB - xA})$$
$$\beta = \tan^{-1}(\frac{yC - yB}{xC - xB})$$
$$\theta = \alpha - \beta$$
$$AB = \sqrt{(xB - xA)^2 + (yB - yA)^2}$$
$$BC = \sqrt{(xC - xB)^2 + (yC - yB)^2}$$
$$DB = BE = R * \tan(\frac{\theta}{2})$$

Therefore, taking into consideration the quadrant of the angular change θ:

$$xD = xB - \text{sgn}(\theta) * DB * \cos\alpha$$
$$yD = yB - \text{sgn}(\theta) * DB * \sin\alpha$$
$$xE = xB + \text{sgn}(\theta) * BE * \cos\beta$$
$$yE = xE + \text{sgn}(\theta) * BE * \sin\beta$$
$$xF = xD + \text{sgn}(\theta) * R * \sin\alpha$$
$$yF = yD - \text{sgn}(\theta) * R * \cos\alpha$$

where:

α = Incremental angle for line AB with respect to x-axis.

β = Incremental angle for line BC with respect to x-axis.

xA, xB, xC, xD, xE and xF = Absolute x positions for the respective points.

yA, yB, yC, yD, yE and yF = Absolute y positions for the respective points.

Function sgn(θ) return +1 if $\theta > 0$ and -1 if $\theta < 0$

There are some important considerations when deriving a fillet solution:

1. Vector lengths AB and BC need to exceed a minimum size(if either are zero then there will be no solution).
2. If DB>AB or BE>BC then there is no solution.
3. If AB parallel to y-axis or BC parallel to x-axis then there is no solution.
4. α and β should lie in the range of +/- 180 degrees and both angles must turn at the same direction.
5. θ should be restricted to the range +/- 180 degrees.

4.2.2 Constructing a Visual Basic Corner Fillet Function

The MINT function will accept x and y displacements for each of the original two relative vector moves. These will be passed By Reference so that modified values to account for the fillet can be passed back to the calling code (if there is no solution then the original values remain unchanged). The required radius will also be passed as a parameter. The function will also return (again via 'By Reference' parameters) the relative displacement of the center point of the arc and its angle. The overall function return is a Boolean value (True or False) to indicate to the calling code whether a solution was found for the specified vectors and radius.

Some precaution steps are noteworthy. The Visual Basic compiler only manipulates angles in radian and does not support negative angle (although negative angle is accepted, it only means drawing a sector rather an arc). Any angle in degree should be changed to radian by multiplying with $\frac{\pi}{180}$. The turning angle in MINT program is opposite to the Visual Basic. So we should multiply the final angle by -1. Let the following parameters be defined before moving into the next section:

X1 = change in first axis (x-axis) for first vector

Y1 = change in second axis (y-axis) for first vector

X2 = change in first axis (x-axis) for second vector

Y2 = change in second axis (y-axis) for second vector.

R = required fillet radius

θ = calculated (circle) angle for fillet xF = relative x displacement of circle from end of first vector

yF = relative y displacement of circle from end of first vector

$$\alpha = \frac{Y1}{X1}$$

$$\beta = \frac{Y2}{X2}$$

4.2.3 *Corner Fillet Function*

The first step in building a corner fillet function is to tackle the α and β so that they are suitable in all directions as shown in APPENDIX 1.

4.2.4 *Corner of Any Size*

Since $\alpha = \frac{Y1}{X1}$, and $\beta = \frac{Y2}{X2}$, changing a corner size is direct that is by altering any of the increment length X1, X2, Y1, or Y2.

If we fix X1 = X2 = x, Y1 = Y2 = y and wish to draw a corner with angle θ, it will look like figure 4.2.4:

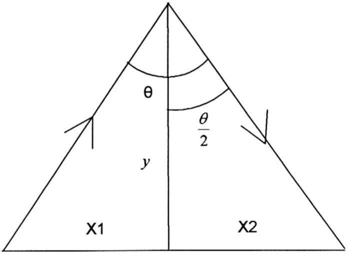


Figure 4.2.4: Corner of any size

A table can be made to assist in the calculation. An example of a table is shown below (y is fixed at 40 units):

$\frac{\theta}{2}$ deg	θ deg	$x = y\tan\left(\frac{\theta}{2}\right)$
5	10	3.50
20	20	7.05
15	30	10.72
20	40	14.56
25	50	18.66
30	60	23.10
35	70	28.01
40	80	33.57
45	90	40.00
50	100	47.68

The calculated x values should be rounded to suit the application.

4.2.5 *Axes Rotation*

One apparent disadvantage of the above Rounded Corner Method is neither X1, X2, Y1, nor Y2 should be zero. That means we cannot have a line which is parallel to the x and y axis. One quick solution is to assign the increment x and y with a very small value, says 0.001. This could be reasonable since the motor motion cannot resolve such a small step.

Another more accurate method is to rotate the axes [71] to a desired angle so that both increment x and y are non zero while keeping the θ unchanged. In order to do this, a rotation matrix R_m is defined below:

$$R_m = \begin{bmatrix} \cos(\delta) & \sin(\delta) \\ -\sin(\delta) & \cos(\delta) \end{bmatrix}$$

so that

$$\begin{aligned} X1 &= R_m X1 \\ X2 &= R_m X2 \\ Y1 &= R_m Y1 \\ Y2 &= R_m Y2 \end{aligned}$$

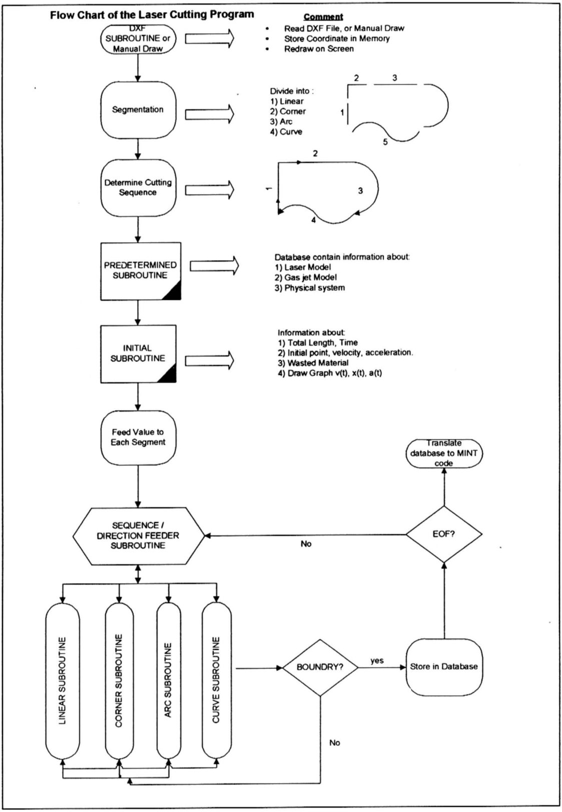
The axes rotation method makes sense since X1, Y1, X2, Y2 are all incremental rather than absolute coordinates.

4.2.6 **Corner Fillet Function Source Code**

The corner fillet function source code is shown in APPENDIX 2.

4.2.7 CO_2 Laser Cutting Program Flow Chart

The below flow chart is used to write the CO_2 Laser Program.



4.2.8 Cutting Results and Analysis

The cutting was carried out using 650W, gas assist of 1 bar, standoff distance of 1mm and the speed ranges from 25 to 30 mm/s. The experiment is focused on the cutting quality of different curvatures which are represented by the arc radii. Figure 4.2.6.1 shows the cutting quality of different straight lines (speed checking purpose) for front and back views for speeds from left to right 26mm/s, 27mm/s, 28mm/s, 29mm/s, and 30mm/s. The thickness of the mild steel plate is 3mm.

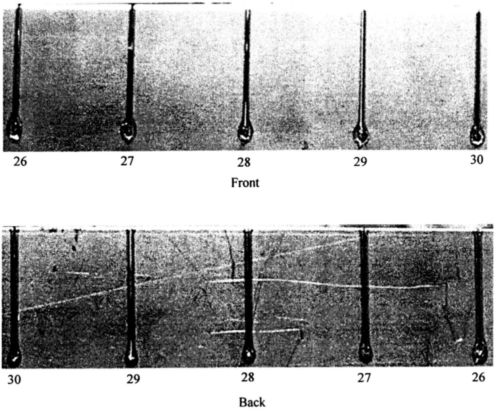


Figure 4.2.6.1: Cutting Quality of different lines for front and back view for speed from left to right 26mm/s, 27mm/s, 28mm/s, 29mm/s, and 30mm/s

The corner cutting experiments were carried out using the speeds ranging from 26mm/s to 30mm/s.

It is reasonable to use the maximum speed in these experiments since the least heat affected zone is expected. So most of the results presented here used the maximum cutting speed of 30mm/s (different speeds used are indicated otherwise). The following results show the cutting quality of the corners cut with fillet arc radii of 1mm, 3mm and 0.1mm and different rotating angles varying from 10^0 to 70^0.

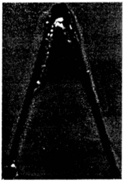
1. Cutting with Arc Radius of 1mm

10^0 Front

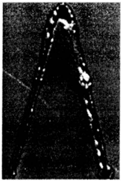
10^0 Back

20^0 Front

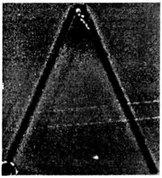
20^0 Back



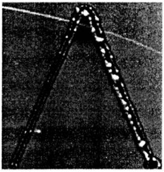
30^0 Front



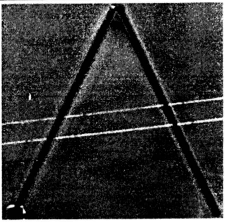
30^0 Back



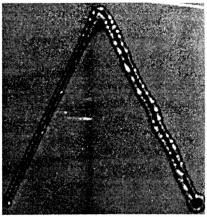
40^0 Front



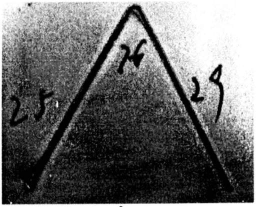
40^0 Back



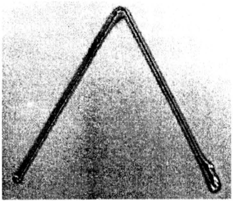
50^0 Front



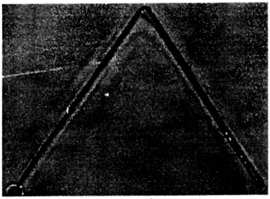
50^0 Back



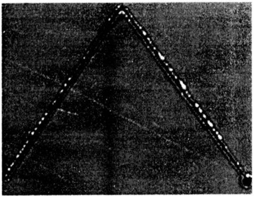
60^0 Front



60^0 Back



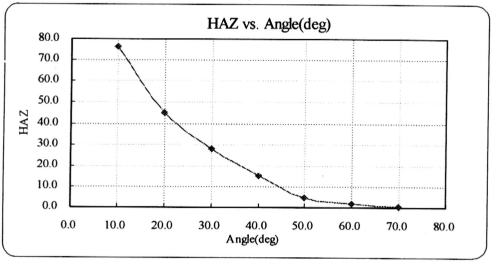
70^0 Front



70^0 Back

Figure 4.2.6.1:Cutting Quality of different corners cut with different turning angles for front and back view for fillet arc radius of 1mm. Pictures are enlarged by 1.5 times

Angle (deg)	HAZ (mm^2)
10.0	76.0
20.0	45.0
30.0	28.0
40.0	15.0
50.0	4.5
60.0	2.0
70.0	0.5



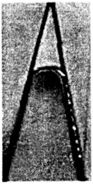
Comments on results:

The cut was carried out using Laser Power of 650W, Gas assist of 1bar, and standoff distance of 1 mm. From the graph we concluded that for arc radius of 1mm, angles less than 30^0 are not suitable to be cut using the rounded corner cutting method since the HAZ is too large. Angle more than 70^0 is not shown because the HAZ is not significant.

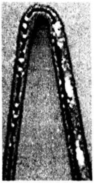
2. Cutting with Arc Radius of 3mm

10^0 Front

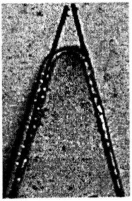
10^0 Back



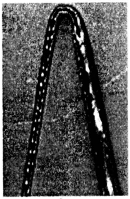
20^0 Front



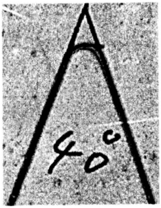
20^0 Back



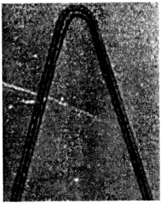
30^0 Front



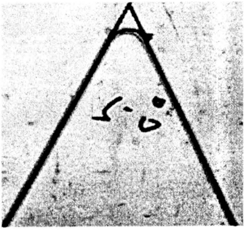
30^0 Back



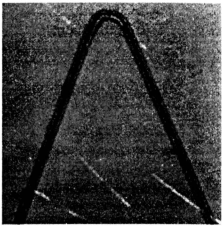
40^0 Front



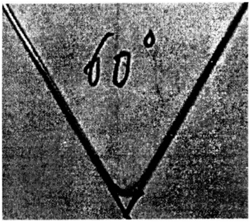
40^0 Back



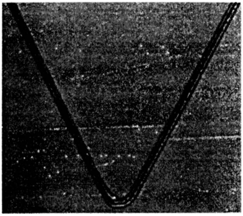
50^0 Front



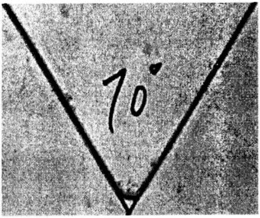
50^0 Back



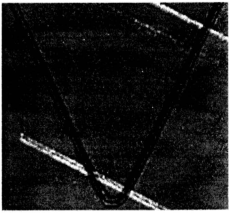
60^0 Front



60^0 Back



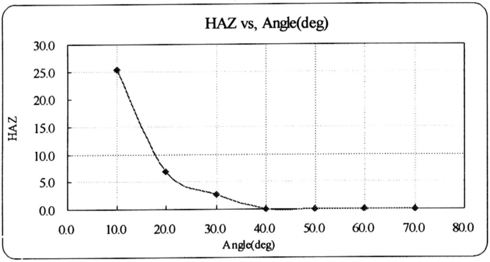
70^0 Front



70^0 Back

Figure 4.2.6.2: Cutting Quality of different corners cut with different turning angles for front and back view for fillet arc radius of 3mm. Pictures are enlarged by 1.5 times.

Angle (deg)	HAZ (mm^2)
10.0	25.4
20.0	6.9
30.0	2.7
40.0	0
50.0	0
60.0	0
70.0	0



Comments on results:

The cut was carried out using Laser Power of 650W, Gas assist of 1bar, and standoff distance of 1 mm. From the graph we concluded that angles less than 20^0 are not suitable to be cut using the rounded corner method for arc radius of 3mm since the HAZ is quite high. Overall, the HAZ is much less than the case of rounded corner radius = 1mm. The drawback of the increasing radius to 3mm is clear, that is the sharpness of the corner reduces which leads to inaccuracy of the corner curvature.

3. *Cutting with Arc Radius of 0.1mm*

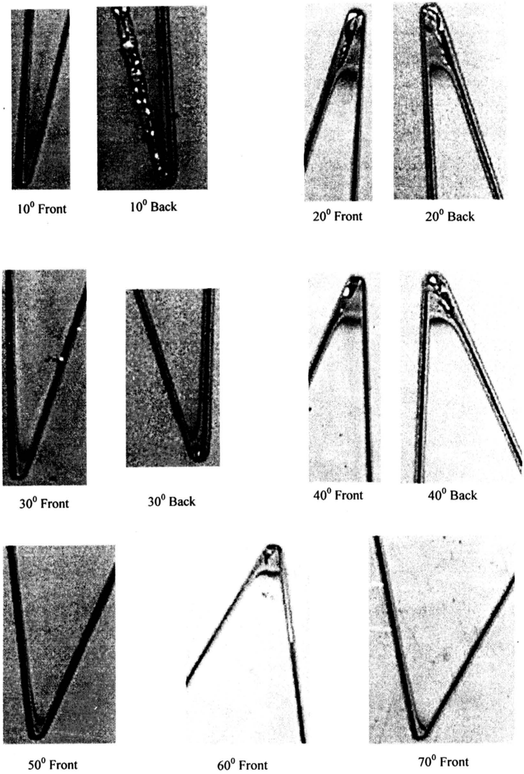
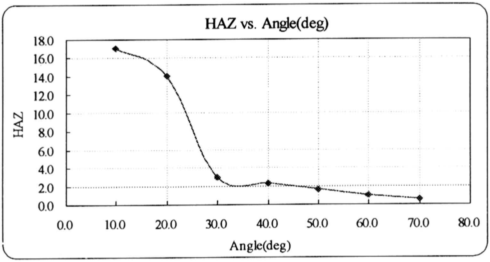


Figure 4.2.6.3: Cutting Quality of different corners cut with different turning angles for front and back view for fillet radius of 0.1mm. Pictures are enlarged by 1.5 times.

Angle (deg)	HAZ (mm^2)
10.0	17.0
20.0	14.0
30.0	3.0
40.0	2.3
50.0	1.6
60.0	1.0
70.0	0.5



Comments on results:

Cutting using arc radius less than 1mm such as 0.1mm suffers from severe edge damage as shown in Figure 4.2.6.3 for all turning angles. Moreover, the following error and the resolution of the motor results in reduced sharpness. It is not recommended to cut using radius less than 1mm.

4.2.9 Discussions

The cutting results show some corner overheating effects. The corner overheating can be explained by the double heating process at the corner edge as indicated in Figure 4.2.6.2. Double heating up at corner edge becomes significant when the angle decreases. This overheating effect results in surface colour change and the molten materials tend to stick on the overheated side. Although causing no significant damage to the material itself, more work must be done to the machining process such as repainting the material surface and cleaning the attached dross for practical industrial uses.

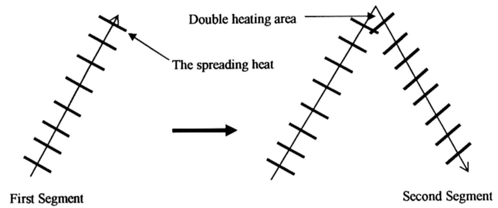


Figure 4.2.6.2: Double heating mechanism

Despite the disadvantage of increasing HAZ (Heat Affected Zone) with smaller angle in the rounded corner method, it is useful in cutting at high speed when compared with other methods. Rounded corner method eliminates motor acceleration and deceleration jerk when turning at the corner edge. Cutting less than 1mm arc radius is not encouraged due to the motor is too sensitive to the following error which is in the range of 0.1mm. Minor motor jerk is experienced when cutting corner with arc radius less than 1mm.