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Effect of Tooling Parameters on Bending Force in Air Bending of CR4 steel

Tilak Raj Gupta*
Ph. D. Scholar, Department of Mechanical Engineering,
I.K.G. Punjab Technical University,
Kapurthala (Pb), 144603, India.

H.S Payal
Professor, Department of Mechanical Engineering,
St Soldier Institute of Engineering and Technology (PTU),
Jalandhar (Pb), 144001 India.

Abstract

This study attempts to investigate the effect of process variables like the geometry of die and punch, the orientation of sheet metal and punch speed on bending force in air bending of CR4 steel, by varying one parameter at a time approach. Experiments were conducted using different combinations of sheet orientations, punch velocity, punch radius, die width, and die radius keeping sheet metal blank size constant. Universal Testing Machine was used at different speeds. Effect of parameters that is bending force has been analyzed graphically. The increase of bending force was observed due to an increase of punch radius, and punch speed. Whereas bending force was decreasing due to an increase of die width, and die radius. By changing the orientation of steel sheet from longitudinal to transverse, bending force was increasing. It was observed that the bending force follows polynomial equation of 2nd order by curve fitting method. The results will be useful as a guideline for tool design engineers and press shop engineers in the sheet metal forming industry

Keywords: Air bending; bending force; CR4 steel; die and punch geometry; punch speed; steel sheet orientation

INTRODUCTION

Bending process is commonly used in fabrication industry making use of the theory of plasticity. In this process, the sheet metal is shaped by straining the metal around a straight axis. During this operation, internal side is compressed and external side is

* *Corresponding Author: Tilak Raj Gupta. Email: trg2in@yahoo.com*

stretched as illustrated in Figure 1. This process is of three types, V-die bending, air bending and wipe die bending. The present study is about air bending, known as free bending also. It is a flexible bending process, where, by changing the punch travel various bend angles are achieved using the same tooling. In this process, the sheet metal blank comes in contact with two outside edges of the die and punch nose. It is not supported at bottom and form is made by punch radius and die's opening as illustrated in Figure 2 (a). Air bending is more flexible than its counterpart V- die bending. Different bend angles are achieved by changing the punch and die in V- die bending process Figure 2 (b). As the punch travel decides the bend angles in air bending, the tool changes required to achieve different angles are reduced. Therefore, use of air bending in automotive and other metal forming industries is very frequent [1-3]. Air bending is suitable for prototype development, part production and small batch production due to flexibility, lesser numbers of changes and low cost of tooling. Air bending is falsely judged as an easily understandable process. Bending behavior of metal sheet in air bending process is complex for sheet material, tool and process [4]. In the recent years, air bending has received the research interest as the process has been recognized as complex one [5].

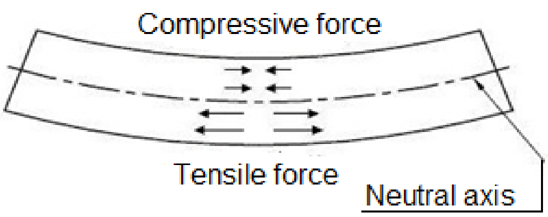

Figure 1. Theory of Plasticity

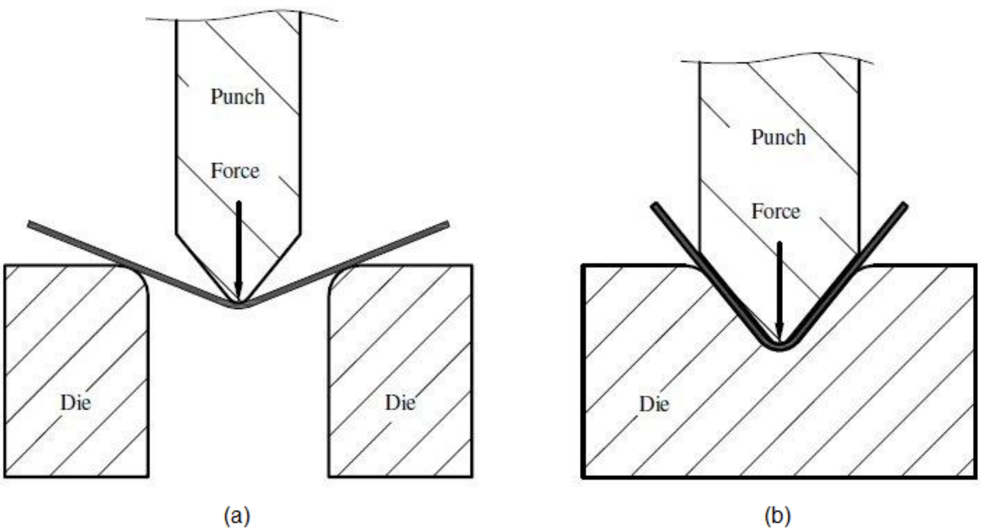

Figure 2. (a) Air bending (b) V- die bending

Bending force depends on the punch travel. It starts from zero to maximum and may decrease near the completion of the bend; then it increases abruptly as the punch bottoms down in die bending refer Figure 2 (b). In the case of air bending, once the force starts decreasing, it does not increase again [6] refer Figure 2 (a). Bending force Fmax can be estimated by the equation (1), [6].

$$Fmax = K\{(UTS)\ Ls\ (Ts)^2\} / Wd \tag{1}$$

In this equation, K includes various factors including friction; UTS is the ultimate tensile strength; Ls is bend length; Ts is sheet thickness & Wd is die width. Bending force for air bending can be calculated by equation (2). [7]

$$F = \{4M \cos^2(\theta/2)\} / \{(Wd + 2Rd) - 2(Rd + Rp + Ts) \sin(\theta/2)\} \tag{2}$$

In this equation, M is bending moment, Wd is the die opening, Rd is the die radius, Rp is punch radius, Ts is sheet thickness and θ is the bend angle. So, bending moment, which depends on parameters like material properties and the die geometry etc., is directly affecting the bending force. An analytical approach cannot correctly estimate bending moment during air bending [8-10]. Thus, tool designers use the easy equation (1). In this equation, as already mentioned, K is not constant rather a factor which varies, so experimental study needs to be carried out further.

Huang, Y. et al. worked on the V- die bending process for studying the effects of variable process parameters and observed that on the increase of die radius, punch load for bending reduces in the initial position and increases in the final position of the bending of steel sheets [11]. Naraynasamy et al. predicted bending force in air bending of interstitial free steel sheets using response surface methodology for his study [3]. Balaji, S.V. et al. conducted experiments with 8mm thick plate for 3 different punch radii, using single die setup, and inferred that the load increases to bend the workpiece as the punch radius increases [12]. Srinivasan, R.et al. studied air bending process for bending force behavior of electro galvanized steel sheets [13]. Chatti, S. et al. studied the air bending process by super positioning the incremental stress and observed that bending force and energy requirement both got considerably lowered [14]. Khalatbari, H. et al. studied the incremental forming process to relate formability and time efficiency in high-speed incremental forming [15]. Gupta, Tilak Raj et al. investigated bending and spring back of electro galvanised steel and presented the effect of punch velocity and bend angle [16]. Khadra, F. A. et al. used the kriging approach for forecasting spring back behavior in air bending [17]. Salahshoor, M. analyzed the effects of tool and process parameters in hydroforming process and observed the process path has a great effect on formability [18].

Anisotropy of steel sheet is an important factor influencing its formability. Cold rolling, a thermo-mechanical process, of steel sheets results in anisotropy. The transverse ductility is thus reduced [6].

CR4 steel is an aluminum killed steel and has uniform grain structure making it useful for intricate deep-drawing with a non-aging quality. It is manufactured as per IS 513: 2008 [19] in India. Table 1 shows chemical composition & Table 2 shows mechanical properties at room temperature as per IS 513: 2008 [15]. This grade of steel is free from stretcher-strain, even after prolonged storage. It is used in automotive body parts like back door inner, reinforcement sub-assembly for hinge pillar. Electrical machinery parts, due to its easy spot weldability and formability with high strength. It is friendly with painting and decorative coating. Suresh, K. et al. studied incremental forming and observed a grain refinement in similar steel, after the process [20].

Table 1. Chemical composition of CR4 steel as per IS 513:2008

Quality		Constituent, Percent, Max			
Designation	Name	Carbon	Manganese	Sulphur	Phosphorus
CR4	Extra deep drawing Aluminium killed (Non-aging)	0.08	0.40	0.030	0.020

Table 2. Mechanical properties at room temperature of CR4 steel as per IS513:2008

Quality		Yield Stress MPa	Tensile Strength MPa	Elongation Percent Min	Hardness Max
Designation	Name	Max	Max	Lo=50	HR30T
CR4	Extra deep drawing Aluminium killed (Non-aging)	210	350	37	50
Yield stress can be specified Min 140MPa & Tensile Strength can be specified Min 270MPa					

In the current scenario, a need was felt to study the air bending process experimentally for CR4 steel and to investigate the effects of process parameters like tool geometry, the orientation of sheet metal and punch speed on bending force and correlate the same with punch travel, because bend angle is adjusted by punch travel in industry. These results will be useful for design engineers and press shop engineers for deciding press specifications and tool strategy and tool setting in the fabrication industry.

MATERIALS AND METHODS

The material used in this study was 1mm thick CR4 steel sheet, for which chemical composition was analyzed by spark atomic emission spectrometry as per ASTM-E415-2014 test method and results obtained were as per Table 3. The tensile test was conducted as per IS 1608:2005 considering the anisotropy. Tensile test samples were cut along rolling direction, transverse direction and at 45° to the rolling direction. Results obtained are given in Table 4. Results were as per specified limit.

Table 3. Chemical composition of CR4 steel

Element	%	Element	%
Carbon	0.057	Copper	<0.01
Manganese	0.189	Niobium	<0.005
Sulphur	0.013	Nitrogen	<0.004
Phosphorus	0.018	Boron	<0.0005
Aluminium	0.043	Lead	<0.001
Silicon	< 0.017	Cobalt	<0.005
Chromium	0.018	Vanadium	<0.005
Molybdenum	<0.005	Tungsten	<0.005
Nickel	<0.025	Iron (By Difference)	99.61

Table 4. Mechanical properties of CR4 steel

Orientation	Yield stress	Tensile strength	Elongation Lo=50	Hardness
	(M Pa)	(M Pa)	%	HV5
0°	181.2	318.7	45	95
90°	190.6	318.7	43.8	
45°	193.4	335.5	37	
Average	189.65	327.1	40.7	
Xaverage = X0+ 2X45+X90				

Experiments were conducted on HT-U 1605- HS, twin column Universal Testing Machine. The machine was equipped with a 500Kg load cell and electrical servo control programmable drive to control speed and distance, having 1 mm/min to 500 mm/min variable cross head speed with computer interface for analysis and chart recording. Figure 3 shows the experimental setup.

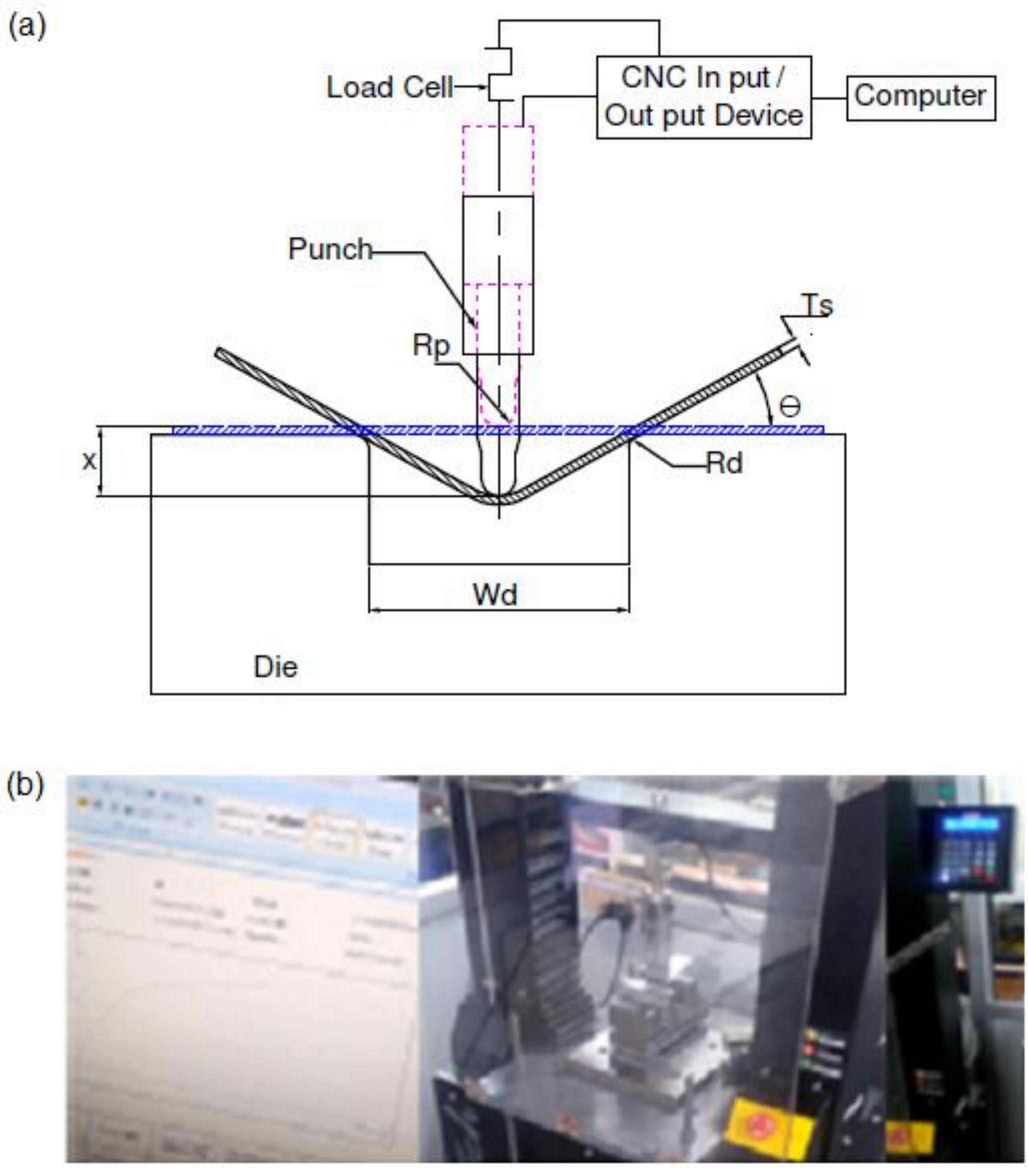

Figure 3. Experimental setup: (a) schematic diagram and (b) pictorial view

Various parameters used for experimentation for bending are given in Table 5. Rolling direction was considered 0° and bending was done across of the rolling direction. Across rolling, transverse, direction was considered 90° and bending was done in the rolling direction. Three punches with different radii and one flexible die set having different die radii and die widths were used. Three different punch speed with different punch travels were used to see the effect on bending force at different angles. Peak bending force & terminating bending force were recorded for each punch travel.

Table 5. Overview of tool parameters used in experiment

Input parameters				Response
Constant	Work blank width	Ws (mm)	**35**	Bending force y (kgf)
	Work blank length	Ls (mm)	**150**	
	Work blank thickness	Ts (mm)	**1**	
Variables	Die width	Wd (mm)	40, **60,** 80	
	Punch radius	Rp (mm	**8**, 12, 16	
	Die radius	Rd (mm)	3, **5**, 8	
	Punch travel	x(mm)	5, 10, 15, 20, 25	
	Orientation of sheet	(°)	**0**, 90	
	Punch speed	Vp (mm/sec)	**0.4**, 0.6, 0.8	

RESULTS AND DISCUSSION

Effect of various parameters on bending force was plotted at various punch travel on the graph and illustrated.

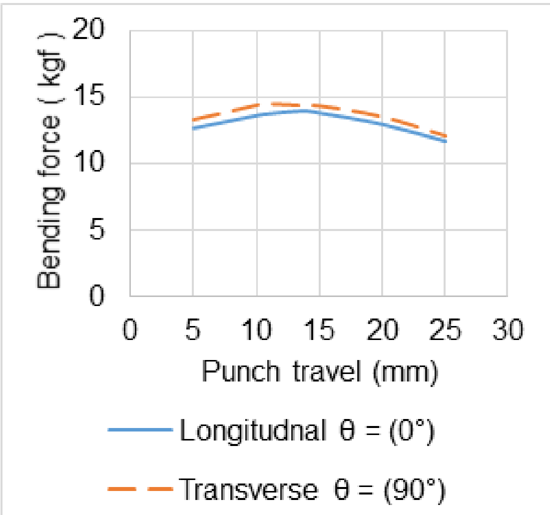

Figure 4. Effect of orientation
(Rp = 8 mm; Rd = 5 mm; Wd = 60 mm; Vp = 0.4 mm/sec)

Figure 4 shows the bending force for CR4 steel sheet for 0° and 90° orientations. It was observed that at 90° orientation the bending force was more as compared to 0° since ductility is reduced in transverse direction [6]. It was also observed with the increase of punch travel the bending force was increasing and after reaching maximum load on a further increase of punch travel bending force decreases in both 0° and 90° orientations. Reason being for larger punch travel, bending moment changes and deformation zone spread out producing a larger amount of friction work. The effect of bending moment and friction increases the bending force for a given punch travel. Punch travel for peak load has shifted indicating different strain behavior for both orientations. Naraynasamy, R. et al. observed the similar results for interstitial free steel sheets [3].

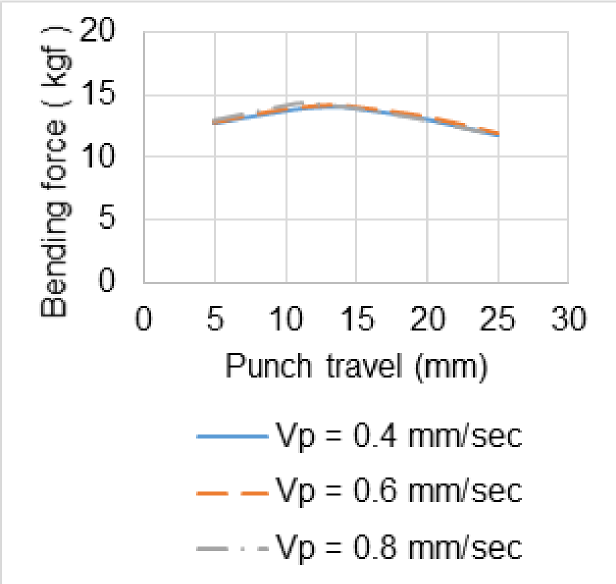

Figure 5. Effect of punch speed
(Rp = 8 mm; Rd = 5 mm; Wd = 60 mm; θ = 0°)

Figure 5 shows the effect of punch speed on bending force. It was observed with the increase of punch speed bending force was increasing for each punch travel, till maximum load increases, after that it falls at a higher rate. It may be due to the positive strain rate sensitivity of CR4. The reason may be, the dynamic friction is more dominant than static friction and so the force of friction, a part of bending force, is higher for higher punch speed. The value of the coefficient of friction decreases with the increase of speed. The increase was more prominent at higher punch travel near peak load. Naraynasamy, R. et al. observed the similar results for interstitial free steel sheets [3]

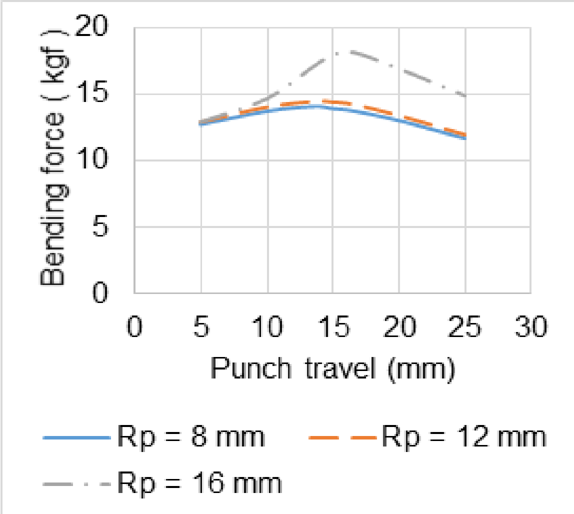

Figure 6. Effect of punch radius
(Rd = 5 mm; Wd = 60 mm; Vp= 0.4 mm/sec; θ = 0°)

Figure 6 shows the effect of punch radius on bending force. It was observed with the increase of punch radius bending force was increased. Because on increase of punch radius, the contact area of punch increases. So, the free length between die and punch reduces and moment arm decreases, which leads to decrease of bending moment. It provides poor leverage so bending force increases. It is to be noted that the effect of punch radius was not significant on bend force for low ranges of punch travel since contact area of punch does not increase much. It was thus seen that the influence of punch radius becomes stronger only at larger punch travel. Similar results were obtained by Huang, Y. et al., Balaji, S. V. et al. and Srinivasan, R. et al. [11-13]

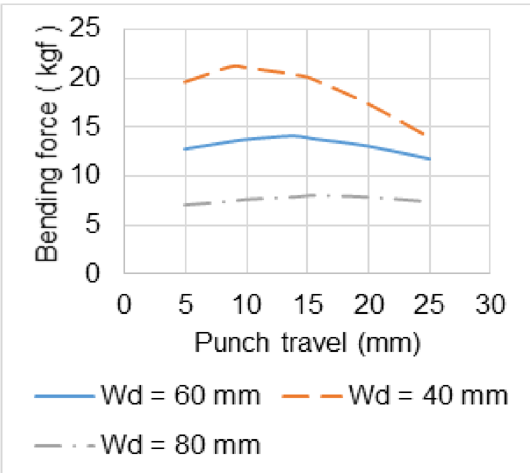

Figure 7. Effect of die width
(Rp = 8 mm; Rd = 5 mm; Vp = 0.4 mm/sec; θ = 0°)

Figure 7 shows the effect of die width on bending force. It was observed with the increase of die width bending force was decreased for each punch displacement. That was in conformation with the theoretical equation (1). Because on increase of die width free length between the punch and die increases, so moment arm increases, which leads to increase of bending moment, it provides better leverage so bending force decreases. Similar results were obtained by Srinivasan, R. et al. [13].

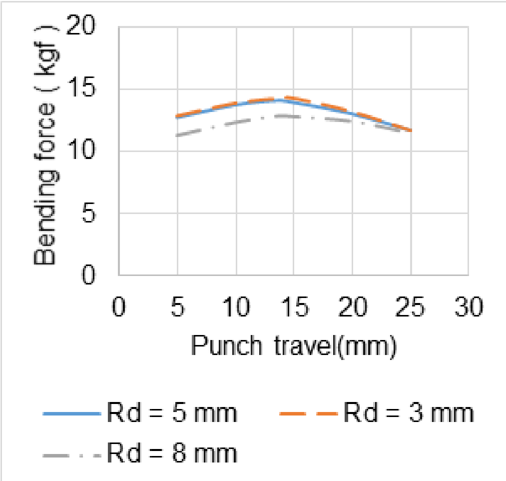

Figure 8. Effect of die radius
(Rp = 8 mm; Wd = 60 mm; Vp = 0.4 mm/sec; θ = 0°)

Figure 8 shows the effect of die radius on bending force. It was observed with the increase of die radius, bending load get reduced. It was understandable, as happens in the case of die width. In this case, the point of contact between steel sheet and tool, that is, die and punch are spaced much apart, so moment arm increases which lead to the increase of bending moment. Thus, an increase of die radius decreases the bending force. The difference was increasing at higher punch travel near maximum load. Due to further punch travel, the difference was reducing.

Table 6. Correlation of punch travel and bending force

Variable parameters	Type of curve	Equation	(R^2)
Vp =0.4mm/sec; Wd = 60mm; Rd = 5mm; R = 8mm θ = 0˚	Exponential	$y= 14.239e^{-0.005x}$	0.2661
	Linear	y = -0.0639x+14.18	0.2541
	Logarithmic	y = -0.428ln(x)+14.363	0.0708
	Polynomial		
	Order: 2	$y = -0.0169x^2+0.4521x+10.911$	0.9881

Variable parameters	Type of curve	Equation	(R^2)
	Order: 3	$y = 0.0002x^3-0.0277x^2+0.591x+10.409$	0.992
	Order: 4	$y = 0.00008x^4-0.0045x^3+0.07034x^2-0.2142x+12.555$	0.9987
	Order: 5	$y = -0.00003x^5+0.0023x^4-0.0659x^3+0.8788x^2-5.1269x+23.307$	0.9999
	Power	$y= 14.481x^{-0.035}$	0.0781
All equations applicable for $5 \leq x \leq 25$, (x = punch travel, and y= bending force), For bending y_{max} is required once punch travel x crosses this force.			

Table 6 shows various equations of trend line and their coefficient of determination, R^2, computed using Microsoft Excel 2016 program for variable parameters, Vp = 0.4 mm/sec; Wd = 60 mm; Rd = 5 mm; Rp = 8 mm, θ = 0°. It was observed that polynomials are preferable among all equations and polynomial of a 2nd order was the best fit since R^2 is very close to 1 and for a higher order of the polynomial, the value was not increasing much and leads to inflexion. It was observed polynomial of a 2nd order was fitting to all the tested combinations with R^2 ranging from 0.8975 to 0.992 as shown in Table 7.

Table 7. Correlation of punch travel and bending force

Sl.No.	Experiment	Polynomial equation Order :2	(R^2)
1	Vp=0.4mm/sec; Wd= 60mm; Rd=5mm; Rp= 8mm; θ =0˚	$y = -0.0169x^2+0.4521x+10.911$	0.9881
2	Vp=0.4mm/sec; Wd= 60mm; Rd=5mm; Rp= 8mm; **θ =90˚**	$y = -0.0164x^2+0.4240x+11.699$	0.9873
3	**Vp=0.6mm/sec**; Wd= 60mm; Rd=5mm; Rp= 8mm; θ =0˚	$y = -0.0178x^2+0.4815x+10.9$	0.9898
4	**Vp=0.8mm/sec**; Wd= 60mm; Rd=5mm; Rp= 8mm; θ =0˚	$y = -0.0174x^2+0.4428x+11.353$	0.9531
5	Vp=0.4mm/sec; Wd= 60mm; Rd=5mm; **Rp=12mm**; θ =0˚	$y = -0.0193x^2+0.5294x+10.742$	0.9874
6	Vp=0.4mm/sec; Wd= 60mm; Rd=5mm; **Rp=16mm**; θ =0˚	$y = -0.037x^2+1.2408x+7.2077$	0.8975

Sl.No.	Experiment	Polynomial equation Order :2	(R^2)
7	Vp=0.4mm/sec; **Wd= 40mm;** Rd=5mm; Rp= 8mm; θ =0˚	$y = -0.0327x^2+0.673x+17.46$	0.9876
8	Vp=0.4mm/sec; **Wd= 80mm**; Rd=5mm; Rp= 8mm; θ =0˚	$y = -0.0075x^2+0.2454x+5.9817$	0.9684
9	Vp=0.4mm/sec; Wd= 60mm; **Rd=3mm**; Rp= 8mm; θ =0˚	$y = -0.0186x^2+0.4987x+10.831$	0.9876
10	Vp=0.4mm/sec; Wd= 60mm; **Rd=8mm**; Rp= 8mm; θ =0˚	$y = -0.0136x^2+0.4172x+9.5994$	0.992
All equations are applicable for $5 \leq x \leq 25$, (x = punch travel and y= bending force), For bending ymax is required, once punch travel x crosses this force.			

CONCLUSION

As per the results obtained from the experiments and discussion, it is concluded that

- Die width is the main source for reducing the bending force and by increasing die radius it can be further reduced marginally. These two parameters can be used to produce a part on a low capacity press.
- A decrease of punch radius decreases the bending force. Change of orientation of steel sheet and velocity has a marginal effect on bending force.
- Maximum bending force on the graph should be considered, since peak force shifts with the shift of one parameter to the other and not fixed for punch travel.
- Bending force follows polynomial equation of 2nd order, so bending force chart can be tailor made after few trials for shop requirement.

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