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Formability enhancement of high strength steel using modification of contact with friction conditions

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ABSTRACT

High strength steels are most widely used in automobile industries due to their superior mechanical properties and light weight. However, the formability is poor compared to conventional steels due to high hardness and carbon content. Process parameter, such as, contact with friction condition between the forming tools and the blank can be modified to enhance formability of high strength steel. In this work, the forming die is coated with Titanium aluminium nitride (TiAlN) and the effect of TiAlN thin film coating on the formability of EN10 131 high strength steel is investigated. Small circular cup geometry is chosen for deep drawing experiments and Taguchi technique is used to design the experiments with different levels of the process parameters. The novelty of this study lies in the use of surface coating on the forming tool to modify the friction conditions that exist between high strength steel blank and the die. TiAlN coating on the die has improved the formability of steel considered. The analysis of variance is carried out to study the influence of process parameters on the maximum punch force and their contribution was computed. Contact with friction condition plays a major role, in addition to the blank diameter, in improving the sheet metal formability. The quality of the deep drawn part, in terms of thickness distribution, is influenced by TiAlN-coated die surface

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1. Introduction

High strength steels (HSS) are advanced materials, with favourable chemical compositions, hardness and carbon equivalent. Different strengthening alloys and mechanisms are applied to attain suitable strength, ductility, toughness, and fatigue properties for applications in automobile and other industries. High strength steel offers several advantages, including, weight reduction, increase in crashworthiness, safety, etc. The enhanced structural capabilities of HSS create more challenges during forming and affect the quality of the formed part. These include, higher press load requirement, stronger forming tools, increased spring back compensation and control [1].

Various techniques have been developed to improve formability of high strength steel. Low friction cermet die is used to increase the formability of stainless steel in the ironing of drawn cups. However, increase in ironing speed shows little effect on the formability of

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stainless steel even with cermet die [2]. Contact with friction condition, between the forming tools and the blank, is a major factor that influences the formability of ultra-high strength steels using deep drawing process [3]. Maeno et al. [4] were able to improve the formability of ultra-high strength steel by reducing the contact with the die and blank holder as well as elevating the blank temperature. Flange hardening is minimised by increasing the forming speed and in addition, the temperature drop in the blank is eliminated due to less contact with the tools. By employing this approach the formability of ultra-high strength steel was found to improve. Padmanabhan et al. [5] illustrated the use of Taguchi technique in the experimental design of stainless steel forming and reported that die radius has a major influence on the deep drawing process. Mayavan et al. [6] reported that formability can be improved by reducing the friction between the blank and die, compared to the friction between the blank and the punch. Reducing the friction between blank and the die reduces the drawing stress and results in preventing blank thinning. The formability of high manganese twinning induced plasticity (TWIP) steel was evaluated using Enrichen test under quasi-static and high speed deformation. The Enrichen index values are similar to those from conventional Enrichen test. High deformation rate has little influence on stretch formability of TWIP steel [7].

The effect of niobium inclusion on the formability of TWIP aided bainitic ferritic steel was investigated [8]. The inclusion of niobium has remarkably improved the formability of TWIP steel. The formability of TWIP-cored three-layered steel was investigated using deep drawing tests. The limiting draw ratio of TWIP steel decrease as the volume fraction of TWIP-core increase [9]. Moreover, the forming of tailor welded blanks is a demanding task due to considerable lowering of its formability due to weld line hardening and its movement during forming. An attempt has been made to improve the formability of tailor welded blanks by modifying forming parameters and blank holder geometry [10]. It was found that the coating on selective die sections can enhance material flow in forming different sections of the tailor welded blank. Low formability of ultra high strength steel restricts their application for many components in a car body [11]. The authors observed that the formability limitation can be reduced by employing laser surface modification technique. A laser beam is used to soften the sheet material where high formability is required. FE simulations were utilised to identify the areas where softening is desirable.

The hole expansion experiments on dual phase (DP 980 and DP1180) steels were carried out to determine their formability [12]. Under machine edge condition, the hole expansion ratio is more than that of sheared edge condition with a conical punch. Experiments performed with conical punch displayed high hole expansion ratio than flat bottom punches. Volume fraction, martensitic carbon content and structure play key role in the formability up to a critical value of the martensite volume fraction. Draw bend experiments were performed with three dual phase steels to determine their failure modes [13]. A strip of sheet metal is bending around a roller by two grips. The speed of the back grip is controlled. Three forms of failure were observed depending on draw speed, draw speed ratio and R/t ratio. Shear failure progresses for smaller R/t ratio and high deformation rates. The temperature increases are remarkable, up to 100°C, and subsequent loss of strength in affected regions.

A deformation-based control method is employed to enhance the formability of heated sheet metal in reference [14]. The local deformation is suppressed by partial cooling around possible cracking zones to harden them before forming. Consequently, the partial cooling method was applied to a deep drawing experiment with a heated steel sheet. The recommended technique improved 71% in the forming limit depth compared with results attained using a constant initial temperature distribution.

Forming of ultra-high strength steel sheets results in wrinkling, causes seizure and wear of forming tools and reduce the forming tool life. The punch, having gradual contact, is employed to avoid wrinkling of ultra-high strength steel sheet forming [15]. In shrinkage flanging, the flange height limit without wrinkling is enhanced by 27% using the gradual contact punch compared to the flat punch. The wrinkles are reduced by decreasing the punch apex angle. The maximum forming force for shrink flanging, by means of gradual contact punch decreased compared to the flat punch.

An attempt has been made to draw aluminium cups under dry contact conditions without lubricants [16]. Initial investigations displayed good results with Diamond like Carbon (DLC)-coated tools without lubricants. The properties of DLC coating are tailored to acquire favourable tribological conditions. Lovell et al. [17] used boric acid and canola oil mixed to form an environmentally friendly lubricant for sheet metal forming process. In order to determine the interfacial friction characteristics of boric acid and canola oil in the forming operation, a strip tensile friction simulator was used. The test results suggest that boric acid and canola oil outperformed other lubrication approaches with respect to the overall sheet formability. The forming tests indicate that the composite coating prevents adhesion. The forming tool requires less amount of additional lubricant to achieve desired performance. Chen et al. [18] investigated the effect of surface texturing on TiN-coated die in the tribological performance of sliding members. This technique improved adhesion properties and bonding between TiN coating and the die substrate material. Adding oil lubricant to the surface modified contact pair exhibits enhanced tribological performance characteristics, resulting in the lowest friction coefficient. Elmkhah et al. [19] used multi-layered coating (TiN/TiAlN/TiN) on AISI H13 tool steel to study the tribological and mechanical characteristics for forming applications. Though the adhesion and tribological behaviour of multi-layer coated surface is superior compared to single layered TiAlN coating, the micro hardness of the former is high compared to the latter.

The effect of process parameters such as punch corner radius, die corner radius and draw depth on thinning of mild steel and aluminium were investigated [20].The results will help tool designers in the choice of proper size of punch and die corner radius in order to reduce the thinning of drawn cups. The influence of process parameters on punch forces, plastic strain and thinning were investigated in incremental forming [21]. The simulations were planned with Taguchi orthogonal array. FEA software LS-DYNA was used to perform simulations Punch diameter, step depth and wall angle were used as input process parameters for analysis. The analysis shows that wall angle has the maximum effect on all three output variables. The influence of contact is investigated on the adaptive simulation of deep drawing process having varying frictional coefficient and sheet thickness [22].

The tribological behaviour of TiN and TiCN coatings depend upon the substrate material on which it is deposited [23]. Pin-on-disk experiments were conducted under lubricated and dry conditions at 100°C with Tungsten Carbide as the counter material. Coefficient of friction of 0.08 and 0.03 were attained for TiN and TiAlN coatings under lubricated conditions.

Sivarajan et al. [24] reported that TiAlN coatings presented remarkably high wear resistance than the other two investigated coatings, namely, Aluminium chromium nitride (AlCrN) and Titanium nitride (TiN). TiAlN coating is the choice of tool material (AISI D2) in this study to modify friction behaviour and improve wear resistance. As the literature suggests, the forming die surface plays a critical role in the formability of high strength steel and hence, in this study, an attempt is made to modify the surface of the die alone, leaving the punch and blank holder as it is. Several approaches are practiced to minimise friction between sliding members, such as use of harder materials for the tools, use of suitable lubricant, superior surface finish on the tools, etc. However, use of liquid lubricant can produce adverse effect during its removal before use, creating a hazardous environment. A logical and clean approach to the reduction of friction between tools is to use thin film coating on the forming tool. Nonetheless, in the last decade, very little research work have been carried out on the effect of coating on forming tools, especially on its influence in high strength steel formability. In the present study, a new approach to enhance the formability of high strength steel using TiAlN thin film die coating is investigated under various deep drawing process conditions for small circular cup geometry. Taguchi technique is used for the experimental design and ANOVA is used for the analysis of the results. The experimental procedure is described in the next section, followed by the results. Thickness distribution of the formed cup is determined and ANOVA is used to identify the contribution of the process parameters. Finally, concluding remarks are provided.

2. Materials and methods

Strenx 700 CR (EN10131) high strength steel blanks from SSAB Sweden with thickness of 1.5 mm were used in this work. The mechanical properties and chemical composition of the sheet material are given in Tables 1 and 2 [25]. Small circular cup geometry is chosen for this deep drawing study, as shown in Figure 1(a). Circular blanks of diameter 54, 57, 60 mm were cut from the sheet using laser-cutting machine. The punch, die and blank holder were made of AISI D2 steel and heat treated to RC60. The dimensions of the punch, the die and the blank holder are given in Figure 1(b).

The deep drawing experiments were carried out in a 400 kN capacity universal testing machine. The blank is held in place by a blank holding device as shown in Figure 1(c). Three contacts with friction condition, namely, dry condition, oil lubrication, and TiAlN die coating, were used in the deep drawing process. The PVD BALINIT LUMENA TiAlN coating was carried out in Oerlikon Balzers Pvt Ltd., Chennai, India, and the coating properties are given in Table 3. The punch and blank holder were left uncoated. The

Table 1. Mechanical properties of Strenx 700 CR EN10131 high strength steel.

Steel grade	Yield Strength(MPa)	Tensile Strength (MPa)	Elongation (% min)
Strenx 700 CR EN10131	700	1060	7

Table 2. Chemical Composition of Strenx 700 CR EN10131 High Strength steel.

C	Si	Mn	P	S	Al	Ni + TI	Fe
0.16	0.4	1.8	0.02	0.01	0.015	0.1	Balance

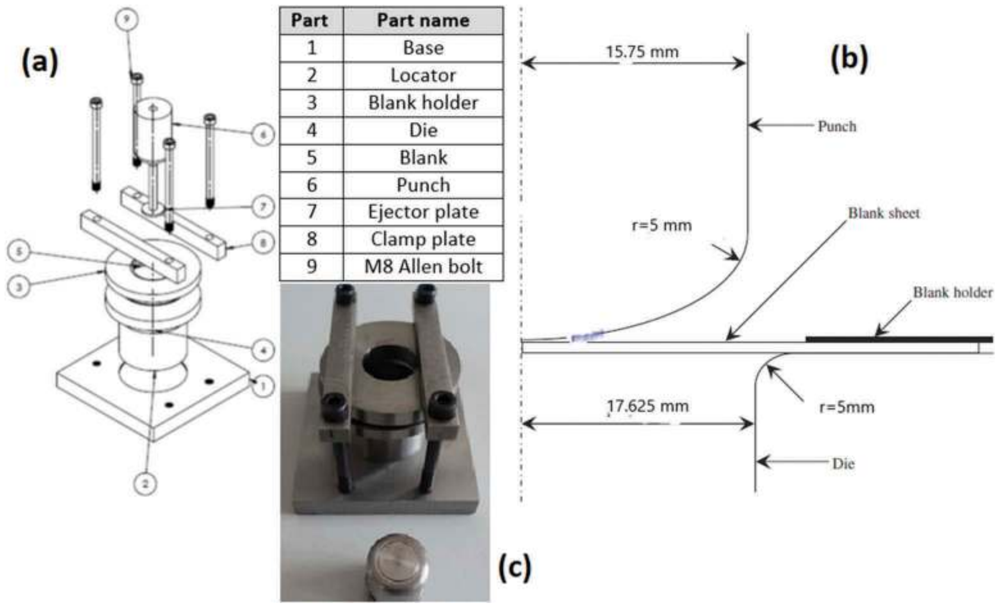

Figure 1. (a) Exploded view of forming tool with blank holding system (b) Geometry of forming tools (c) Assembled forming tools.

Table 3. Coating properties.

Coating Name	BALINIT LEMENA (Oerlikon Balzers)
Coating material	TiAlN
Micro hardness (HV0.05)	3400
Coefficient of friction against steel	0.30–0.35
Coating thickness	10 µm
Residual stress	1.1 GPa
Maximum service temperature	900°C
Coating temperature	450°C
Coating colour	Violet grey
Coating structure	Nano structured

punch force was measured using a load cell mounted on the Universal testing machine. The punch displacement was measured using an LVDT. The punch force and punch displacement are recorded by a data acquisition system as the cup is drawn. The punch speed was maintained at three levels, including, 0.17, 0.2 and 0.245 mm/s. The deep drawn part quality is function of the thickness distribution and flange profile in the formed part, while this has to be achieved at low punch force and optimal blank holder force. Such high quality parts are free from wrinkling and tearing. The blank holder force should be low at first and then increased as the cup is drawn to eliminate the likelihood of wrinkling. The values of blank holder force were estimated by trial and error.

In this study, Taguchi method of experimental design was used to formulate the forming experiments. An unbiased comparison of the process parameters levels and a remarkable reduction in the total number of necessary experiments are achieved by Taguchi technique [26]. The process parameters investigated include friction condition, blank diameter and punch speed. The parameters with their levels of operation are given

Table 4. Parameters and their levels.

Parameter	Level 1	2	3
Lubrication Type (L)	TiAlN Coating	Dry	Oil Lubricated
Blank Diameter (B), mm	54	57	60
Punch speed (P), mm/s	0.17	0.2	0.245

Table 5. Orthogonal Array (L9) of Taguchi method.

Experiment	Parameter L	B	P
1	1	1	1
2	1	2	2
3	1	3	3
4	2	1	2
5	2	2	3
6	2	3	1
7	3	1	3
8	3	2	1
9	3	3	2

in Table 4. The L9 orthogonal array, with factors and their levels, is given in Table 5. The results obtained from the experiments are subjected to statistical analysis, namely, ANOVA. ANOVA is used to determine the contribution of the parameters that govern the deep-drawing process and that markedly influence the deformation. Thus, the impact of each process parameter on the quality of the deep drawn circular cup can be found and the degree of influence of the process parameters on the formability of the high strength steel sheet is determined.

3. Results and discussion

Table 6 shows a set of deep drawing results for blanks using dry, oil lubrication and coated die conditions. Figure 2 shows the variation of punch force with respect to its displacement for the experimental conditions listed in Tables 4 and 5. The maximum punch force is observed for a blank diameter of 54 mm with TiAlN-coated die is 82.2 kN, whereas the maximum punch force recorded under dry and oil lubrication forming conditions are 98.56 and 94.1 kN, respectively. TiAlN coating enhances the contact with

Table 6. Results for Maximum punch force and Signal-to-Noise ratio.

Experiment	Maximum Punch Force in kN	SN Ratio
1	82.2	−38.2974
2	107.5	−40.6282
3	120.2	−41.5981
4	98.56	−39.874
5	110.82	−40.8924
6	124.4	−41.8964
7	94.1	−39.4718
8	110.22	−40.8452
9	134.98	−42.6054

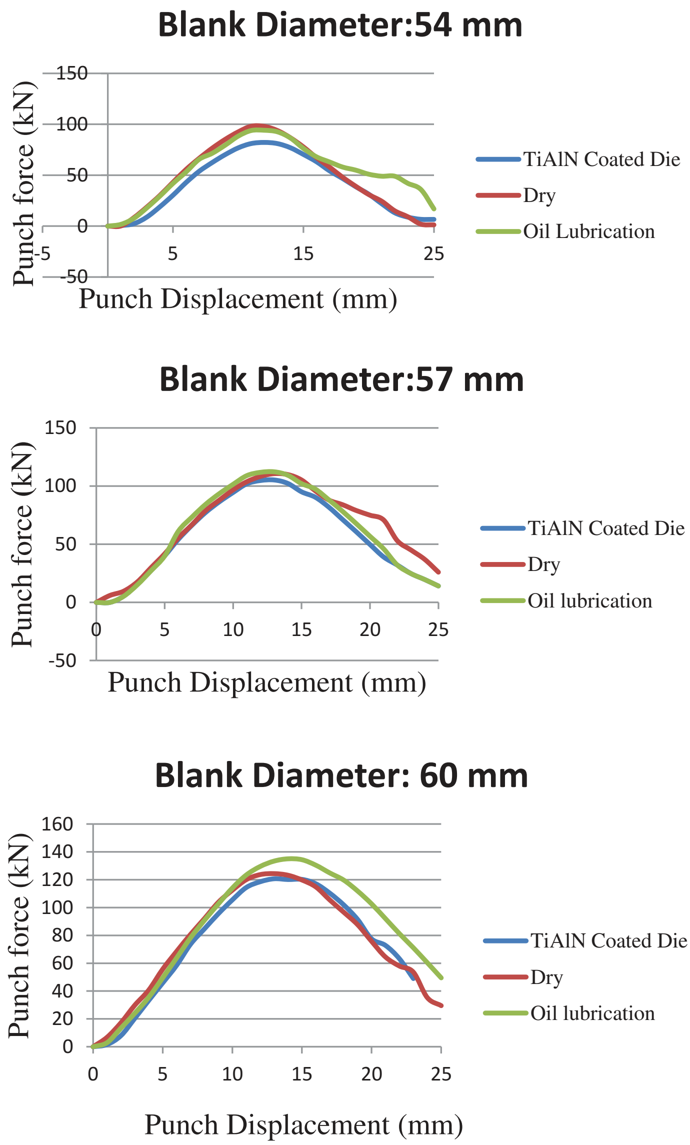

Figure 2. Punch force evolution.

friction conditions at the die-blank interface, causing the blank to flow with ease and smooth. Similar trend is observed in experiments with blank diameter of 57 and 60 mm. This indicates that for any combination of blank diameter and strain rate, a lower punch force is required if coated die is used. The friction amounts to a considerable portion of deep drawing force. Reduced friction force, due to TiAlN-coated die, results in reduced punch force needed for deep drawing the cup. The reduction in punch force for a combination of process parameter indicates improvement in the formability of high strength steel. The circular cups formed under different forming conditions are shown in Figure 3.

(a)

(b)

(c)

Figure 3. (a) Drawn cups of Strenx 700 CR EN10131 High strength steel (TiAlN Coated Dies)Blank Diameter 54,57,60 (b) Drawn cups of Strenx 700 CR EN10131High strength steel (under dry forming conditions Blank Diameter 54,57,60) (c) Drawn cups of Strenx 700 CR EN10131 High strength steel (under oil lubrication) Blank Diameter 54,57,60.

Abe et al. [27] reported that TiN-coated die is not suitable for deep drawing high strength steel sheets. Seizure occurred in uncoated die in their studies. However, this investigation points out that TiAlN-coated die is suitable for deep drawing of high strength steel, such as EN10131, with a tensile strength of 980 MPa. Moreover, seizure never occurred in the forming of this grade steel. The contact with friction condition, due to TiAlN coatings, is found to be superior to the coated die developed by Abe et al. The abrasive wear is reduced due to nitride layer and improved supporting effect. The combination of high hardness and low friction has provided the superior lubricating effect. TiAlN-coated dies are able to improve the tribological behaviour in the deep drawing of high strength steel, consequently improving its formability.

3.1. Thickness distribution

The quality of deep drawn part is measured in terms of the thickness distribution. Uniform thickness distribution indicates high quality while large variation in the thickness indicates poor quality of the deep drawn cup. Three samples cups, obtained from three different experiments (3, 6, 9) were subjected to thickness verification. The thickness of the formed cup at various locations was measured using Mitutoyo Spherical Face Spherical Spindle Micrometre (Model:395-271-30). The resolution of micrometre is 0.001 mm and accuracy of ±2 µm. The thickness was measured at 4 critical locations at (1) bottom centre of the cup, (2) 10 mm from bottom centre(bottom), (3) 20 mm from bottom centre (lower wall), and (4) 25 mm from bottom centre (middle wall). The measurements are made along rolling direction and transverse to rolling direction. Measurements were made with cup formed under dry forming condition, cup formed with liquid lubrication and a cup formed with TiAlN-coated die. The thickness distribution of the three cups is shown in Figure 4. All the cups are formed with constant punch geometry. Maximum thinning is observed while forming under dry condition, as indicated in Figure 4(a) and similar trend is observed while using liquid lubricant, shown in Figure 4(b). Uniform thickness distribution is observed with minimum thinning when the cup is formed using TiAlN coated die, as shown in Figure 4(c). There is a considerable variation in sheet thickness distribution in rolling direction and transverse to rolling direction, in all three contacts with friction condition. From this it is evident that the thickness distribution of sheet depends on the marginal plastic anisotropy available in the material. The thickness distribution is highly uniform in the cups formed with TiAlN-coated die. This is due to the fact that TiAlN coating on the forming die has improved the friction condition of the forming process.

3.2. Analysis of variance (ANOVA)

The marked decrease in maximum punch force is observed while deep drawing EN10131 with TiAlN-coated die and is similar to the values observed by Seah et al. while deep drawing mild steel with TiN-coated die [28]. TiN radical nitride die developed by Sresomroeng et al. [29] show high friction coefficient and experience material transfer when in contact with advanced high strength steel. However, in this investigation, galling on deep drawn cups is completely absent with TiAlN-coated dies. Moreover, the peeling of TiAlN coating in the forming die is not observed during the deep drawing experiments.

Formability is a major quality characteristic in sheet metal formed part that reflects the influence of design parameters accurately. In this study, the formability is represented by maximum punch force achieved in deep drawing of high strength steel sheet. The signal-to-noise ratio (S/N) is calculated using the condition being smaller is better for the nine experimental combinations which are presented in the Table 6. Since the experimental design is orthogonal, the effects of the process parameters are identified in terms of the S/

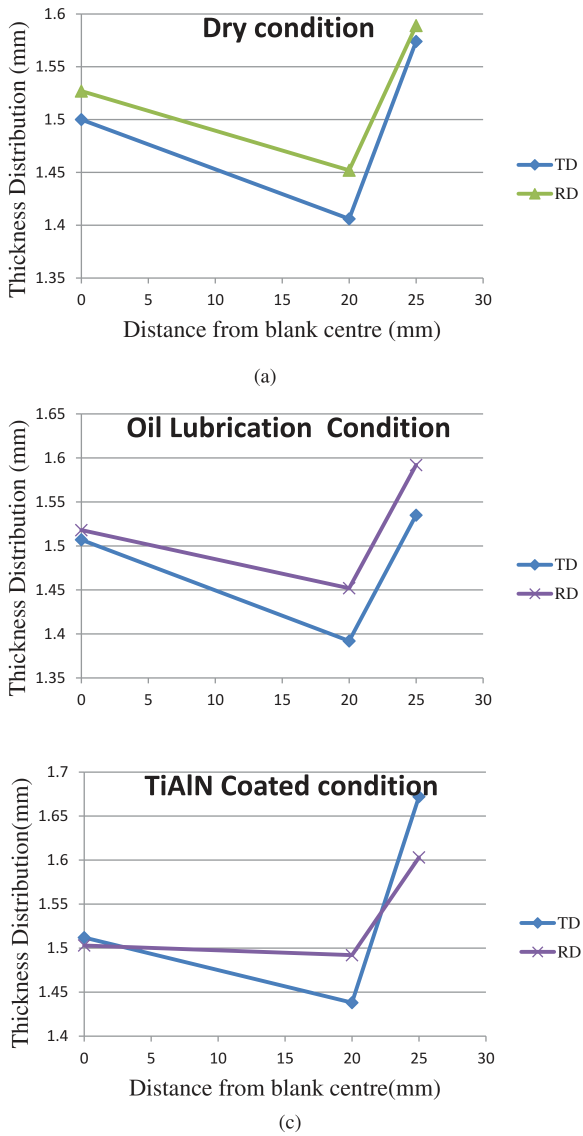

Figure 4. (a) Thickness variation under dry condition. (b) Thickness variation in oil-lubricated condition. (c) Thickness variation with TiAlN-coated condition.

N ratio and mean response. The mean values of S/N ratio of the three process parameters at three levels are shown in Figure 5. From this, the levels corresponding to the highest S/N ratio are chosen for each process parameter and identified as the optimum condition. Minimisation of the maximum punch force is considered as optimum condition in this investigation. It is evident from Figure 5 that the optimum levels of the process parameters are: TiAlN coating on the die; blank diameter of 54 mm and punch speed of 0.17 mm/s that corresponds to experiment 1. In addition, the main effects of the process parameters on the mean response are investigated. The mean response refers to the average value of quality characteristics for each factor at different levels. Thus, the average

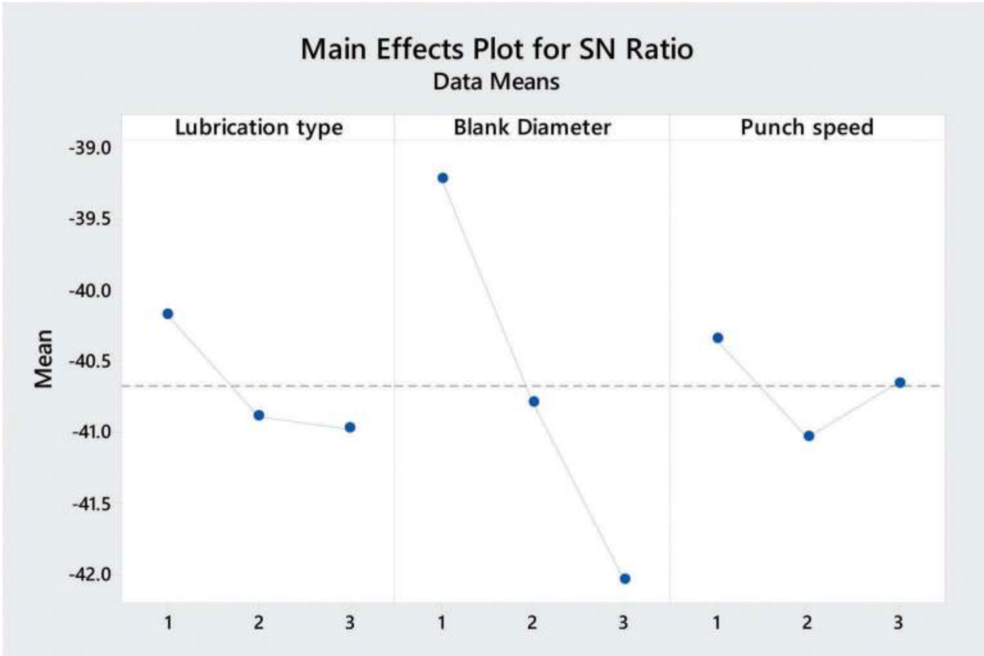

Figure 5. Effect of parameters on average S/N ratios.

value of the maximum punch force for each factor at three levels is computed and plotted in Figure 6. The mean response analysis shown in the figure indicates optimum level of parameters as obtained from the S/N ratio analysis.

ANOVA was carried out to study the relative significance of the parameters. Table 7 shows the calculated results of the ANOVA with 95% confidence. The percentage contribution of various parameters shows that lubrication type and blank diameter has significant effect on maximum punch force. However, punch speed has negligible effect on maximum punch force. Blank diameter has the maximum percentage contribution with 87.3 %, followed by lubrication type (7.77) and punch speed (0.13).

4. Conclusions

In this paper, a novel approach to enhance the formability of high strength steels is presented. The forming die is coated with a thin film of TiAlN and its influence on the forming of high strength steel (Strenx 700 CR EN10131) is investigated. The punch and the blank holder are used as it is, without coating. The formability of high strength steel considered (EN10131) is enhanced by the use of TiAlN-coated die in deep drawing of circular cups. The quality of the deep drawn circular cup is significantly influenced by the TiAlN-coated die as observed in the thickness distribution. Cups drawn with coated die has more uniform distribution compared to dry lubrication and oil lubrication conditions. Galling and failure of cups due to peeling-off of coating material is completely absent in the deep drawing experiments. From the S/N ratio analysis, the best combinations of parameter are lubrication type: TiAlN coating, blank diameter: 54 mm and punch speed: 0.17 mm/s. The ANOVA was carried out to study the

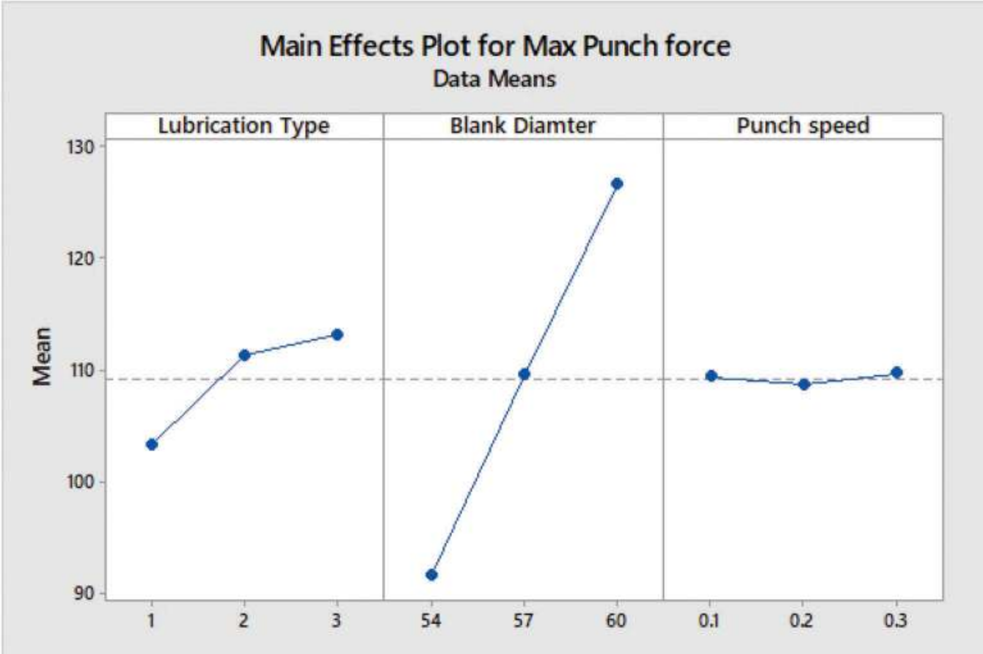

Figure 6. Effect of parameters on average response characteristics.

Table 7. Analysis of variance (ANOVA) for maximum punch force.

Source	Degree of freedom	Adj SS	Adj MS	Percentage Contribution
Lubrication Type	2	162.79	81.394	7.77
Blank Diameter	2	1828.10	914.05	87.3
Punch speed	2	1.54	0.769	0.13
Error	2	100.99	50.497	4.8
Total	8	2093.42		

influence of process parameters on the quality characteristics (formability represented by maximum punch force) of the circular cup and their percentage contribution were computed. The blank diameter has major influence (87.3%) on the deep-drawing process, followed by lubrication type (7.7%) and punch speed (0.13%). Uniform thickness distribution is obtained in the cups formed using TiAlN-coated die.

Disclosure statement

No potential conflict of interest was reported by the authors.

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