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Finite element simulation and experimental investigation of the effect of clearance on the forming quality in the fine blanking process

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Response to Reviewers:	Response to Editor and Reviewer Comments: Ref. No.: MITE-D-20-00578 Title: Finite element simulation and experimental investigation of the effect of clearance on the forming quality in the fine blanking process We greatly appreciate the work of the editor and reviewer in evaluating this manuscript. All remarks and comments from the reviewer have been considered in the revised version of the manuscript.

	Reviewer #1: This is a very interesting paper. It should be accepted for publication. Please add some remarks, if possible, how the results could be applied for other kinds of microsystems. These sentences have been added in the conclusion : This FE model will also extended to investigate the tribological behaviour between a punch with nanostructured surface and a blank under full or severe tribological conditions. A necessary conditions for functionalisation surface such as arrangement, coverage, and depth will be experimentally and numerical studied to extend the tool life in precision blanking.

Finite element simulation and experimental investigation of the effect of clearance on the forming quality in the fine blanking process

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Abstract:

The general concept of blanking seems a simple one but governing parameters are many and have a complex relation-ship, which directly affect the quality of the produced parts. These parameters are assessed using three main criterions: the burr amount, the appearance of the cut edge and dimensional accuracy. However, the optimization of these parts produced depends on full understanding of the fine blanking process. The aim of our work is to develop the numerical computations in order to investigated the influence of selected parameter of the cutting process on the stress state of cold-rolled steel sheets being cut. The material testing and the characterization are carried out in order to fit the constitutive model parameters to the experimental data and to establish the sheet metal constitutive law. The identified model is, then, used for numerical simulations which are performed using LsDyna/Explicit software of various blanking tests. During of numerical simulations of the fine blanking process was observed elongation in shear surface and simultaneous reduction in fracture zone versus clearance punch/die and also that punch is be considered deformable or not. The numerical results of the validation simulations were in agreement with the experimental data.

Keywords: Metal blanking, plasticity, numerical simulation, steel sheet.

1. Introduction

The fine blanking is a forming process characterized by effective precision. It is playing an increasingly important role in the industry [1-4]. The parts with a smooth cutting surface can be obtained using this process type [5,6]. This process is often used to mass-produce metal components used for industries such as aerospace and automotive. The fine blanking process consists in separating a blank from a sheet by means of a high-localized shear deformation due to the action of a punch (Fig.1a). The quality of sheared edge after blanking process depends not only on the material used, but also many process parameters such as the blank holding force, the sharpness of the edge of punch and die, blanking speed, lubrication, temperature and clearance between the punch and the die [7,8].

Numerical simulations offer an efficient way not only to save manufacturing costs and to speed up production, but essentially to predict the final quality of the edge profile of the pieces with adequate precision. However, for a realistic modelisation of the fine blanking process, the identification of the laws of behaviour adapted according to the deformation generated, the strain rate imposed, the temperature produced and the final behaviour to the damage is essential.

Several numerical studies were conducted to understand the effect of process parameters on the geometry of the blanked edge including burr, fracture zone, shear surface and rollover. Faura et al (1998), tried to determine optimum clearance by presenting crack propagation angles throughout the sheared edge [9]. Fang et al. (2002) examined the forming quality of the blanking process and concluded substantial effect of punch/die clearance on the shape of the blanked edge [10]. Hambli et al, (2001) studied the same concept and also integrated neural networks to predict burr heights and to optimize the blanking process [11]. Husson et al.(2008) found that the quality of the sheared edges is lower for greater punch/die clearances and/or tool wear [12]. As shown by Bratus et al.(2010), optimisation of the punch shape and clearance leads to a better geometrical accuracy of the blanked part [13].

Morever, Uemori et al. (1998) examined the linear kinematic hardening and it is concluded that the results of simulation in combined model is very similar to reality [14]. Liu et al. (2002) were minimized the percentage of elastic return by varying the holding load imposed on the blank support [15]. Padmanabhan et al. (2008) analyzed the effect of the return load applied to the metal sheet on the elastic return. They observed that increasing the applied force can lead to reduce in the elastic return angle [16]. Huang et al. (2014) were studied the shear-zone length in fine hydromechanical blanking and the effect of the hydraulic pressure in the V-ring cavity. The results indicate the significance of the hydraulic pressure in the V-ring cavity and ejector chamber [17]. Achouri et al. (2014) were studied influence of the edge rounding process on the behaviour of blanked parts. It is shown that edge rounding by punching improves the component resistance. The punching results also in work hardening of the material in the rounded zones which results in an increase in the local resistance [18]. Gustafsson and al. (2016) were conducted the experimental study of strain fields during shearing of medium and high-strength steel sheet. They showed that the fracture strain was larger for the medium strength material compared with the high strength material and increased with increasing clearance [19]. Wang et al. (2015) were proposed a novel fine-blanking approach. The burnished surface obtained from this approach can nearly achieve the complete thickness of the blank in one operation, suggesting that the fracture zone can be nearly eliminated [20]. Zheng et al. (2019) were investegated on wear-induced edge passivation of fine-blanking punch. They shows that reducing the length of straight lines and radius of arcs results in a large relative sliding distance of material at the punch edge [21].

The aim of this paper is to predict the shear stress and plastic strain distribution in shearing zone during blanking versus punch-die clearance (J) and their effect on the cut edge quality. The results of simulated blanking process were compared with experimental results.

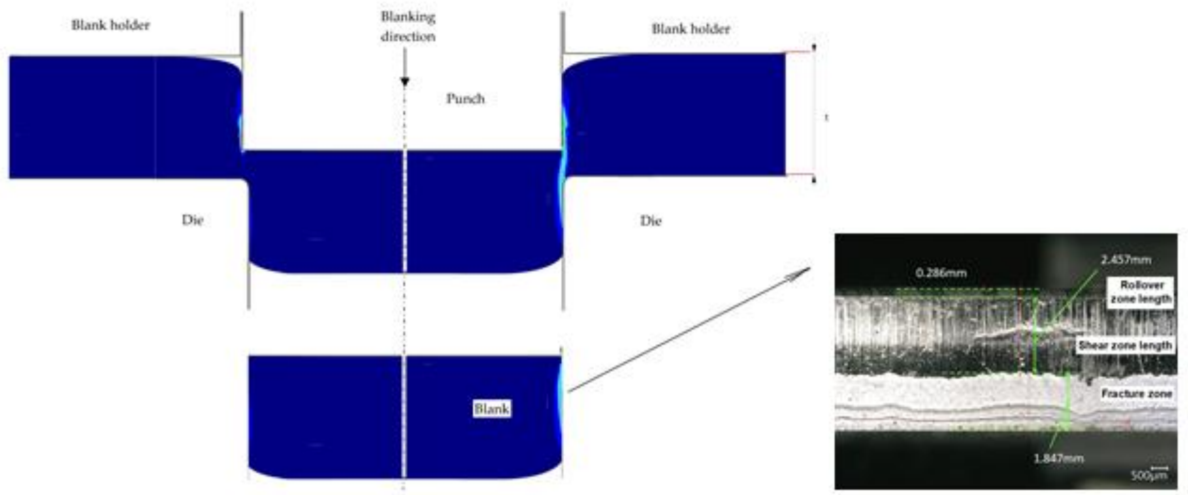

Fig.1. Schematic of the blanking process and typical defects in the blank′s sheared edge [22,23].

2. Materials and sample preparation

2.1. Blanking experiments

The parts were cut in a sheet made of 16MnCr5 with a thickness of 4.6 mm, was a commonly used, raw material quality in blanking process. Table 1 shows the chemical composition and Table 2 shows the associated mechanical properties of metallic materials. To obtain the hardening parameters, tensile tests were conducted using specimens designed according to standards. The tensile test was performed using a servo-electric Instron machine with a maximum load capacity of 100 kN, an accuracy of the load cell of 0.2% with a resolution of 0.01 N and an accuracy of the displacement cell of 0.06% with a resolution of 0.001 mm. Tensile test setup with online strain measurement unit was shown in Fig. 2.

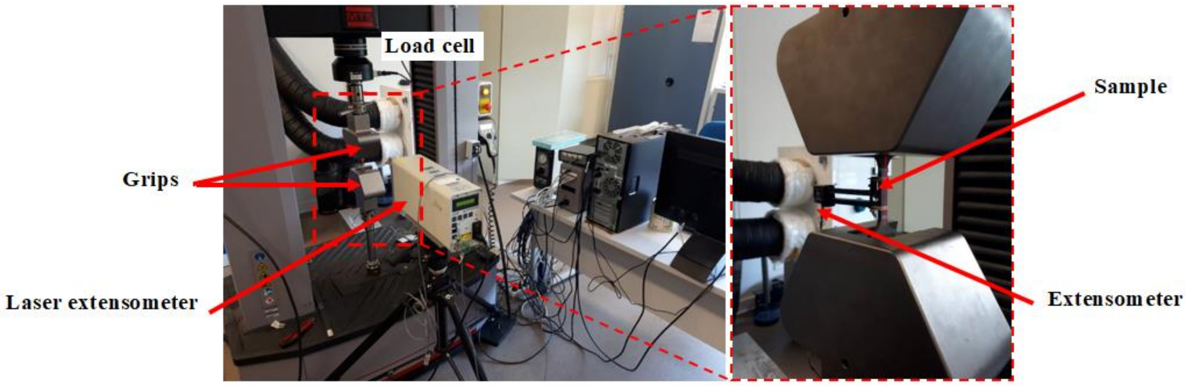

Fig. 2. Experimental setup for tensile testing using servo-electric Instron test.

Flat tensile specimens were cuted in such a manner that specimen loading axis lies in the rolling of the sheet or in perpendicular direction. A constant strain rate of 1mm/s was used for conducting the tensile test. All tests were continued until fracture of the sample. The stress-strain curves of samples with different loading angles, i.e. the angle of the loading directions with respect to the rolling and transverse direction, were shown in Fig. 3. Figure 3, the rolling direction develops a preferred crystallographic orientation in the microstructure that results in an higher strength. Kuwabara et al. (2009) investigated the effect of the rolled direction on the spring back. They found that the effect of spring back in the tangential direction of rolling always is less than the perpendicular direction [24].

In this regard, mechanical properties tend to be lower in the transverse direction which is perpendicular. All of these experimental data was implemented in simulation codes to describe the constitutive model of the steel sheet (see Table 2).

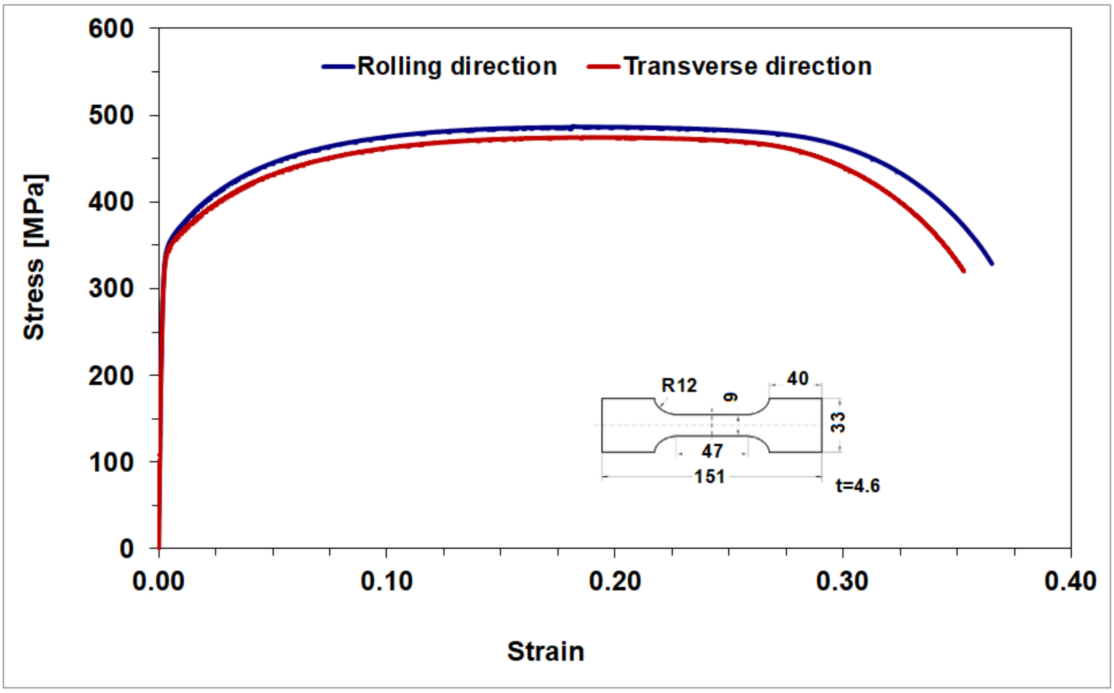

Fig. 3. Stress-strain relationship of 16MnCr5.

All tests were continued until fracture of the sample. Microscopic observations at higher magnification carried out on fractured tensile specimens to reveal the mode of fracture, as shown in Fig.4. The fracture fully ductile with a dull appearance were observed.

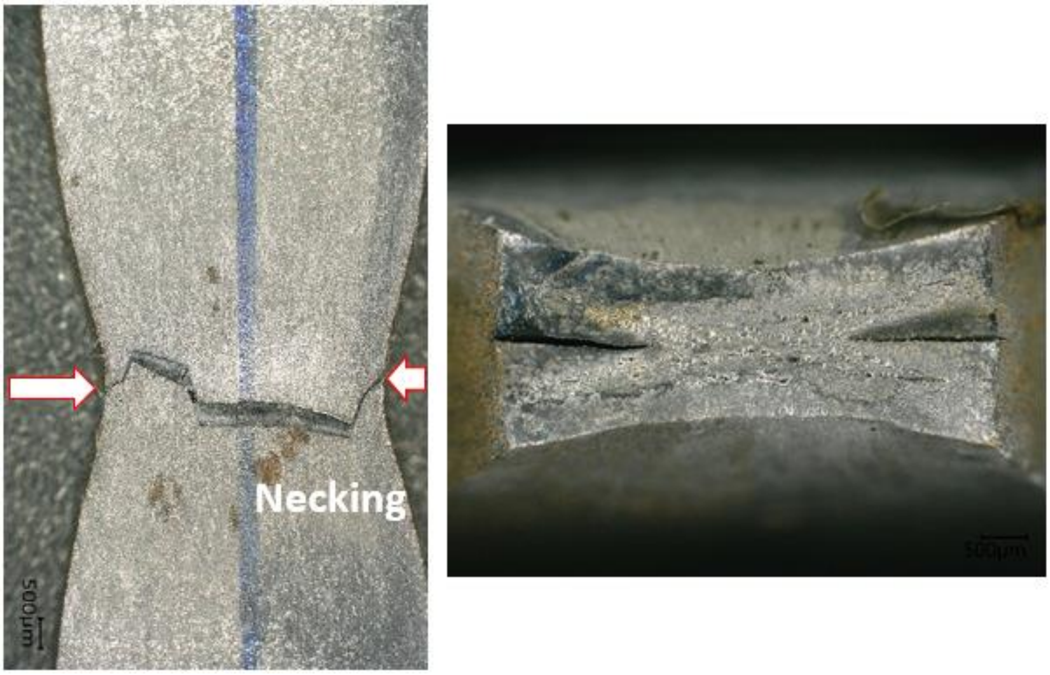

Fig. 4. Optical microscopic structure of necking.

C	Si	Mn	P	S	Cr
0.14-0.19	0.40	1.00-1.30	0.035	0.035	0.80-1.10

Table 1. Chemical composition (average), [%].

Tensile strength R_m	Yield strength $R_{0.2}$	Young's modulus	Poisson's ratio
450 MPa	344 MPa	210 GPa	0.3

Table2. Material properties of the 16MnCr5 sheet.

2.2. Blanking test description

The blanking tool consists of a moving upper part and a fixed lower part. The upper part was instrumented with a displacement, force and thermals sensors, placed close to the punch. The instrumented tool was designed to cut a mechanical component from a 4.6 mm thick sheet metal band. The blanking tests were performed on a mechanical press with a speed of 30 strokes/min. For this part, a cycle time of 1.5 s was used, whereby the actual cut requires approximately 0.4 s. The stroke of the punch (Ø) was set so as to obtain a penetration depth of 5.8 mm. Four clearance of parameters have been used of punch/stripper (J1) and punch/die (J2): (J1/J2) equals to (0.1/0.01), (0.1/0.1), (0.3/0.01) and (0.3/0.1).

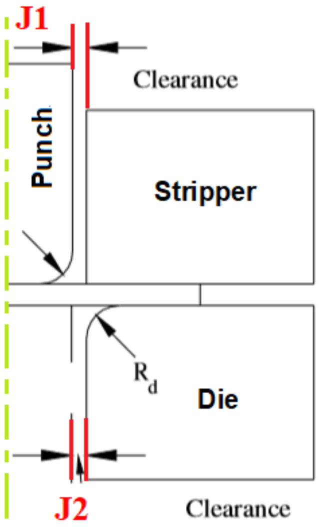

Fig. 5. Geometry of punch, die, stripper, metal sheet and clearance.

All signals were recorded with the acquisition devices. The devices were controlled by a custom designed LABVIEW® routine. Force and vertical tool displacement versus cycle time, from the blanking experiments on the steel sheet material were shown in Fig. 6. The force-displacement and temperature curves were presented to indicate the range of forces and displacements for which strains were evaluated.

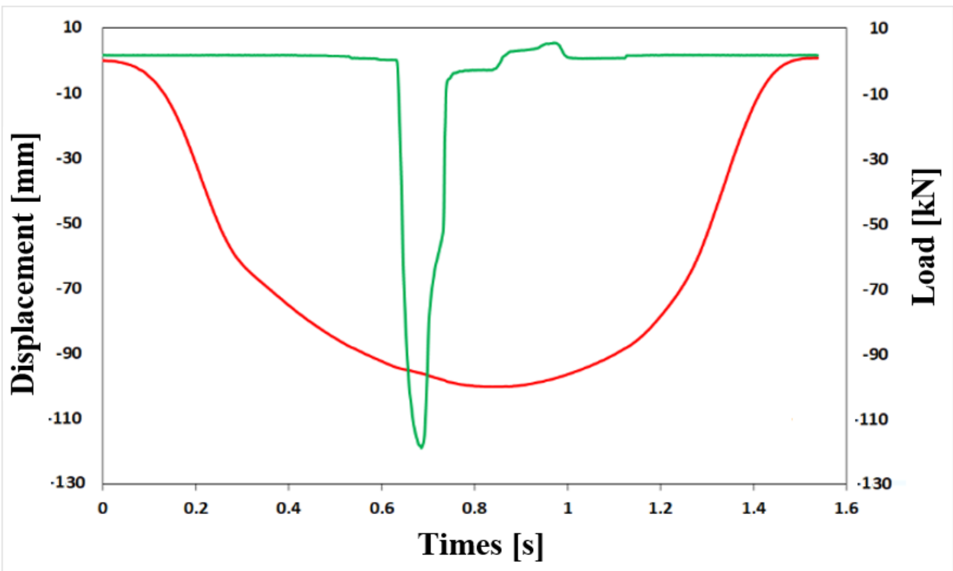

Fig.6. Signals measured during blanking test.

The microstructural analysis was done with a digital microscope from Keyence Co., Ltd., Japan. Microstructural analysis of blanked edges were conducted on a routine basis to assess the edge condition. Figure 7 shows macro photograph of sections of a cut-out zone made with the use of a cylindrical punch. It show the presence of different edge zones: rollover, sheared, fracture and burr zones. The magnification of the zone near the shear cut edge illustrates the degree of deformation of the microstructure. The depth of the shear affected zone was approximately 3.6±0.2 mm, which corresponds to more than one half of the sheet metal thickness. According to Dalloz et al. (2009), the depth of a heavily deformed zone is 0.2 mm when shearing a 1.5 mm thick sheet. The effective measurement length of this zone equal to 0.12 mm on 4.6 mm thick sheet. This is in good agreement with the experimental observation [25]. Micro-hardness testing of sheared samples was used by Weaver and Weinmann (1985) to study the deformation hardening in this region, and Dalloz et al. (2009) showed that a heavily deformed sub-surface region contains crack initiating voids [25,26].

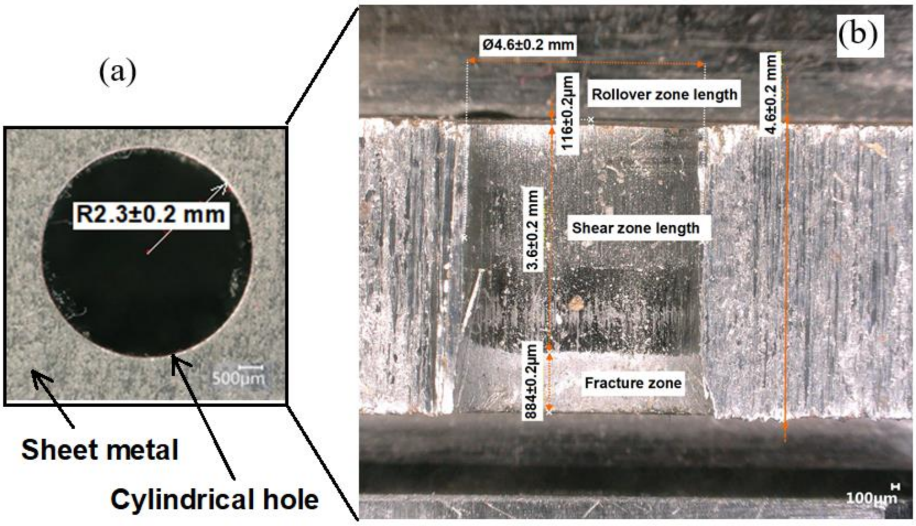

Fig. 7. (a) Blanking process of sheet metal: (a) sheet metal with cylindrical hole, and (b) cross-sections of sample.

3. Finite Element Model

Finite element analyser Lsdyna/Explicit were employed for the numerical simulation of the finite element model. The lower die and blank holder were considered as rigid bodies and assumed to be non-deformable while the sheet blanking was supposed to be deformable isotropic elasto-plastic material of 4.6 mm thickness. In order to study the effect of deformability or not of the punch on the quality of sheared edge after blanking process, in our simulation, we have taken into account this parameter. The exponential hardening law of sheet blanking was identified using tensile tests. Poisson's ratio was 0.3 and Young's modulus was 210 GPa for all materials. The numerical simulations were carried-out for different values of punching clearance (clearance/sheet thickness). The coulomb friction values fitting equal to 0.1 was used in all contacts.

The blanking workpiece was meshed with with PLANE183 elements with reduced integration. The total number of elements in the workpiece was about 6653 elements with 25 elements through the sheet thickness. Lagrangian-Eulerian (ALE) adaptive meshing technique in Lsdyna/Explicit was employed to avoid element distortion in the large plastic deformation of necking localization in the in-situ tensile tests. The displacement was implemented on the punch and fixed constraint was imposed at the bottom of the die. The axisymetric view of the designed tool and its components were given in Fig.8.

Table 3 present the data concerning the properties of the components of a physical model, such as the numbers of nodes and finite elements, into which the individual components of the physical model are divided (see Fig.8).

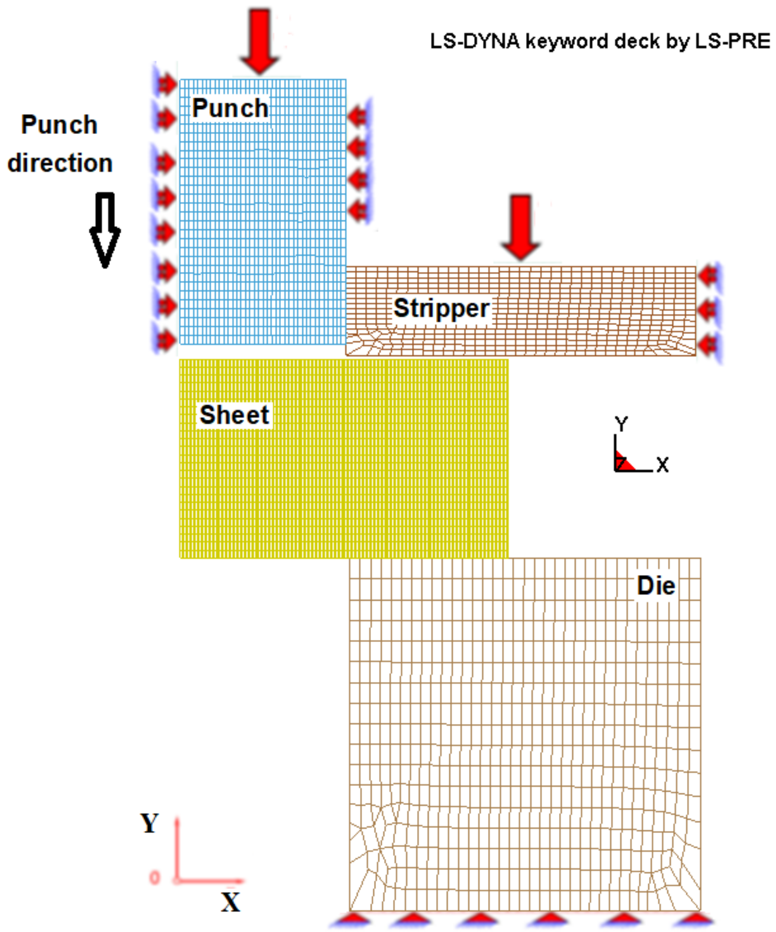

Fig. 8. Geometry and FE mesh used in the numerical simulations of the blanking process.

N°	Name of the part	Kind of Part	Number of Nodes	Number of Elements
1	Punch	Rigid or Deformable	1209	1140
2	Stipper	Deformable	4576	4375
3	Workpiece	Rigid	616	569
4	Die	Rigid	616	569

Total Number : 7017/6653

Table 3. Juxtaposition of data concerning the components of a physical model.

4. Numerical results and discussion

A comparison of shear stress distribution between blanking with reduced clearance of 0.01 mm (case 1) and blanking with 10% or 15% clearance (cases 2&3) was shown in Fig.9. The decrease in clearance limits bending moment acting on the blank due to the lateral displacement between cutting edges. It is also showed the essential influence of clearance on stress values in the shearing zone and consequently on the cut-surface shape.

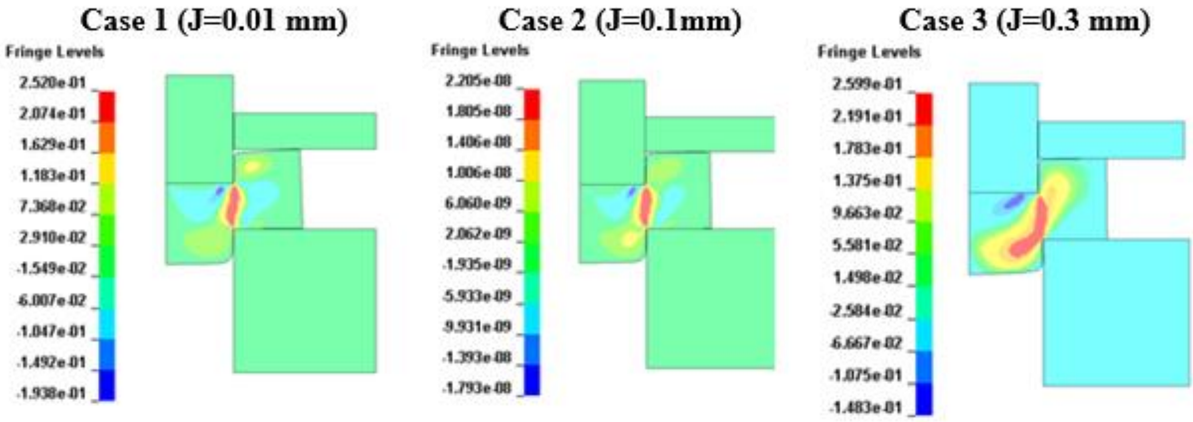

Fig. 9. Shear stress distribution in shearing zone (at 73ms).

A method in which the metal flow line tilting angle was measured and converted to local shear strain, was used by Wu et al. (2012) to characterise the strain distribution within mechanically sheared edges of dual phase steels [27].

The plastic strains distribution evolution obtained through FEM in shearing zone during blanking process (case 2) with sheet compression is shown in the Fig.10. During blanking plasticized zones spreading from the cutting edges of the die and punch, where the plastic deformations initiate, join earlier. Clearance reduction leads to the delay of fracture initiation. All these give smoother cut-surface. As a result, a high quality cut-surface is produced. It should be noted, however, that there is likely to be a minimum clearance limit below which cutting conditions may deteriorate [28]. E. Gustafsson and al. (2016) showed that most of the deformation in the sheet during shearing was concentrated to a band between the tools. The strain band was most straight at 0.15h clearance [29].

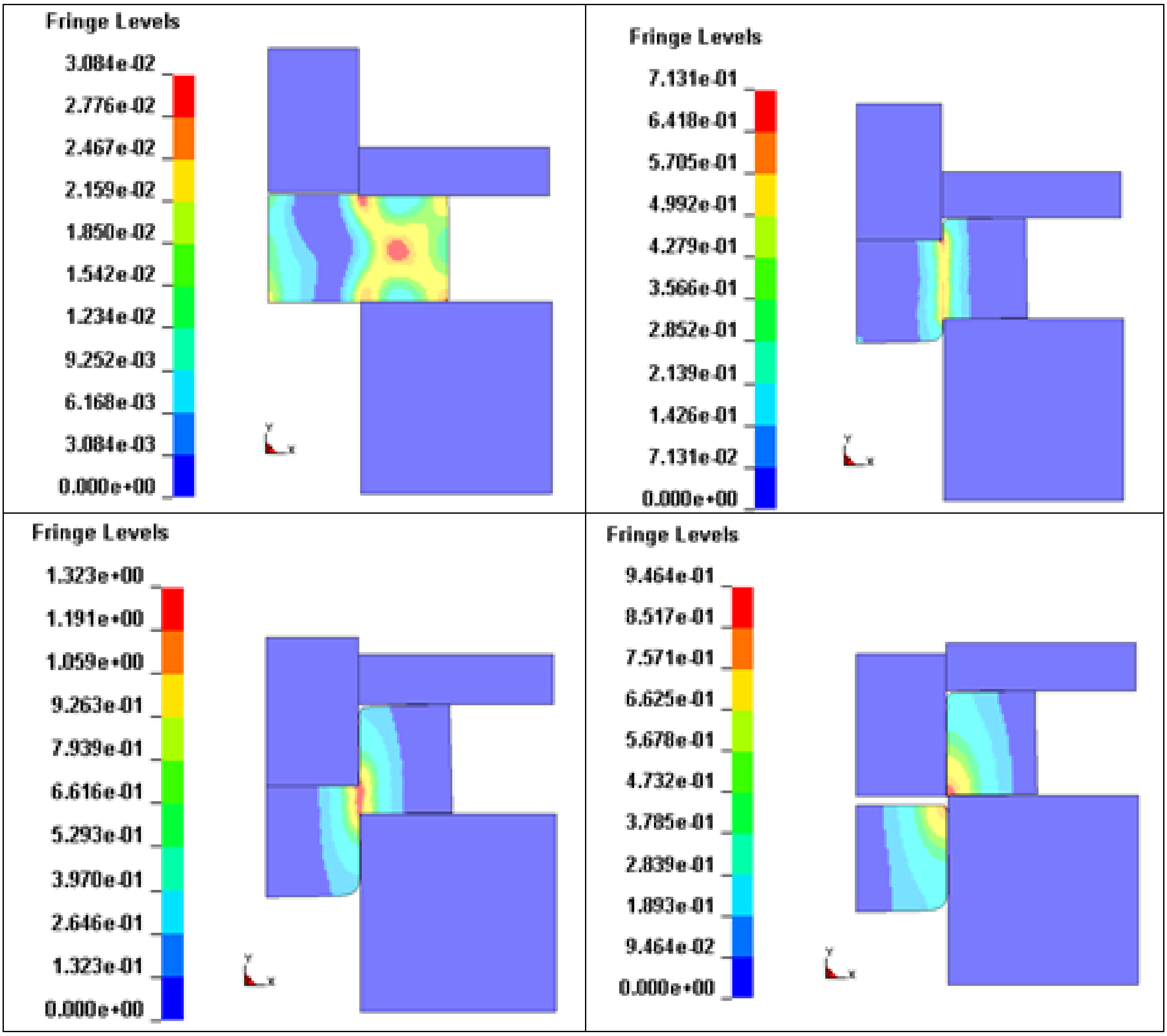

Fig. 10. Plastic strain distribution vs. times during blanking process (case 2).

The blanking clearance can have a great influence upon the surface quality and the shape of the workpiece. For a better understanding of blanking clearance effect on sheared edge different shear ededges, achieved by FE simulations, have been plotted in Fig.11. Calculation results showed the essential influence of clearance on strain values in the shearing zone and consequently on the blanking course and cut-surface shape. The decrease in clearance limits bending moment acting on the blank due to the lateral displacement between cutting edges. Bending moment is responsible for the tensile stresses in shearing zone. It is largely due clear that plastic strains are less intensive for the blanking process when an higher clearance. In the literature, it is related that, on the one hand, tool wear therefore can be affects sheared edge, so does blanking clearance. On the other hand, tools with dull edges promote material flow instead of allowing shearing deformation [30,31].

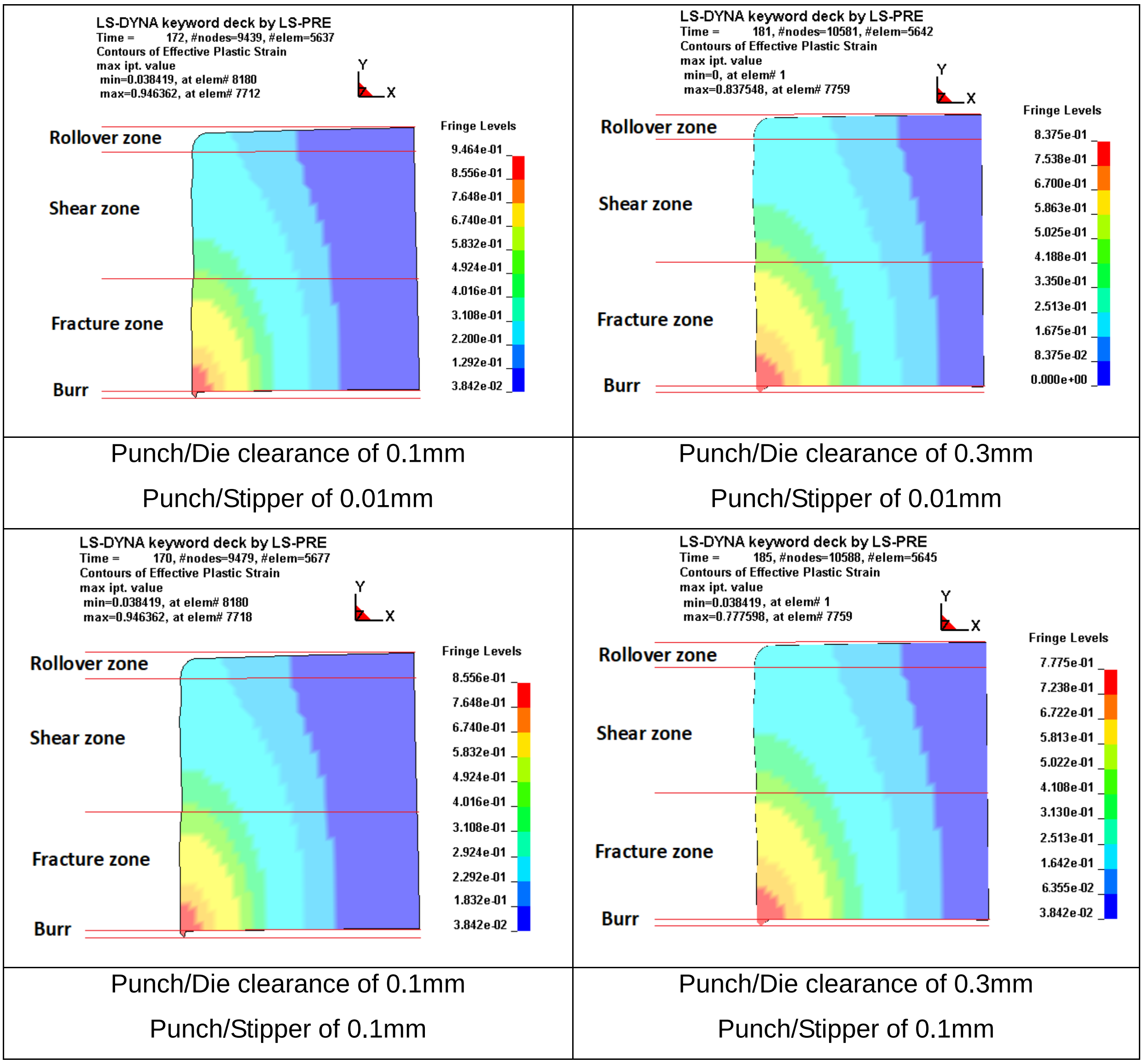

Fig.11. Sheared edges predicted by FE simulations for different blanking clearances.

A comparison of Von-Mises stress distribution between blanking process, with the assumption of a deformable punch or not, is shown in Figure 12. With the increase of punch penetration in the sheet, cracks simultaneously initiate under the punch corner radius and over the die corner radius. Then the cracks propagate along a straight line connecting both cracks. The consideration of the deformability of the punch with a same punch/die clearance leads to increasing of tensile stresses in shearing zone, and to the delay of fracture initiation. As a consequence low quality cut-surface is produced.

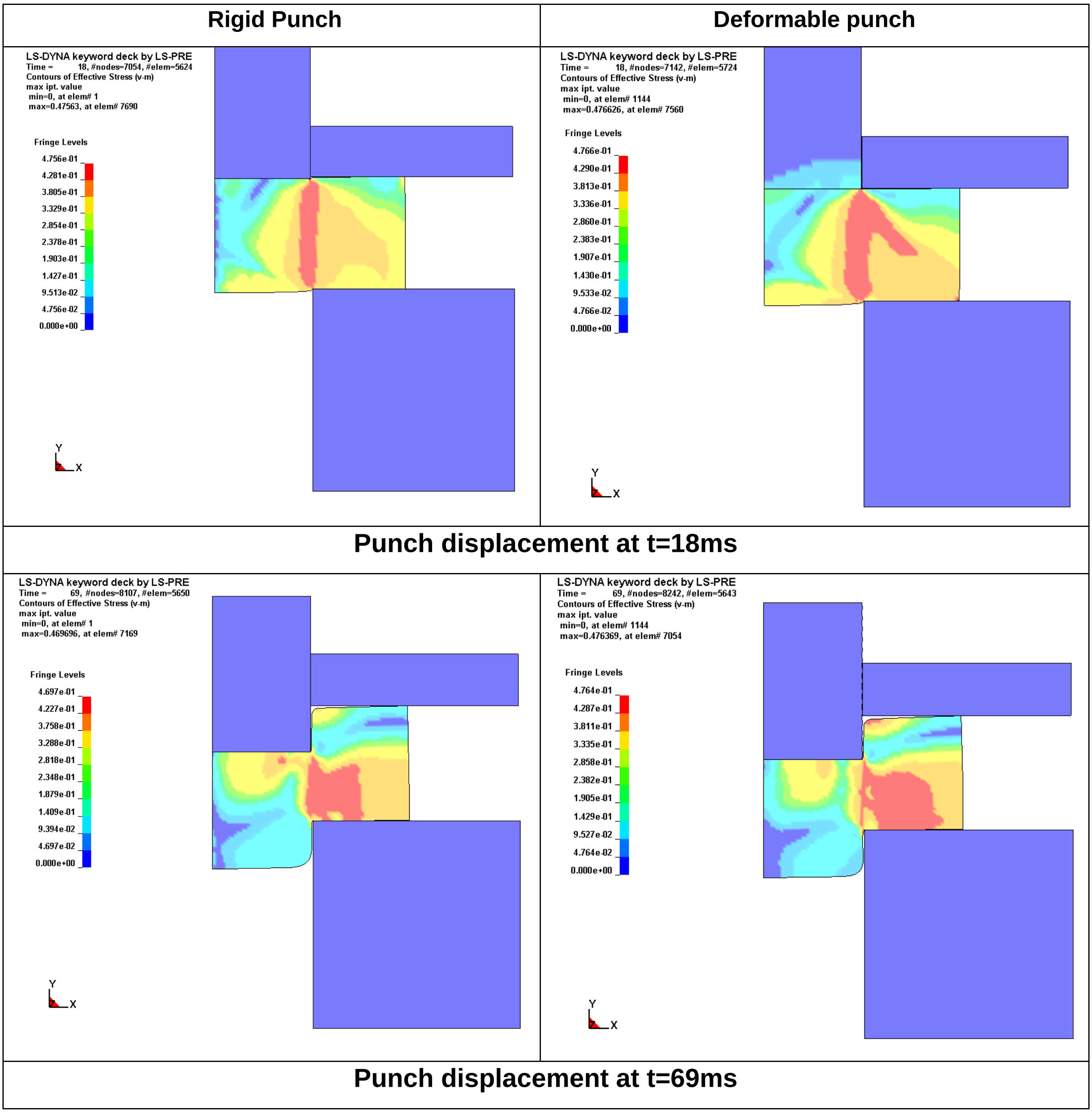

Fig. 12. Punch penetration to metal sheet for a large blanking clearance value (J1/J2=0.01/0.1mm).

5. Experimental validation

The comparison on simulation and experiment results of burr height is shown in Fig.13. The simulation results indicate that shape of blanked product can be predicted. As can be expected in the case of a large clearance, the profile of the workpiece boundary causes a bad quality due to the presence of large rollover and longer fractured zone. This result is in agreement with the literature [31-33]. The rollover depth is over estimated by our simulations with an approximate error margin of 31%, since the springback phenomena after unloading and tools warming up during the cutting procedure have not been considered. Nevertheless, the predicted sheared edge is a little in agreement with the sheared edge obtained experimentally. To conclude, the presented model predictions are moderately in agreement with the experimental data.

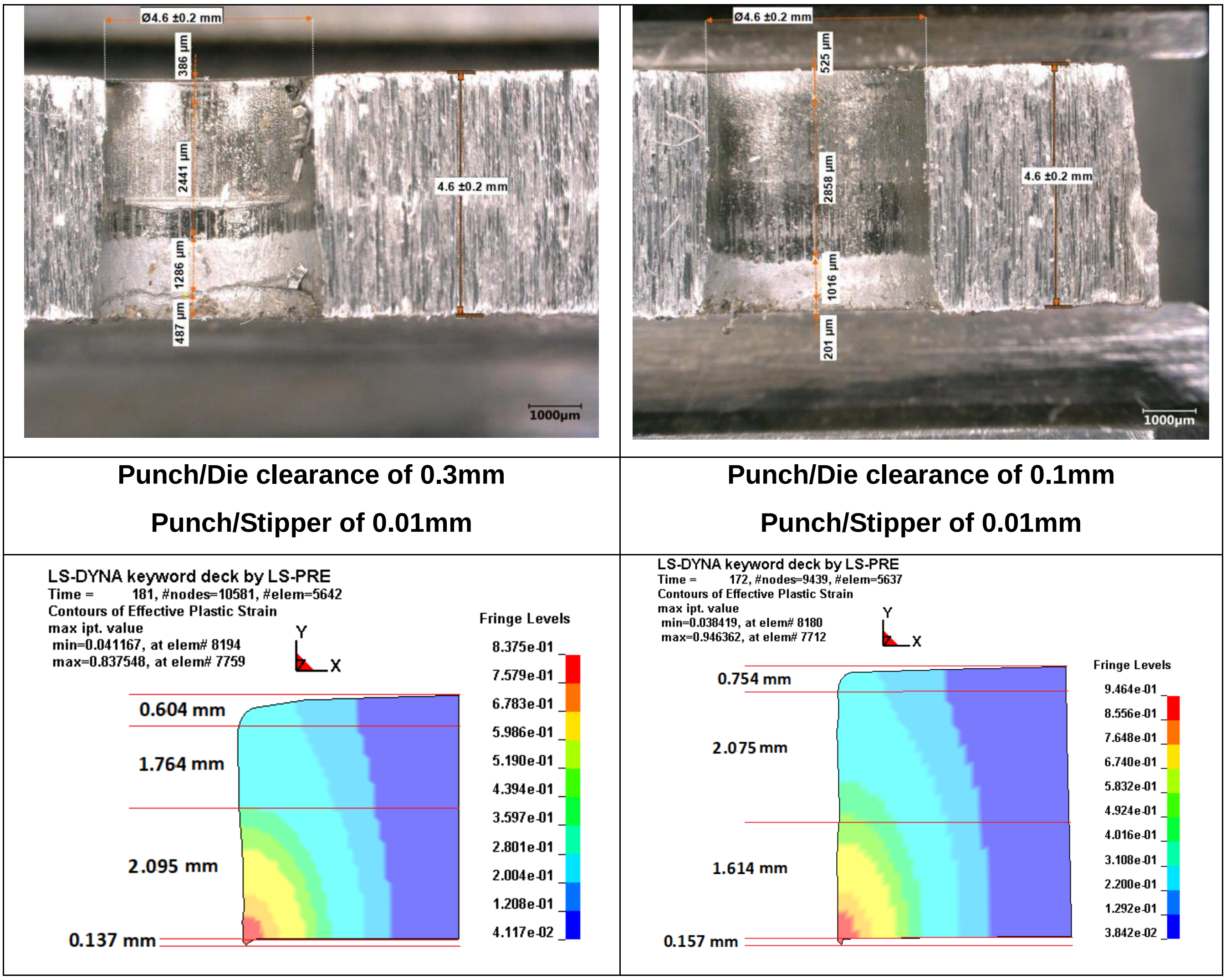

Fig. 13. Characteristic features of sheared edge achieved by optical microscopy analysis and of sheared edge predicted by FE simulations.

6. Conclusions

This paper presents numerical simulation of blanking process for coldrolled steel sheet metal. The problem was modeled using axial symmetry in commercial finite element software Lsdyna®. Data obtained by experimental measurement were used to create adapted elasto-plastic material model for blanking simulation. Based on the results achieved, the following conclusions can be formulated:

• During of numerical simulations of the blanking process was observed elongation in shear surface and simultaneous reduction in fracture zone versus clearance punch/die and also that punch is be considered deformable or not.

• The blanking course and cut-surface shape quality dependent among others of clearance punch/die. Generally, clearance reduction leads to the delay of fracture initiation, and consequently, all these give smoother cut-surface.

• Tools with high blanking clearance it may deteriorate a little sheared edge quality.

• Results from the numerical model correctly agrees with the experimentally obtained results in terms the punched edge profiles. However, the model less specific about the size of each area,

Numerical simulation can be used to find optimal parameters for the blanking process and it is also more cost efficient than using physical prototypes. Further work is still required to introduce other effects concerning the behaviour of the rolled metal sheets, such as sheet anisotropy, temperature effect and spring-back effects. This FE model will also extended to investigate the tribological behaviour between a punch with nano-structured surface and a blank under full or severe tribological conditions. Necessary conditions for functionalization surface such as arrangement, coverage, and depth will be experimentally and numerical studied to extend the tool life in precision blanking.

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