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Numerical model for a quantitative estimation of sliver formation in shearing process

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Abstract. In the present research work a model for the estimation of the probability of sliver formation during the shearing process, based on the amount of damage in the element adjacent to the shearing edge, is proposed. A full material characterization, considering different temperatures and strain rates, have been carried out in order to determine the model constants for Johnson–Cook (JC) flow stress and damage model. A 3D numerical simulation replicating the shearing process has been implemented in ABAQUS/Explicit and the results of the shearing surface have been compared with those of laboratory experiments, proving the validity of the developed simulation. Finally, while varying holder force, clearance and punch velocity, the average damage in the elements adjacent to the shearing edge have been calculated and the results allowed to conclude that punch velocity has the higher influence on the damage in the shearing edge but also that holder force and clearance percentage cannot be neglected. A too high punch velocity, as well as a higher holder force, result in an increase of the damage state, whereas a higher clearance percentage allows reducing it. Based on the proposed correlation between damage in the burrs and probability of sliver formation, the combination of process parameters those assure to reduce the probability of sliver occurrence can be identified.

1. Introduction

Shearing is one of the most indispensable process used in the sheet metal manufacturing industry. During the shearing process, a portion of the material, namely the scrap, is sheared off from the workpiece, allowing to create the desired hollow profile. Burrs are usually thought to be the main, and most undesirable, defect which may occur during the shearing process but other issues, like the sliver formation, can affect the quality of the products realized by means of shearing process. The sliver is a small material particle which detaches either from the workpiece or the scrap and which can attach to either punch or following workpiece, causing surface defects. Frequently, in order to avoid quality issues on the part, an additional high time-consuming and costly post-processing deburring operation is required. The research in the literature are related to the sliver formation in the trimming, or shearing, of aluminum alloys and several efforts, has been spent in developing manufacturing approaches to reduce, or eliminate, this phenomenon. Among them, Golovashchenko [1] investigated sliver and burr generation in trimming operations and proposed an elastic support to eliminate bending of scrap part, as well as the introduction of a small radius of the upper tool to prevent separation of sliver from the scrap. Le et al. [2] conducted a detailed experiment campaign on sheared edge for the



Al-alloy 6111 for various punch-holder clearances, from 5% to 40% of the thickness, highlighting that, for a certain clearance between punch and holder, for cutting angles between 10% and 20% the stretchability increases, in comparison to orthogonal cutting. Wang et al. [3] examined the fracture mechanism of aluminium blanks predominated by shearing and stretching along the sheared edges under the influence of cutting clearance, proving that trimming process with scrap support helps in eliminating burrs on the sheared edge for a large range of clearances and can improve the sheared edge stretchability. Lo et al [4] also investigated the effects of clearance, punch shear angle, punch material on the final blanking product quality and defined a burr prediction method based on the grey prediction theory. Hu et al. [5] adopted Rice-Tracey damage model to predict the edge fracture in traditional and advanced trimming process of AA6111-T4 sheets, developing the first model for the precise estimation of clearance effect on the burr height for that specific aluminium alloy. In the trimming of aluminium, three different typologies of sliver have been observed, as shown in the work of Li [6], namely hair-like, needle-like and flakes, each one related to different clearance percentage and cutting angle. Statically, the 80% of the sliver formation is regarded to the hair-like sliver; the needle-like sliver is generated by the cutting blade rubbing off the burnish area whereas the third typology is normally generated by the frictional interaction between the blade and the sheared surfaced and can be reduced by optimizing the cut angle.

Although in the literature much effort has been spent in studying the sliver formation, and in developing proper countermeasures to eliminate them, no work seems to deal with the sliver formation in the shearing process of steel plates. In the present research work, the shearing of a 3mm AISI 1008 steel plate is studied from both the experiment and numerical point of view in order to correlate the strain, and damage states, in the area near the shearing edge to the higher, or lower, the probability of sliver formation to happen. As proved in the work of Bai et al. [7], strain and damage are strongly correlated since the increase of damage makes the material load carrying behavior to be reduced; in their work, a linear incremental dependence between damage and strain was proposed and validated.

In addition to that, Wang et al. [3] detailed how, in the last stage of the separation between the part and the scrap, the burr are subjected to an additional deformation, of part which is under plane strain conditions. Finally, to prove a correlation between damage in the burr and probability of sliver formation, in the conclusions of the work of Golovashchenko [1], the study of the sheared surface shown how sliver can be formed as local burrs due to the stress field induced by the trimming process. Considering together the contribution of [7, 3, 1] allows defining the rationale behind the approach proposed in this paper, which aims to correlate the damage state, in the proximity of the shearing edge, to the probability of sliver formation. To this aim, a numerical model has been implemented in ABAQUS/Explicit and validated by comparing the profile of the sheared surface with that of laboratory experiments, allowing to prove the quality of the numerical implementation. In the FEM simulations the flow stress, as well the damage, have been modeled by means of the relevant Johnson-Cook models. For the determination of the constants to utilize in both models, the high-temperature tensile test has been conducted at different strain rates, considering different shapes of the specimen, in order to account for the triaxiality term in the damage model. Based on the amount of damage on two different layers adjacent to the shearing surface, and varying different process parameters, namely punch velocity, holder force and percentage of clearance, the probability of sliver formation is defined, allowing to link together process parameters and defect arising.

2. Material characterization

The component under investigation in this research work is realized with AISI 1008 steel. The chemical composition is reported in Table 1 [8].

Table 1. Chemical Composition of AISI 1008 (in weight %)

	Carbon (C)	Manganese (Mn)	Phosphorous (P)	Sulphur (S)
Ref. [8]	0.065	0.204	0.018	0.018

The material properties of the AISI 1008 steel, utilized for the manufacturing of the considered part, have been determined by means of the tensile test at different temperature and strain rates. In addition to that, tensile tests have been also conducted at room temperature on specimens with different shape of the calibrated zone, in order to calculate the triaxiality to be utilized in the damage model.

2.1. Johnson-Cook flow stress and damage models

The Johnson-Cook flow stress model, Eq. (1), is appropriate for describing the stress-strain relations of metals undergoing large deformations at high strain rate and temperature. In Eq. (1), σ and ε are the equivalent stress and strain respectively, whereas A , B , n , C and m are the relevant model constants, to be determined by means of material testing.

$$\sigma = (A + B\varepsilon^n)(1 + C \ln \varepsilon^*)(1 - T^{*m}) \quad (1)$$

In Eq. (1), $\varepsilon^* = \varepsilon / \varepsilon_{ref}$ is dimensionless strain rate whereas $T^* = (T - T_{ref}) / (T_m - T_{ref})$ is homologous temperature. ε_{ref} and T_{ref} are reference strain and temperature, respectively, whereas T_m is melting temperature and T is the considered deformation temperature of the material.

Concerning the Johnson-Cook damage model, Eq. (2), also known as the JC extended fracture criterion, expresses fracture strain sensitive to stress triaxiality, strain rate, and temperature.

$$\varepsilon_f = [D_1 + D_2 \exp(D_3 \eta)][1 + D_4 \ln \varepsilon_p][1 + D_5 T^*] \quad (2)$$

The parameters from D_1 to D_5 are the failure model constants, $\eta = \sigma_m / \sigma_{equ}$ the stress triaxiality where σ_m and σ_{equ} are the mean and equivalent stress, respectively. Increasing damage values reduces the load carrying capacity of the material until the damage parameter D reaches 1, which represents the moment when the failure is assumed to occur. In Eq. (3), σ_D and $D = \sum(\Delta\varepsilon / \varepsilon_f)$ are the flow stress of the damaged material and the damage parameters respectively. Finally, the damage parameter is a function of the plastic strain $\Delta\varepsilon$ and of the equivalent fracture strain ε_f .

$$\sigma_D = (1 - D)\sigma_{equ} \quad (3)$$

2.2. Johnson-Cook models parameters estimation

The high-temperature test has been carried out by utilizing the specimen shape shown in Figure 1(d). The remaining specimens, Figure 1(a), 1(b) and 1(c), have been utilized for the determination of the triaxiality, a key parameter for the correct calculation of the damage evolution. For the calculation of the JC flow stress and damage model constants, the procedure detailed in [9] has been utilized.

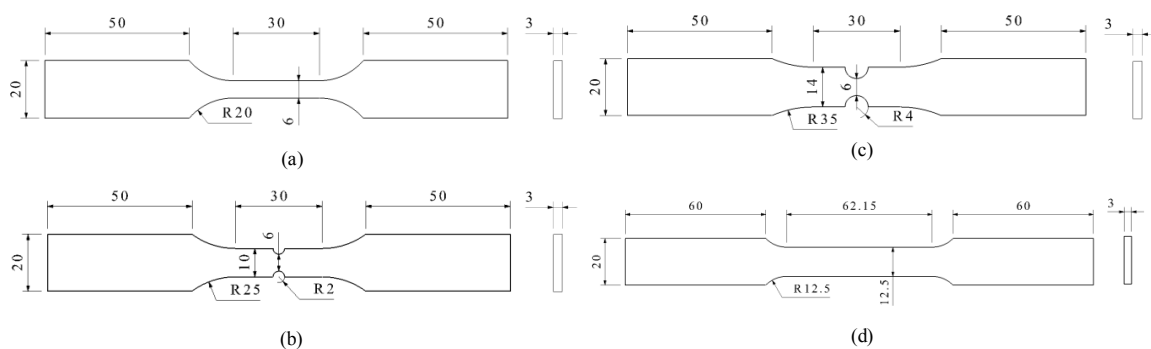


Figure 1. (a), (b) and (c) Triaxiality and (d) strain-temperature dependence tensile test specimens

For the determination of the constants of the JC flow stress model, 298.15K, 473.15K, 573.15K and 673.15K temperatures have been tested and 0.001s^{-1} , 0.015s^{-1} , 0.05s^{-1} and 0.1s^{-1} strain rates have been considered as conditions for the tensile test, choosing 298.15K and 0.015s^{-1} as reference temperature and strain rate. At T_{ref} and ε_{ref} , Eq. (1) becomes $\sigma = A + B\varepsilon^n$ and, by applying natural logarithm on both sides, B and n are calculated. At the reference temperature T_{ref} , by ignoring the softening term $(1 - T^{*m})$ in Eq. (1), and by operating a linear fitting of the resulting equation, the parameter C is derived. Likewise, at reference strain rate ε_{ref} , hence ignoring the strain rate effect term $(1 + C \ln \varepsilon^*)$, m is also calculated. Following the procedure detailed so far, the JC flow stress model constants have been determined as follows: $A = 220$ MPa, $B = 350.02$ MPa, $n = 0.4691$, $m = 0.404$ and $C = 0.015$ and have been utilized in the set-up of the material properties in the numerical model. For the acquisition of the data for the calculation of the triaxiality, the specimen shapes shown in Figure 1(a), 1(b) and 1(c), relevant for $R=0\text{mm}$, $R=2\text{mm}$ and $R=4\text{mm}$ radii in the notching zone, have been tested at 0.001s^{-1} , 0.015s^{-1} , 0.05s^{-1} and 0.1s^{-1} strain rates. Each test has been repeated three times to account for intrinsic variations and the resulting curves are shown in Figure 2.

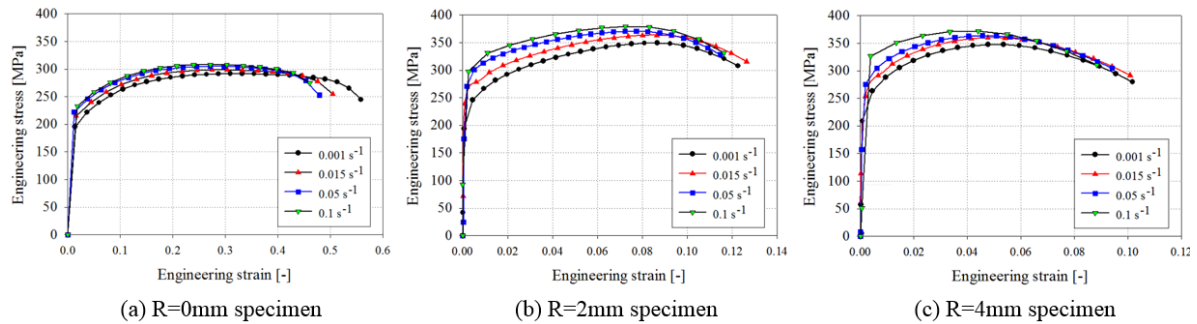


Figure 2. Engineering Stress-Strain curves for (a) $R=0\text{mm}$, (b) $R=2\text{mm}$ and (c) $R=4\text{mm}$ specimens

The stress-strain data obtained from the material characterization have been implemented in an ABAQUS/Static tensile test simulation for the determination of the stress triaxiality, and the relevant results are reported in Table 2. In the tensile test simulation, the calibrated zone has been meshed with 0.3mm side size elements whereas the jigs area with 2.5mm side size elements, Figure 3, allowing to reduce the overall computational time. The model has been meshed with C3D8R hexahedral eight noded linear brick element with reduced integration. To verify the accuracy of the triaxiality estimation made by utilizing the numerical simulation, the results from the numerical model are compared, in Figure 4, with those from the analytical formulation derived by Bai et al. [10], Eq. (4).

Table 2. Stress triaxiality obtained from FE simulation

Strain rate (s^{-1})	Stress triaxiality η		
	$R=0\text{mm}$	$R=2\text{mm}$	$R=4\text{mm}$
0.001	0.330093	0.91125	0.797129
0.015	0.330069	0.914667	0.784414
0.05	0.330097	0.843471	0.774084
0.1	0.330112	0.877693	0.706382

$$\eta = \frac{1}{3} + \sqrt{2} \ln \left(1 + \frac{a}{2R} \right) \quad (4)$$

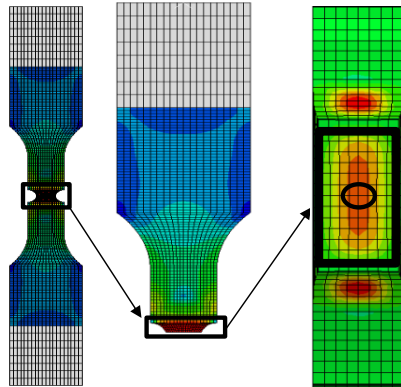


Figure 3. Stress triaxiality calculation from the center section

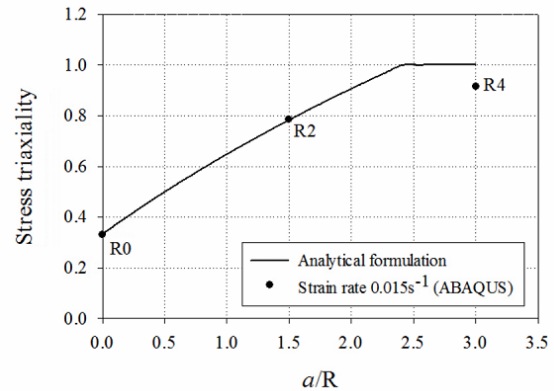


Figure 4. Comparison between analytical and numerical solution

For the estimation of the constants for the Johnson-Cook damage model, by employing Eq. (2), the parameter D_1 , D_2 , D_3 are calculated from η , with respect to fracture strain ε_f . Similarly, the failure parameters D_4 , D_5 were obtained from different temperature and strain rates data with respect to the fracture strain ε_f . The damage model constants are as follows: $D_1 = 0.5972$, $D_2 = 0.4172$, $D_3 = -0.3893$, $D_4 = -0.01439$ and $D_5 = 0.4$.

3. Numerical implementation of the shearing process

The numerical model to predict the silver formations is built in ABAQUS/Explicit commercial code employing the material and damage model parameters mentioned in the previous section. The numerical shearing process established is shown using the schematic representation Figure 5, considering all the tools, namely punch, die and holder, as a non-deformable body with discrete rigid elements. Besides, the workpiece is treated as a deformable body an eight noded linear brick element with reduced integration, namely, the C3D8R, has been utilized. For an accurate prediction of the strain and damage state, a finer mesh has been utilized in the proximity of the shearing surface edge whereas a coarser one has been adopted in the regions closer to the outer edge of the plate, as shown in Figure 6. In the fine mesh region, the element has a side length of 0.005mm whereas in the coarse one of 1.5mm. The contact properties between the tools and the workpiece surfaces are treated with Coulumb friction model assuming the coefficient of 0.2, to represent the part production conditions.

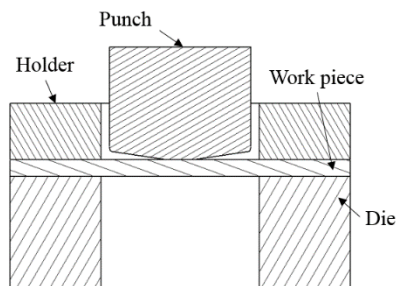


Figure 5. Geometry adapted in shearing process

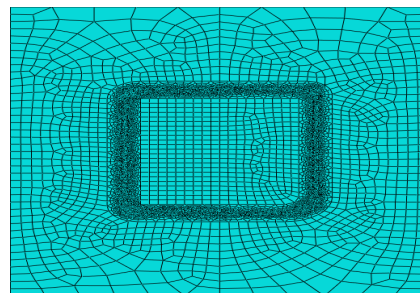


Figure 6. Mesh on the workpiece

The initial thickness of the steel plate is 3mm and, in the first tested study case, the following load and boundary conditions have been applied: punch velocity of 100mm/s, holder force of 100N and clearance 5%, respectively. By implementing the damage model constants in the material section of the numerical simulation, if an element of the mesh reaches the critical damage value it is removed from the model, allowing to replicate the shearing process.

In Figure 7(a) and (b) the result of the numerical simulation and the section of the real product are shown, respectively. In order to validate the developed numerical model, the relevant height of rollover, zone A, of the burnish, zone B, of the fracture, zone C, and of the burr, zone D, have been measured in both the simulation and in the cut specimen. The comparison of the heights, relevant for the four different zones, is reported in Table 3, proving that the developed model is able to replicate the shearing condition of the real, being the maximum perceptual error between the two measurements, limited to 8.96%.

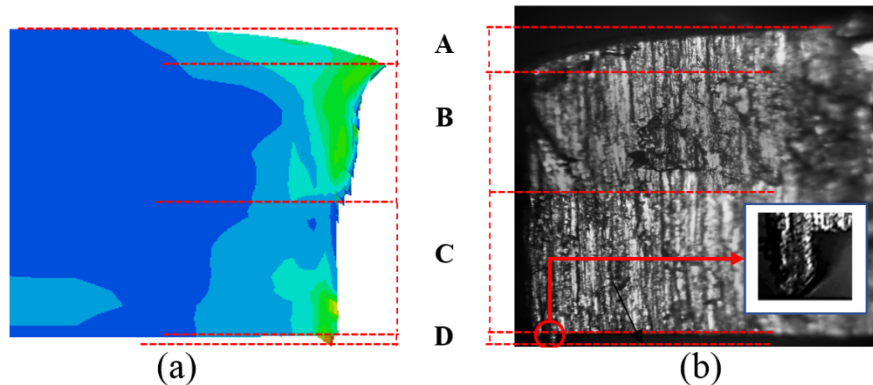


Figure 7. Comparison of sheared profile between (a) numerical and (b) experimental results

Table 3. Comparison table for characteristic feature of sheared edge

AISI (1008)	Rollover depth(A)	Burnish depth(B)	Fracture depth(C)	Burr height(D)
Experiment results	0.373	1.210	1.172	0.241
Numerical model	0.352	1.353	1.081	0.212
% Error	5.6%	10.5%	7.76%	12%

4. Result and discussion

Based on the validation of the proposed numerical model, several different study case has been run in order to understand the influence of punch velocity, holder force and percentage of clearance on the damage state in the proximity of the sheared zone and, accordingly, define the higher or lower probability of sliver formation. The 3D shearing simulation, after the detachment of the scrap from the part, in shown in Figure 8. Due to the effect of the shearing, the material next to the newly-created cavity undergoes stretching and, for this reason, the amount of damage can reach a value close to one (fracture).

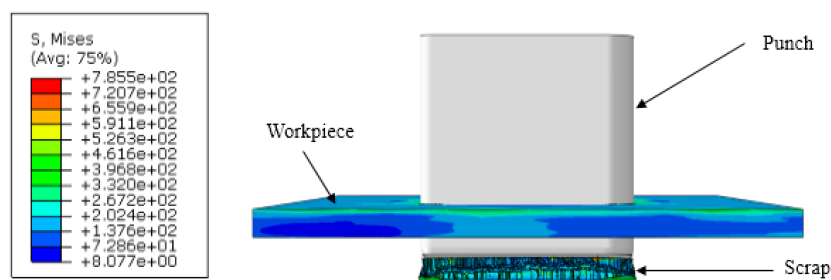


Figure 8. 3D shear simulation after detachment of the scrap from the part

By measuring the relative damage on layer 1 and layer 2, Figure 9, it is possible to understand the influence of the process parameters on the damage state which shows a link between process parameters and sliver formation. In order to catch the average trend of the damage on the overall sheared edge, 43 points have been mapped along both perimeters, and the relevant results of the relative damage have been exported and utilized for the analysis presented in this paragraph.

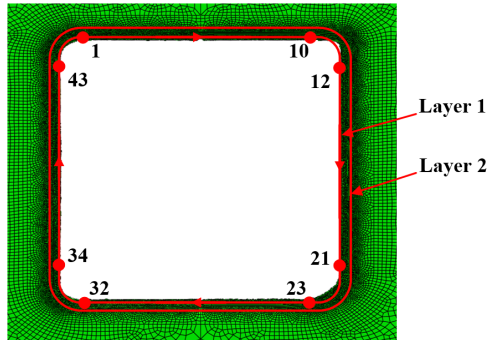


Figure 9. Layers identification on the part (after shearing process)

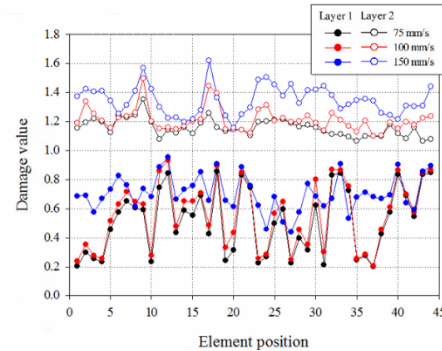


Figure 10. Position-based damage value for different punch velocity on layer 1 and 2

As shown in Figure 10, for 75mm/s and 100mm/s punch velocity, the result, in terms of damage value along the layer 1 and 2 is almost comparable but, for 150mm/s punch velocity, there is an abrupt increase of the damage, with a stronger effect on the layer 1 rather than that on the layer 2. In Figure 10, 11 and 12 the results of damage for the layer 2 have been shifted up of 1.0, in order to compare the results of layer 1 and 2 on the same chart.

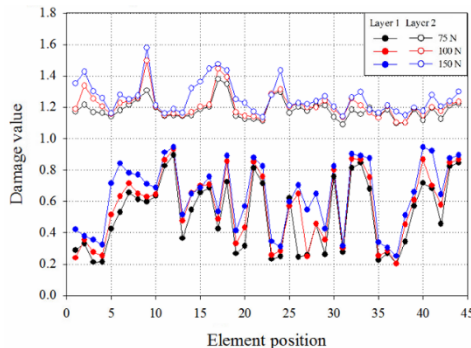


Figure 11. Position-based damage value for different holder load on layer 1 and 2

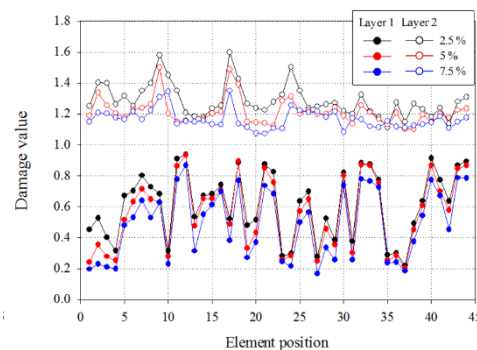


Figure 12. Position-based damage value for clearance on layer 1 and 2

For different holder forces, Figure 11, the trend of the damage value looks similar to the variation shown for the punch velocity. The damage in layer 1 and 2 remain almost constant for 75N and 100N and gradually increase for higher holder force, namely 150N. This allows concluding that a higher holder force results in higher damage values on the part. Concerning the clearance, Figure 12, the trend shows a lower damage on both layer 1 and 2 for the 7.5% clearance. On the contrary, a higher and almost similar damage state is observed for the 2.5% and 5% clearances. In particular, with 2.5% clearance, the thin volume between the part wall and punch restrict the material flow, increasing the average damage up to 8.3%, in comparison to 5% clearance. The overall average damage values, with respect to process parameters, are listed in Table 4. As stated in Golovashchenko [1], the amount of damage is correlated with the probability of sliver formation hence, the average value of damage on layer 1 can be used as an indicator for a higher, or lower, probability of sliver to occur. Passing from 100mm/s to 150mm/s, in terms of punch velocity, results in a 20.5% increase of the average damage value on the layer 1. Concerning the holder force, a change from 100N to 150N results in an increase

of the average damage value, same on layer 1, of 12.6%. Finally, an increase of the clearance from 5.0% to 7.5% positively affects the damage with an 12.8% reduction, on layer 1. The damage variation on layer 2 has shown to be not as much relevant as those of layer 1 since the average damage values are always far lower than those of layer 1.

Table 4. Average damage values with respect to various process parameters

Average damage value	Punch velocity			Holder force			Clearance		
	150mm/s	100mm/s	75mm/s	150N	100N	75N	7.5%	5%	2.5%
Layer 1	0.706	0.561	0.514	0.642	0.561	0.513	0.489	0.561	0.612
Layer 2	0.348	0.212	0.157	0.261	0.212	0.185	0.167	0.212	0.287

5. Conclusion

In this study, a numerical model and an approach to estimate higher or lower formation of sliver are proposed. For the proper implementation of the numerical model, a full material characterization has been carried out, allowing to estimate the strain, strain rate and temperature dependence of the flow stress as well as triaxiality factor. In the numerical simulation, both the plastic and damage regions of the material behavior, have been modeled by utilizing the Johnson-Cook formulations, whose parameters have been derived from the material characterization. In order to validate the proposed numerical model, the sheared surface has been compared with that of the real product, showing a reasonable replication of all the four zone and an error limited to 8.9%. By utilizing the developed and validated numerical model, different combinations of process parameters have been tested in order to understand their influence on the average damage state, measured on 43 points along two different layers, the first one on the shearing edge and the second one on the mesh layer next to the first one. Based on the correlation between damage state in the burr and its correlation with the higher, or lower, probability of sliver formation to arise, the influence of punch velocity, holder force and clearance percentage have been taken into account. Considering the result, it can be concluded that either a high punch velocity or a high holder force result in a higher average damage state on layer 1 whereas higher clearance positively affect the average damage, promoting its reduction. The preliminary results shown in this paper opens the way to the understanding of the sliver formation in the shearing process of steel plates, a topic which is not yet discussed in the literature. However, more effort has to be spent for a more quantitative definition of, but not only, the sliver size as well as more process parameters, such as punch wear, friction and cutting angle should taken into account in order to increase both accuracy and reliability of the prediction.

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