High-speed sheet metal forming: Numerical study of high speed Nakajima testing

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Keywords: Forming, high strain rates, material characterization

Abstract

In recent years, the forming community has shown an increased interest in the effect of strain rate on the formability of sheet metals. The assessment of sheet metal formability in dynamic deformation conditions requires the development of experimental techniques which allow to decouple the material response from the test related parameters. In this paper, results of numerical finite element simulations of dynamic Nakajima experiments on a dog bone sample are presented. The simulations are performed in order to verify the reliability of the technique under different frictional contact conditions and punch velocities. The necking locus, strain path linearity and stress state evolution are extracted and investigated in-depth. The numerical study highlighted several drawbacks which led to the conclusion that dynamic Nakajima tests might not be the most appropriate way to investigate sheet metal formability at high strain rates.

1. Introduction

Sheet metal forming is commonly used in industry to produce metal components for different applications. The formability of a metal sheet is generally quantified by tests which impose different strain paths to material samples. The sheet metal forming community often adopts the forming limit diagram (FLD) developed by Keeler et al. and Goodwin [1, 2]. The shape and location of the FLD in the principal strain space define the boundary between strain states that are always free of necks, i.e. below the FLD, from those prone to necking and splitting. Several studies showed that the formability of sheet metals can significantly be improved by increasing the deformation rate. Balanethiram et al. [3] observed that the formability in biaxial stretching conditions can increase with a factor of almost three when the material is tested at high strain rates. Wood [4] found that the forming limit can improve by a factor of two or more when performing experiments in dynamic loading conditions. In quasi-static loading conditions, formability is experimentally assessed by means of techniques described in the ISO 12004-2:2008 standard, such as Nakajima and Marciniak tests. However, the techniques still have no well-defined dynamic counterparts. The strain rate effect at the right-hand side of the FLDs is investigated by electro-magnetic, electro-hydraulic and explosive forming. A few researchers introduced new approaches which combine Hopkinson bar experiments with existing standard techniques. Sasso et al. [5] developed a testing device combining the split Hopkinson pressure bar (SHPB) with a Nakajima test, Gilat et al. [6] modified a SHPB to perform dynamic punch tests, Grolleau et al. [7] proposed an adaptation of the SHPB apparatus to perform dynamic bulge tests. However, all these approaches still have limitations in terms of linearity and variety of imposed strain paths. Deviations from the ideal linear strain path are often caused by experimental factors such as contact conditions, friction, lubrication, clamping system, and many more [8]. Indeed, the linearity of the strain path is one of the most important requirements for the determination of FLDs. This paper investigates the reliability of dynamic Nakajima tests using dog bone material samples to characterize sheet metal formability in dynamic loading conditions. Numerical finite element simulations in Abaqus/Standard are performed considering different frictional contact conditions and punch velocities. Necking onset, strain path linearity and evolution of the stress components are carefully exanimated. The reliability of dynamic Nakajima tests as experimental technique to characterise sheet metal formability in dynamic loading conditions is broadly discussed based on the numerical results.

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2. Methods

Numerical simulations of Nakajima tests are performed using the commercial finite element program Abaqus/Standard. The simulations aim at reproducing actual Nakajima experiments in which a hemispherical rigid punch penetrates a sheet metal fixed to a rigid die. Boundary conditions are imposed to replicate the actual experimental conditions. Due to limitations in deformation capacity typical for dynamic tests, the dimensions of the components, shown in Figure 1, are reduced compared to the guidelines of ISO 12004-2:2008. The sample material is Ti-6Al-4V, which has been studied in-depth at the DyMaLab research group of Ghent University [9]. Associative J2-plasticity with isotropic hardening is adopted to describe the material behaviour. The strain rate and temperature dependent hardening is modelled by the Johnson-Cook hardening law, the parameters are reported in Table 1.

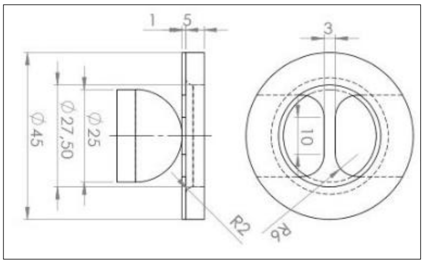

Figure 1: Dimensions components Dynamic Nakajima simulations

Table 1: Mechanical properties Ti-6Al-4V [9].

E	ν	ρ	A	B	n	m	Melting temperature	Room Temperature
MPa	-	*Ton/mm³*	*MPa*	*MPa*	-	-	*°C*	*°C*
117000	0.3	4.4E-9	951	892	0.7	0.71	1630	20

A recent approach proposed by Martinez-Donaire et al. [10] is used to detect the time at which necking occurs. As shown in Figure 2, the onset of necking is detected by monitoring the strain rate evolution at a point B external to the necking region. The time at which the strain rate in B reaches its maximum value is used as criterion to identify the time at necking during the simulation; hence to extract the strain and strain rate values at the necking section. The methodology is local and does not take into account experimental conditions such as sample geometry, punch shape, contact and friction. Different friction coefficients and punch velocities, are adopted in order to establish their influence on the mechanical response of the sheet metal. Three simulations with fixed punch velocity of 5m/s and different friction coefficients: 0, 0.04 and 0.3, are executed to investigate how friction affects the necking position, the strain path linearity, the principal in plane stress components and the strain rate level. Strain path linearity is estimated by fitting major and minor in plane strain components using a linear fitting function, characterized by a correlation coefficient R, which gives an indication of the linearity. The analysis is repeated for three elements placed at the necking section through the sheet thickness: at the external surface, at the internal surface in contact with the punch and, finally, at the middle section of the sheet. The study on the stress components is reduced to the elements at the external surface and at the middle section of the sheet. Furthermore, the effect of the test velocity is studied by repeating the simulation for three different punch-velocities: 5,10 and 15m/s, while the friction coefficient is kept constant at 0.04.

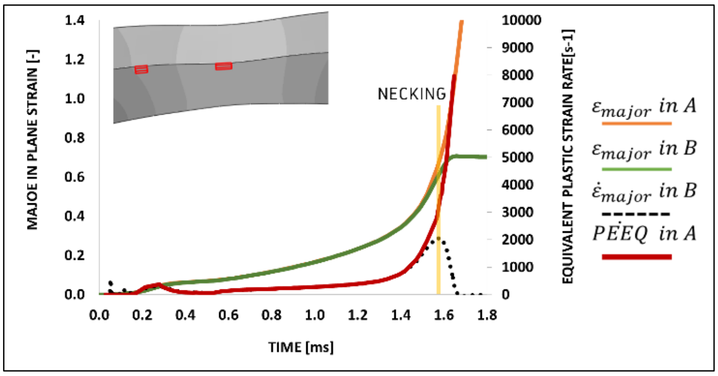

Figure 2: Martinez-Donaire approach to detect the time at onset of necking for a punch velocity of 5m/s without friction

Table 2: Summarizing table: results simulations punch velocity 5m/s

Friction coefficient *[-]*	Time at necking Martinez-Donaire approach *[ms]*	Major in plane strain at necking in A *[-]*	Equivalent plastic strain rate at necking in A *[s^{-1}]*
-	1,58	0,70	3300
0,04	1,71	0,68	2050
0,3	1,44	0,61	1550

3. Results

3.1 Necking detection

The use of the Martinez-Donaire criterion is illustrated in Figure 2 which shows the major in plane strain and strain rate at a point B close to the neck, and the plastic equivalent strain (PEEQ) and major strain in the neck. All values are taken at the external surface of the sheet. The time, strain and strain rate at the onset of necking are summarized in Table 2 for different friction conditions and a punch velocity equal to 5m/s. The position of the necking section is post-mortem detected. The effect of the friction on the strain localization is further investigated by plotting the initial position of the nodes A,B,C and D which delimit the necking as showed in Figure 3a. In Figure 3b, an increment of the friction coefficient makes the necking locus shift from the centre of the specimen to the shoulders of the sample.

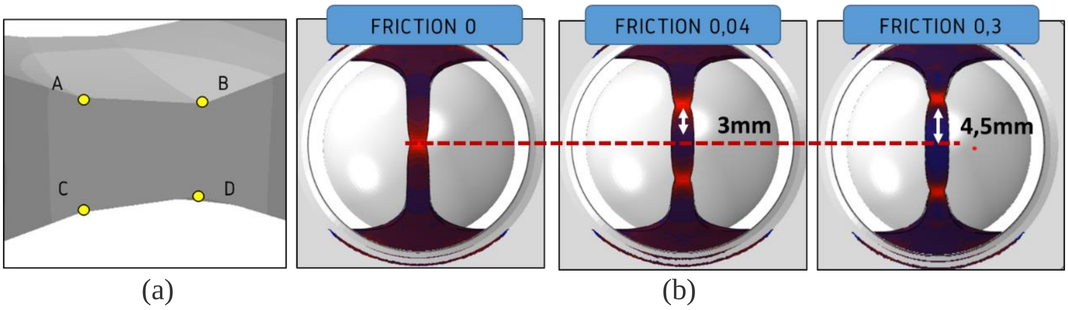

Figure 3: (a)Nodes delimiting the necking, (b) Necking locus shift

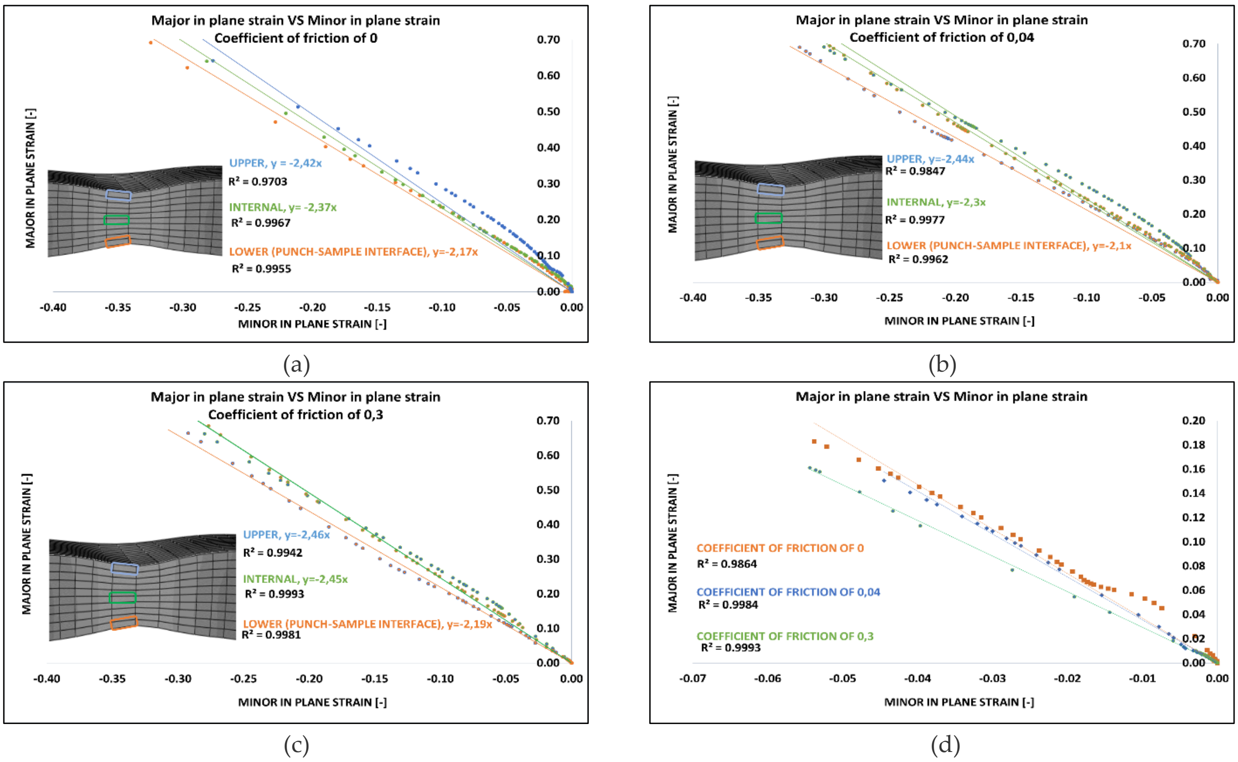

Figure 4: Study of the strain path for different friction coefficients 0(a),0.04(b),0.3(c). Strain path analysis in small strain regime(d)

3.2 Strain path linearity and stress components evolution

In Figure 4 the major versus minor in plane strains in the neck section are presented till the onset of necking together with a linear fit. Results are presented for the three friction conditions in three different elements through the sheet thickness. The most pronounced mismatch with the linear fit is observed for the element placed at the upper surface of the sheet metal, for which R is around 0.97. Only slight deviations of the slope, about 3 degrees, are observed comparing the linear paths for the elements through the sheet thickness. The evolution of the stress components at the upper surface (circular dot) and internal section (uniform line) in the neck are reported in Figure 5a, b and c. All the curves in Figure 5 show a peak corresponding to the instant at which the contact between the punch and sheet metal starts. The peak value depends on the combination of different factors: contact forces, punch curvature, and friction coefficient. In addition, the stress component at the external surface of the specimen is zero, while moving towards the punch-sample interface, it becomes more and more influent.

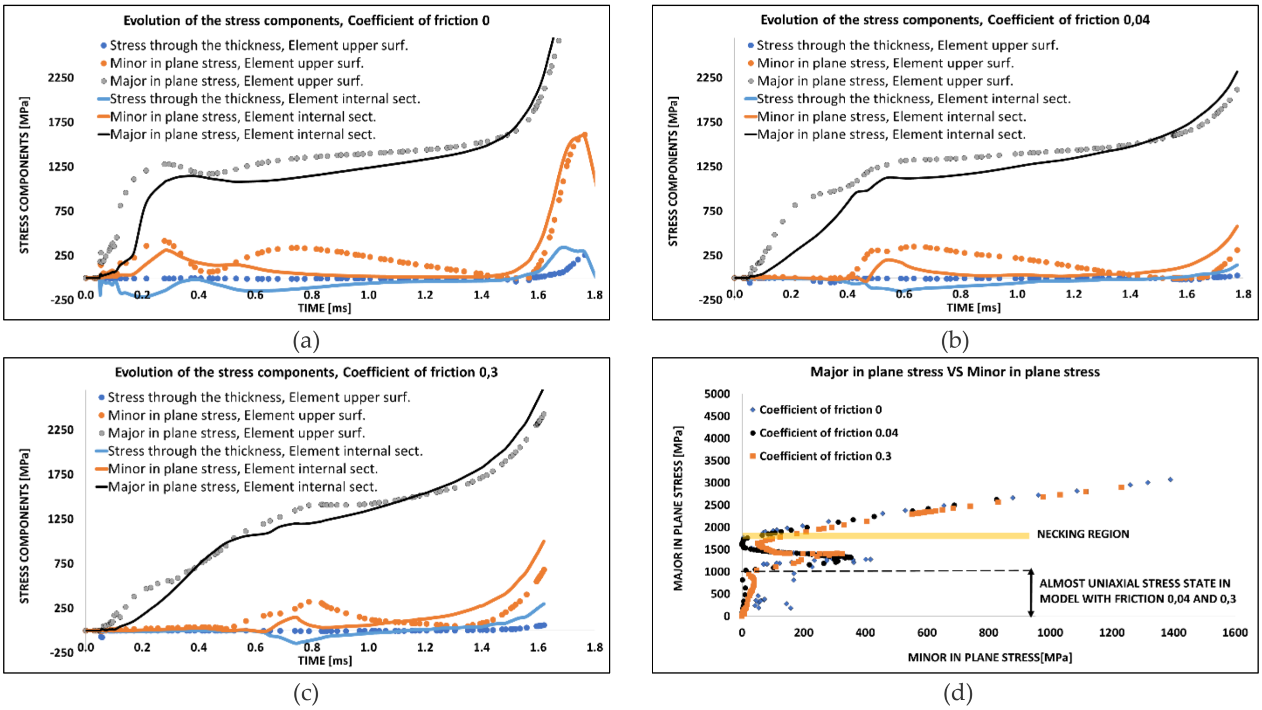

Figure 5: Stress components evolution at the upper surface (circular dot) and internal section (uniform line) in the neck for different friction coefficients : 0 (a), 0.04(b), 0.3(c). Figure 5d: stress path element at the upper surface of the neck for different friction coefficients.

3.3 Effect of the punch velocity

The comparison of the punch force–displacement curves in Figure 6 shows just a small amplification of the force level due to the increase of the punch velocity. Since the force-displacement curves take into account the global response of the specimen, the curves cannot be used to characterise the mechanical response of the metal sheet. The Martinez-Donaire criterion is applied to determine the major in plane strain and equivalent plastic strain rate at the necking onset for each punch velocity. The results of the simulations are summarized in Table 3.

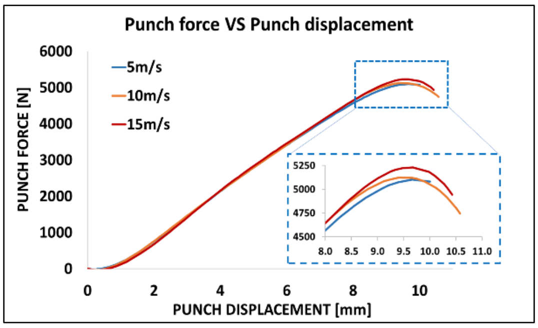

Figure 6: Punch force-displacement for initial punch velocities of 5, 10 and 15 m/s

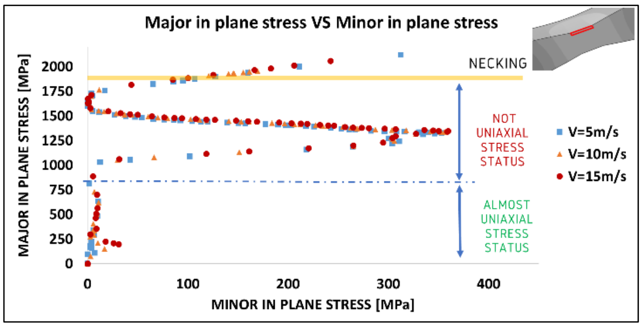

Figure 7: Major in plane stress versus minor in plane stress for initial punch velocities of 5, 10 and 15 m/s

Table 3: Summarizing table: results simulations for three different punch velocities 5,10,15 m/s

Punch velocity *[m/s]*	Max. Punch Force *[N]*	Time at the Max. punch force *[ms]*	Time at necking Martinez-Donaire approach *[ms]*	Major in plane strain at necking *[-]*	Equivalent plastic strain rate at necking *[s^{-1}]*
5	5120	1,93	1,71	0,68	2000
10	5180	0,96	0,85	0,7	4050
15	5215	0,64	0,57	0,7	6350

4. Discussion

4.1 Necking detection

From an experimental point of view, the necessity of controlling and monitoring the friction coefficient introduces huge limitations, especially in dynamic loading conditions. Indeed, it is known that friction is highly dependent on the relative slipping velocity between the surfaces involved in the contact. Comparing the results for the frictionless contact conditions with the results for higher friction coefficients, a small reduction of the major in plane strain is observed, whereas the equivalent plastic strain rate is almost halved. The introduction of a friction coefficient as low as 0.04 results in a reduction of the equivalent plastic strain rate from 3300s^{-1} to 2050s^{-1}. A value of 0.04 is considered to be an achievable technological lower limit for friction in forming experiments. In a Nakajima test, the friction between punch and sheet sample is different in every point and it changes during the test. Even for the friction coefficient of 0.04, the necking section already shifts away from the centre. As shown in the results section, friction conditions along the sample gage length cannot be neglected.

4.2 Strain path linearity and stress components evolution

The strain path at the necking section, on the sample surface and through the thickness, is almost linear: the discrepancies between the linear fit functions are negligible. However, restricting the study to the small strain domain ($\varepsilon_{major} < 0.15$, $\varepsilon_{minor} < -0.05$), see Figure 4d, for the element at the upper surface, the slopes of the strain paths deviate from the slopes obtained when the strains till necking are considered, see Figure 4a,b and c. The deviations are even more pronounced during the initial stage of the simulations at which the punch starts deforming the specimen. Friction has a double effect on the stress components evolution. On one hand, the resulting tangential forces modify the stress state at the centre of the sample, on the other hand, friction results in a stress concentration away from the centre, and therefore the shift of the neck to a location with a different loading history. Moreover, the non-uniform stress distribution through the sheet thickness and the changing triaxiality constitute two other important model outcomes. The stress through the thickness, which is zero for the element at the external surface, becomes more and more relevant moving towards the sample-punch interface. In addition, as shown in Figure 5d, the principal in plane stress components evolve in a non-proportional way and the uniaxial loading condition is never reached, see . The stress components study reveals other shortcomings of the Nakajima test. First, the stress state is not uniform along the gage length of the sample, and even not through the sheet metal thickness. Second, the components of the stress evolve non-proportional. Last, the friction and related tangential forces drastically affect the stress in the entire sample.

4.3 Effect of the punch velocity

The punch velocity does not influence the major in plane strain which is almost the same for all the simulations. Consequently, since the time to necking is proportional with the punch velocity, also the equivalent plastic strain rate in the neck increases proportionally with the punch velocity. The determination of the necking locus reveals that for all the simulations the neck appears at the same position: the punch velocity does not play any role on the strain localization. The strain and stress path analysis does not show any influence of the punch velocity: in Figure 7 the stress paths perfectly coincide. Thus, it can be concluded that the punch velocity in a Nakajima experiment only affects the obtained strain rate, and that the variables previously considered, i.e. necking locus, strain path and stress components, are not significantly changed.

5. Conclusions

The numerical study reveals that the characterization of sheet metal formability in dynamic loading conditions, by means of Nakajima experiments on dog bone samples, has serious shortcomings. Indeed, based on the analysis of the numerical simulation results, the following can be concluded:

- Friction affects the necking localization together with the strain rate amplitude. Indeed, even when an extremely low friction coefficient of 0.04 is adopted, the strain distribution and its evolution in the sample drastically deviate from those obtained assuming frictionless contact between punch and sample. The influence of friction on the location of the neck can clearly not be ignored. Additionally, also the FLD value, experimentally determined at the onset of necking, is dependent on the friction. Moreover, the strain path is not perfectly linear, certainly not in the early stages of the deformation.
- To assess the formability, the forming community very often exclusively focuses on the in plane strain components. The numerical investigation shows that, even if good results are obtained in the strain space in terms of linearity of the principal strain components, a totally different image is obtained in the stress space. Indeed, the stress components evolve non-proportionally. Moreover, the stress varies along the sample gage length and through the specimen thickness.
- The punch velocity does not play any role in the localization of the strain, as well as in the strain path linearity and the evolution of the stress components. On the other hand, the increment of the punch velocity leads to a proportional increase of the local strain rate at the neck. In real tests, however, the friction coefficient depends on the relative velocity between the punch and the sample. Therefore, full understanding of the test outcome requires experimental campaigns to determine the evolution of the friction in order to calibrate a contact model within the FE software.

As a general conclusion, it can be stated that the numerical study on dynamic Nakajima tests shows that the test outcome is dominated by test conditions rather than by the material behaviour. As such, the material response aimed at is masked by test conditions. Moreover, friction which is difficult, yet impossible, to control has a significant influence on the sample response, including the strain state in the neck.

Acknowledgments and funding statement

This research is supported by the Research Foundation Flanders-FWO, application number 1SC5619N.

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