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Forming Machine Qualification by Analysis of Manufactured Parts Geometry: Application to Aluminium Forming Process

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Today, manufacturing companies work in a concurrent engineering context. In this paper, we develop a methodology to validate the modelling of an aluminium forming process based on dimensional characterisation and finite element comparison. Generally, finite element modelling (FEM) is used to validate die design in parallel with an experimental process. In this work, we use FEM to design forming tools in a first step. In a second step, measurement in the three dimensions gives the sheet metal process machine tool errors, and it is necessary to integrate the reasons for these defects in the process of concurrent engineering in the field of metal forming. Finally, we conclude that multiscale models should be used to model the mechanical process.

Keywords: Concurrent engineering; Design; Forming; Optimisation

1. Introduction

Walczyk and Hardt [1] have noted that as manufacturing companies adopt "lean production" techniques to stay competitive in the world economy, there is an effort afoot in the sheet metal forming sector of industry to reduce the lead time and investment costs of tooling development. Such an effort is sorely needed because the development of dies used to form sheet metal parts is extremely time consuming and expensive. Currently, finite element models are used to design the formed parts and are used in "lean production" techniques. This method or "knowledge" base is applied for example in the mechanical domain to design the internal thread features at the two ends of a shaft [2] or to optimise shape topology design [3]. In this work, we are concerned with the concurrent engineering context. The objectives of concurrent engineering are well known and it is usually used for the metal cutting processes and fewer applications are found in metal forming. By concurrent design, we mean the simultaneous design of a sheet product and its forming process. Concurrent engineering is essentially an approach for an integrated, parallel product and a process design with involves team work, parallel activities and quality assurance [4]. Data on product representation (geometry, materials, etc.) for manufacturing and processes, are used in modelling. Finite element modelling gives results assuming that the forming machine has a "perfect" geometry.

Concurrent engineering needs to define accurately the significant data, which have to be used at each step of the process. These data describe technical aspects (process, product, equipment, etc.) but also logistical aspects (number of parts, batch size, due date) and economic aspects (costs, etc.). These data are used to calculate the several part states, process planning and manufacturing parameters.

In this context, we will determine the process capability by measuring the part geometry and adjusting the process planning. In the first part, we present a classical approach using finite element modelizing and in the second part, we use geometrical analysis to identify machine defects.

Figure 1 shows the scientific approach used in this work. In the first step, we characterise the material rheological parameters by a tensile test. The "U" test determines the Tresca friction value. In this step, the Forge2 FE simulation is carried out assuming that the wall is isotropic. The simulation and experimental part measurements disclose the form errors when comparing simulation and experimental results. The third measurements indicate forming press errors or more exactly press–die errors. Finally, these observations can be used in concurrent engineering to choose the methodology required for each step.

2. Definition and the FEM Model Used

Sheet metal is defined as any piece of metal of uniform thickness less than 6.4 mm thick characterised by a high ratio

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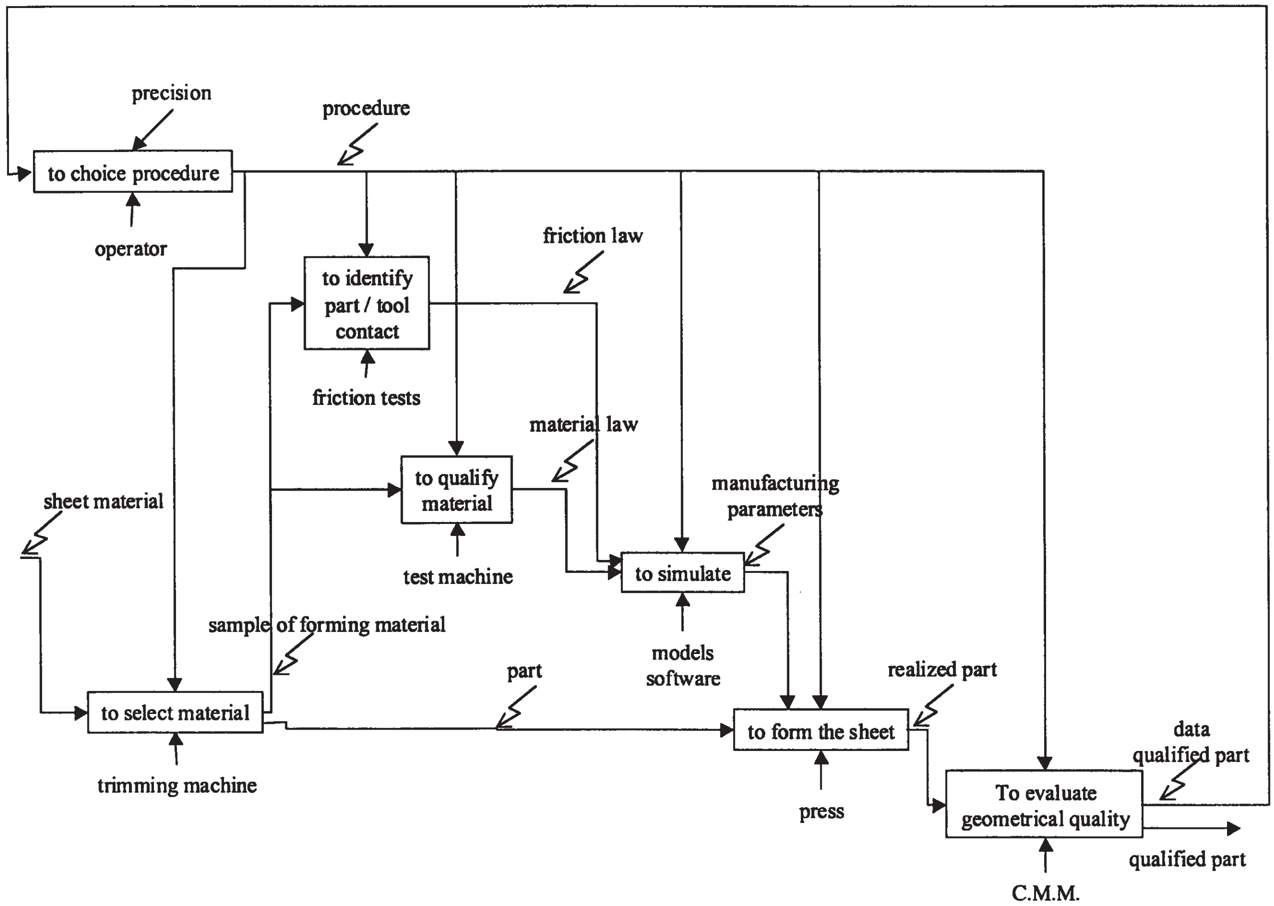

Fig. 1.

of surface area to thickness [1]. Our process has three steps: one for sheet processing and two to reduce the part thickness. For confidentiality, the figures are normalised. The simulation by finite elements is based on the Forge2 code. It is used in the forming process, and using the code it is possible to determine the die stresses. The Norton–Hoff law in the viscoplastic zone is used to model the material (die and blank):

$$s = 2K(2\dot{\epsilon} : \dot{\epsilon})^{\frac{m-1}{2}} \dot{\epsilon} \tag{1}$$

where s is the deviatoric part of σ, and $\dot{\epsilon}$ the strain rate tensor, K is the material consistency and in our case is

$$K = K_0(\epsilon_0 + \epsilon)^n e^{-\beta T} \tag{2}$$

where K_0 is the constant term of the consistency, n is the strain-hardening exponent, β is the temperature term, ϵ_0 is the strain rate regulation term, and m is strain rate sensitivity exponent.

The die/material contact needs an analysis methodology. Dubois et al. [5] have produced an approach based on two steps: mechanical analysis and experimental measurements. The mechanical analysis is carried out by finite element simulation to obtain the estimated mechanical parameters. The experiments can be classified into three categories: specified friction tests, general tests and special tests. These tests must include technological phenomena. Laws like Tresca and Coulomb's law can model the friction contact. In our case, the die/material contact is modelled by the Tresca law, characterised by the $\bar{m}$ coefficient. In our sheet metal process, we cannot use the ring test, which is generally attributed to Male and Cockroft [6]. Another test is used to determine this coefficient, called a "dynamic test".

3. Simulation of Sheet Metal Process

3.1 Identification of Rheological Parameters

Test samples of the initial blank were examined to determine the rheological laws. The three parameters tested are: deformation rate, temperature and lamination direction.

Tests were performed on a tensile testing machine equipped with an electric oven that assured a constant temperature during the traction test. All traction curves were identical and confirm the choice of the FEM simulation by FORGE2 in the axisymmetric case. No dependence of the rheological properties on process temperature were identified, so the term β is equal to 0 in this case, and is the same for deformation rate. Consequently the FEM model used is an elastoplastic model (β and

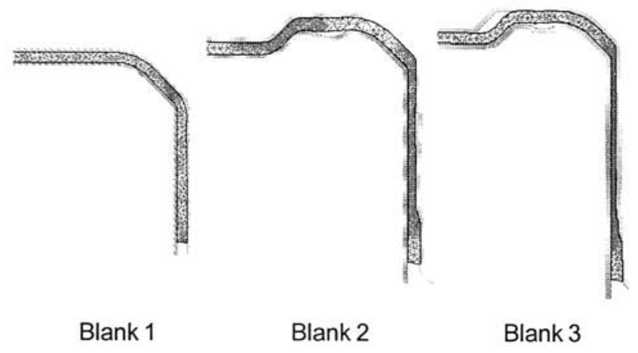

Fig. 2.

m are equal to 0). The simulation is based on the nominal dimensions of the dies using the theoretical process displacement speed, *v*. Figure 2 shows the forming process. The first step is conventional deep drawing. The blankholder force is equal to 60 kN. In a second and third step, we used the material rheological results of the simulation. The speed is always the same because the process is carried out on the same forming machine. These second and third steps reduce the part thickness using a matrix die. To minimise wear, surface treatment is carried out on the die.

The friction coefficient is determined by the "U" test. This test consists of applying a static force on the material sample inside dies, designed as a "U". The sample is obtained from the initial blank, so that we can take account of the surface characteristics (roughness, composition, etc.). To obtain the coefficient, a load is applied, and the blank bends; the ratio between this load and the blankholder force gives the friction coefficient. In our case, the Tresca coefficient is equal to 0.06 for a lubricated process.

3.2 Sheet Metal Process Simulation

All FEM simulation is carried out for non-deformed dies, because the dimensions of dies are greater than the blank thickness. Simulation with deformed dies confirms this hypothesis. Figure 3 shows the initial position and the end position

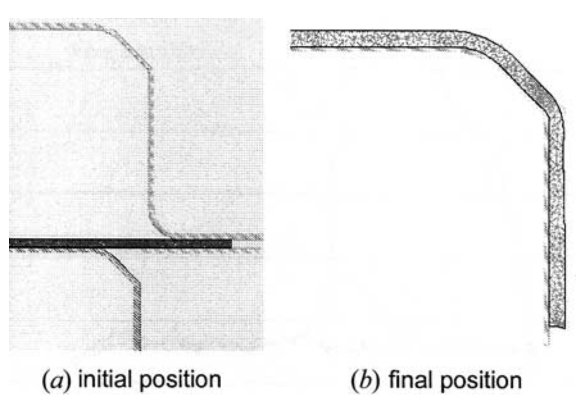

Fig. 3.

of the first step. A remeshing criterion is used for generating a new mesh during the simulation.

In this first step, we study the influence of the blankholder force on the deep-drawing geometry. We simulate two cases. In the first, we impose a maximum load on the blankholder equal to 60 kN. In the second case, we consider a fixed blankholder. In Fig. 4, the load applied on the fixed blankholder is five times higher than on the floating blankholder, so a longer part is produced.

First measurements show conformity between the simulated and the measured profiles. In the fourth section, we propose to investigate the part geometry and the form errors. This final investigation is intended to confirm the simulation and/or the hypothesis used in the FEM simulation.

4. Three-Dimensional Measurement

4.1 Introduction

During the process, the reaction forces from the workpiece will result in deflections of the tool–machine or the press, which will adversely affect the tolerances of the component. Arentoft et al. [7] developed a new experimental test on a open C-press. Their equipment can load the press in both the vertical and horizontal directions during the stroke and the load can be imposed either symmetrically or eccentrically. The stiffness and assumed rotation points were determined by the authors. Chodnikiewicz and Balendra [8] determined the press characteristics matrix by experimental tests. These tests were carried out on cylindrical specimens with parallel or oblique faces. The forming forces were measured using a specially designed measurement system with incorporates the forming die surface and sets of displacement transducers which enable the measurement of the translational and rotational deflections of the press. The relationship between the forming force and the resulting moment can be expressed in the form of a flexibility matrix comprising translational and rotational press deflection data. These tests give the characteristic of the press, but not during the forming process. In this work, we use

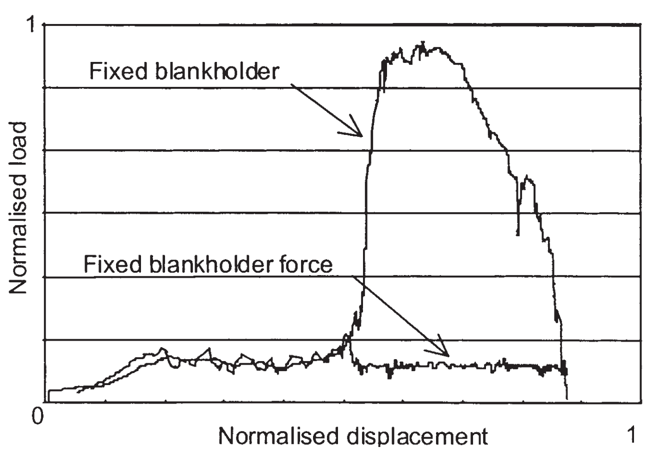

Fig. 4.

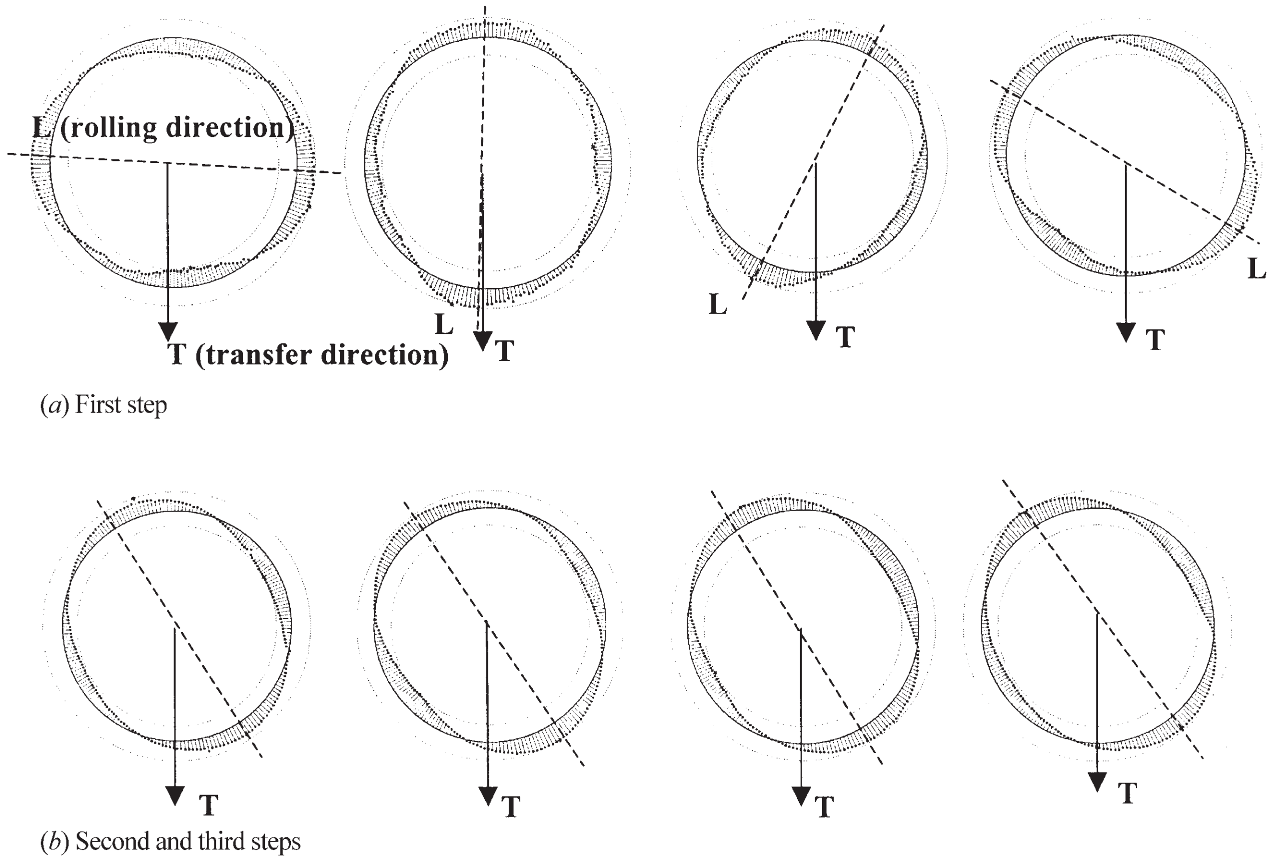

Fig. 5.

three-dimensional measurement to determine the geometrical variation. Our approach does not need a preliminary test on a forming press and uses industrial measurements carried out for quality tests.

The first objective of sheet metal part measurement is to provide a geometrical comparison between the profile simulation and multiple measurement profiles. Part measurement errors have multiple sources that cannot be incorporated in the FEM model, for example the forming machine errors (the dies' real geometry, their relative position or real machine displacement).

To characterise the sources of the influence of the relative error, the measurement protocol, in the first approach, must be as exhaustive and general as possible. We use a coordinate measuring machine with an estimated uncertainty ($k = 2$) of ± 10 μm for the operations.

For the three forming steps, the radical sections of six parts are measured from the inside and outside circles. The distance between two sections is equal to the initial thickness of the blank. Data for each circle acquisition are obtained from 200 points regularly spaced, so the thickness can be determined from the distance between two opposite points (inside and outside circles). The analysis is centred on these points: to produce the form error of a section of the formed sheet metal,

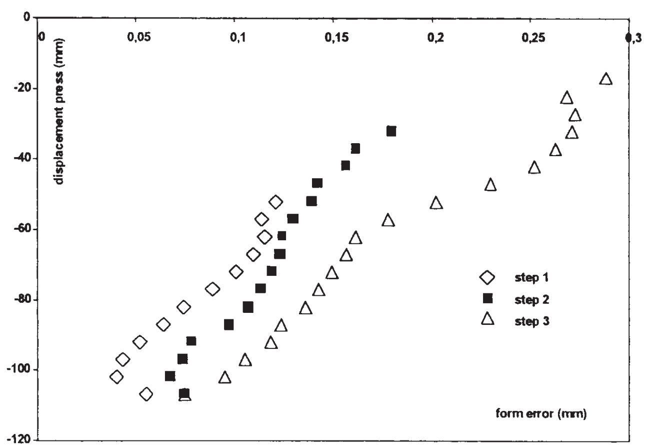

Fig. 6.

a geometrical comparison between the profile simulation and multiple measurement profiles, and the forming machine process error.

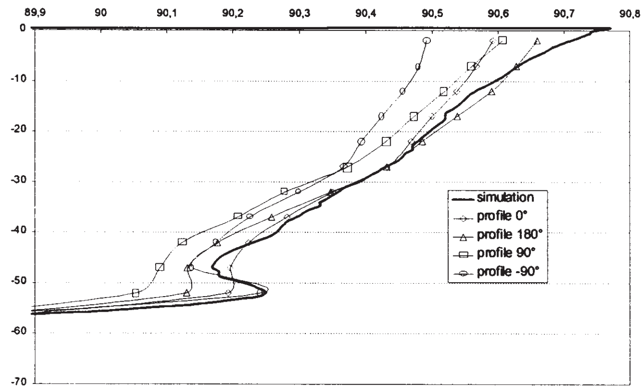

Fig. 7.

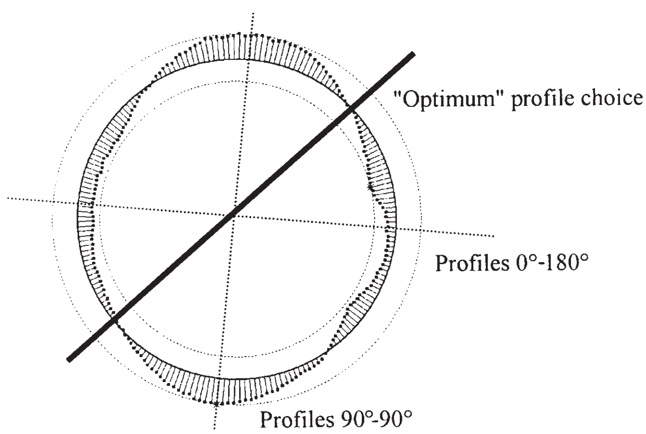

Fig. 8.

4.2 Form Error Analysis

Figure 5 shows typical radial section form errors in the forming steps. The curves are produced at the same height. The default amplitude decreases towards the bottom of the part. The variation is approximately linear and is higher for the third forming step (Fig. 6). The springback of the sheet metal depends on strain hardening and thickness; so this is the case in the third step of the process and confirms the forming process observations.

4.3 Measurement and Simulation Profiles

By definition, in axisymmetric simulation, the simulated profile is the same at all axial sections. In reality the axial measurement sections are different and consequently have different measured form errors. Figure 7 shows four sections of the first forming step and the simulation profiles. To show the correspondence with the finite element simulation, it is necessary to use the average profile to minimise the influence of the form error. We propose to choose least squares profiles because they minimise the form error due to anisotropy or die defects (Fig. 8). This knowledge may be used to optimise the next design in a concurrent engineering process, so that a good simulation will be obtained at the first design step.

4.4 Forming Machine Process Error

Die assembly errors and displacement machine errors are the sources of thickness variations. In this part, we analyse the least squares circle inside centre coordinates and compare them with the least squares circle outside centre coordinates. The curves are identical for all measurement series. Moreover, Fig. 5 shows that in the first step, the form error is directly related to the rolling direction. On the other hand, in the two following steps, the form error no longer depends on the rolling direction but depends on the transfer direction on the parts, so, these form errors are a consequence of the process. In the transfer direction, the guide width is larger than in the transverse direction, so the guiding amplitude errors will be smaller in this direction. Effectively, the transverse error amplitude is larger than in the transfer direction (Fig. 9 and Fig. 10(*a*)). But in zone I, only the third step is formed which can generate press table and guiding deformation caused by the eccentric load in the transfer direction. In zone II, the second step minimises the eccentric load. When all steps are formed, the load is centred and produces the required precision in the transfer direction. In the transverse direction the load is always centred; as a result the three forming steps have the same errors, which are generated by the machine guiding error. Figure 10(*b*) shows the two particular points where the dies touch a new blank.

This experimental approach makes it possible to carry out a dimensional check of the products. The displacement defects of the press are analysed during the forming operation thanks to the shape of the manufactured part. Some authors determine the stiffness of the machines by experimental procedures which make it possible to model the stiffness of forming machines [7,8]. On the other hand, our approach characterises the stiffness of the die unit plus machine, which can be implemented in a computer code, but for the moment, our method does not apply to the optimisation of industrialised parts. In the design phase, our modelling makes it possible to produce an estimate of the working accuracy, for a family of products closely similar to products already manufactured.

5. Conclusion

The correlation between experimental data and FEM results shows that process investigations are needed. By using a geometrical experiment approach, we can identify process-forming errors. Currently, these errors cannot be obtained by FEM simulation, but in a concurrent engineering context, they must be incorporated during the conceptional phase. However, the most difficult step is to obtain homogenous modelling for the total production process.

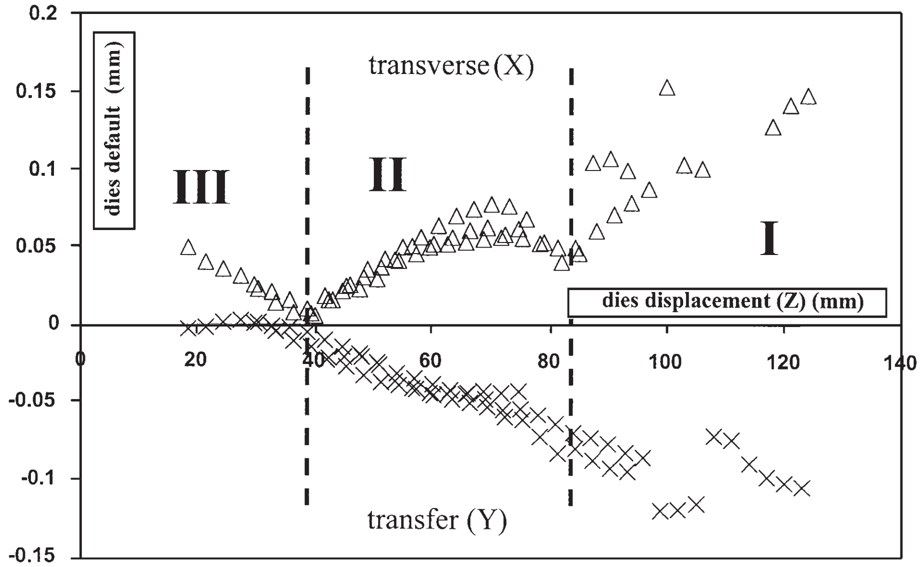

Fig. 9.

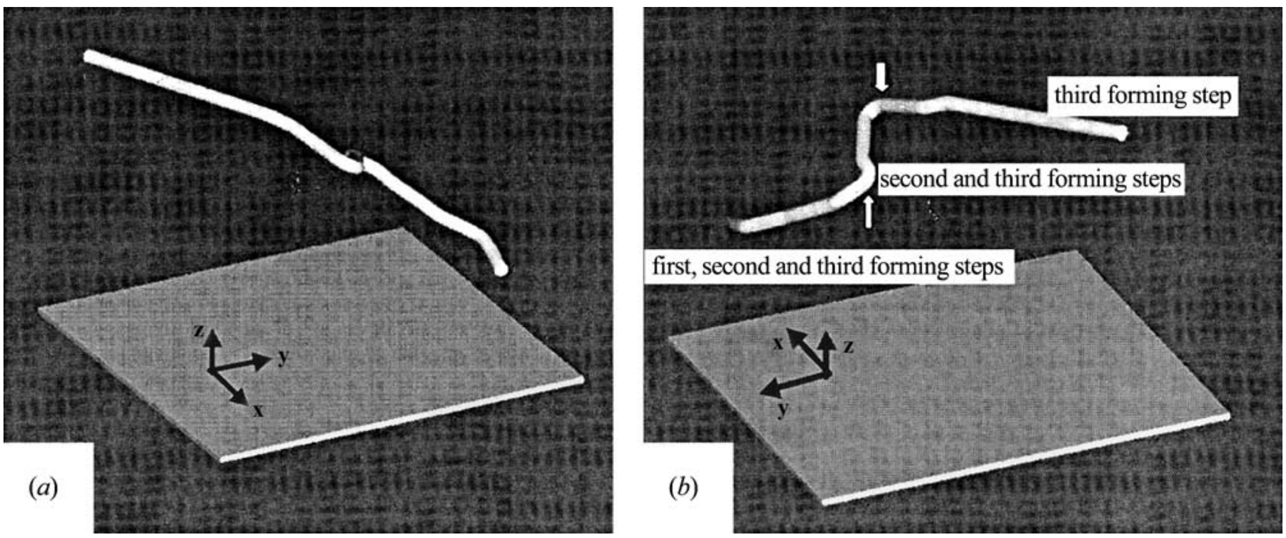

Fig. 10.

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