

## Sheet Incremental Forming: Advantages of Robotised Cells vs. CNC Machines

Massimo Callegari<sup>1</sup>, Dario Amodio<sup>1</sup>, Elisabetta Ceretti<sup>2</sup>, Claudio Giardini<sup>3</sup>

<sup>1</sup>*Dipartimento di Meccanica, Università Politecnica delle Marche, Ancona, Italy*

<sup>2</sup>*Dipartimento di Ingegneria Meccanica, Università degli Studi di Brescia, Italy*

<sup>3</sup>*Dipartimento di Progettazione e Tecnologie, Università degli Studi di Bergamo, Italy*

### 1. Introduction

In recent years the traditional sheet metal forming processes, suitable for high volume batches, do not correctly meet new market requirements characterised by high flexibility, reduced time-to-market, low cost for small batch production, etc. Moreover, they are not suitable for producing low cost prototypes and pre-series components. Thus new sheet metal forming techniques are very often required and pursued by manufacturing industries and have been intensively undertaken by scientific research groups (Siegert *et al.*, 1997; Amino *et al.*, 2000; Shima, 2001; Kochan, 2001; Shim *et al.*, 2001; Filice *et al.*, 2002; Iseki & Naganawa, 2002; Kim *et al.*, 2003; Yoon *et al.*, 2003; Ceretti *et al.*, 2002, 2004; McLoughlin *et al.*, 2003; Allwood *et al.*, 2005; Lamminen, 2005; Meier *et al.*, 2005). Among the new innovative technologies, the sheet Incremental Forming (IF) can be successfully used for small pre-series batches or prototypes. IF is a process where common and simple tools mounted on CNC machines, instead of complex die sets, are used to deform locally a workpiece. In recent years many studies have been done on IF and many are still in progress with the aim of finding both the most affecting process parameters and the suitable machines and working centres to run experiments and production (Park & Kim, 2002, 2003; Jeswiet *et al.*, 2005a, 2005b; Duflou *et al.*, 2005a, 2005b; Hirt *et al.*, 2005; He *et al.*, 2005a, 2005b; Ambrogio *et al.*, 2005; Bambach *et al.*, 2005).

Unlike the standard metal forming process, fast production changes are possible thanks to the very simple IF machine configuration. Even if the time required for making one product is much longer than in the traditional press forming, the IF advantages are gained on tool design and production in prototyping phase. IF could be also successfully applied in completion flexible work cells, for example after hydroforming operations for slots or small parts finishing. Furthermore, instead of using general purpose CNC machines, the modern incremental sheet processes can be directly performed on robotised cells. This will enhance the advantages in flexibility and production time reduction since a robotised cell equipped with the proper tools can produce the part and, on the same fixture, realise the completion operations such as flanging, trimming and so on.

To form the sheet into the desired shape an *ad hoc* tool, mounted on the machine spindle or on a robot gripper, is moved according to the given tool path. Several IF strategies have been developed which mainly differ for equipment and forming procedure. In particular,

the process can be divided into:

- Single Point Incremental Forming (SPIF), where the sheet is deformed by a single tool (no support is present).
- Two Points Incremental Forming (TPIF), sheet deformation is ensured by a tool and a local support (a kind of partial die).
- Full Die Incremental Forming, where the tool deforms the sheet against a die; this die can be realized with cheap materials such as wood, resin or low cost steel; the use of a die ensures a better and more precise shape of the final piece.

The above described strategies can be used on both CNC machines and industrial robots.

This paper presents an overview of the most recent researches carried out by the Universities of Bergamo and Brescia and by the Polytechnic University of Marche about the innovative IF process, describing the used working machines, the equipment devices and the process experimental and simulative optimisation applied to Full Die IF.

More in details, the results of the use of an industrial robot for the IF with Full Die will be analysed in terms of a potential increase of technological opportunities (e.g. the use of 5 axes manufacturing) and of process versatility (e.g. the capability of performing extra flanging or completing works) and compared with traditional 3 axes machining centre results.

## 2. Machines and equipment

### 2.1 CNC milling machine

As reported in the previous paragraph, IF is characterised by different strategies. The one utilised in the present research refers to Full Die Incremental Forming. In fact, since the final goal of this research is to identify working rules for pre-series production, this methodology should allow the achievement of the best results in terms of geometrical and surface tolerances. It must be underlined that it is not necessary to use an expensive material for the die (such as particular resistant steel) since the working loads and deformation areas are reduced, but polymeric materials, thermosetting resins, hardwood and any other material satisfying strength, stiffness and surface finishing requirements can be used so allowing an overall cost reduction.

IF with Full Die is based on the local deformation of a sheet on a die obtained by means of a punch moved by a CNC machine over a die which can have a negative (Fig. 1a) or positive shape (Fig. 1b): in this last case a movable blank holder is required. The main components of the equipment are:

1. a punch mounted on the spindle of the CNC machine;
2. the die, which reproduces the part geometry;
3. the blank holder to keep the sheet in the right position during the process (fixed or movable).

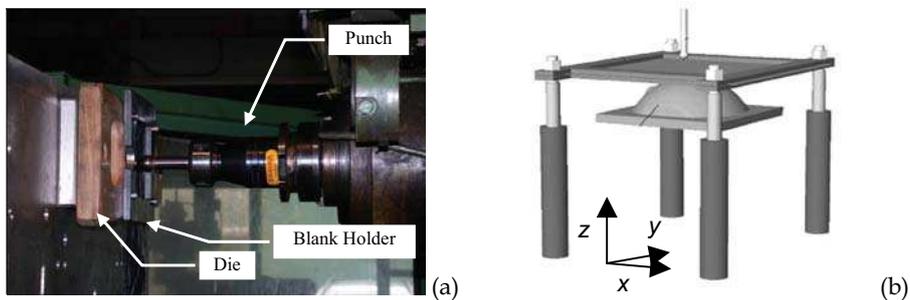


Fig. 1. The set up components.

The die is mounted on the table of the CNC machine and the moving punch deforms the sheet up to the die. The punch path must be optimized by means of an accurate study of the final geometry, in order to obtain a good surface finishing. When the die has a positive geometry the blank holder is moved by four hydraulic actuators to keep the sheet steady in the working position (Fig. 1b) otherwise is fixed (Fig. 1a).

The punch has a cylindrical body with a spherical head. The sphere dimension is an important process variable. In fact, large headed tools assure better material flow and production time reduction, while small sphere dimensions are needed to accomplish the dimensional features of the part (the tool radius must be equal or lower than the minimum radius of curvature of part's surface).

To generate the punch trajectory CAD, CAM and CAE techniques were used. Since the tool movement strategy is very important for obtaining safe components, several tool paths were investigated in previous studies (Ceretti *et al.*, 2003; Giardini *et al.*, 2004a, 2004b, 2004c, 2005a, 2005b) and the best one must be identified by taking into account the positive or negative shape of the die, the shape of the part, the tool dimensions and the sheet material.

## 2.2 Robotized cell

Conventional industrial robots do not have the stiffness nor the accuracy that are generally required for the incremental forming operations (Lamminen, 2005) but the rather new parallel kinematics machines can be designed so as to show good features from this point of view: for the present research the COMAU Tricept HP1 robot has been used, a six axes machine with hybrid structure (a serial wrist is mounted on top of a parallel shoulder), shown in Fig. 2. It is able to apply a maximum thrust of 15 kN over a work envelope of 2000 mm x 600 mm, with a repeatability better than 0.03 mm. The drawbacks of the machine mainly lie in the great anisotropy of its workspace, that is also characterised by a complex shape and a limited dexterity; therefore a simulation tool has been implemented in order to be able to analyse off-line machine kinematics and assess beforehand the feasibility of a certain task.

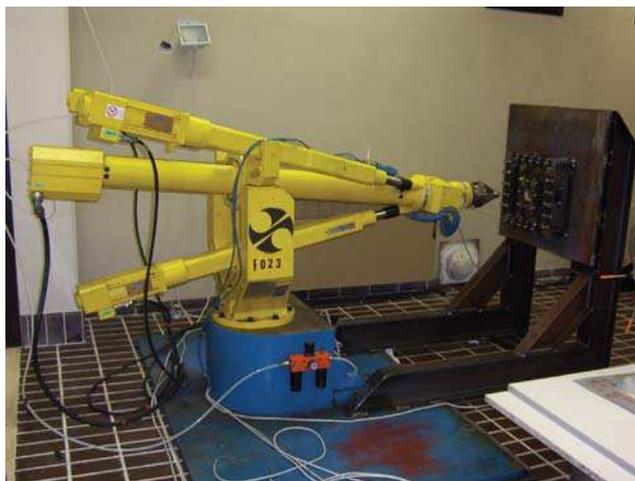


Fig. 2. The hybrid robot Tricept HP1.

A pneumatic gripper holding a punch with a spherical tip is attached to the robot flange. Various punches with different radii are used but in any case the small dimensions of the ball tips allow to obtain the required high local pressures by the application of forces considerably smaller than in conventional stamping. The die and the blank are clamped together by means of several clips, whose design and setting are very important for the quality of the operation: in fact a rigid constraint at frame boundaries can be desired in some cases as well as the possibility to control the material flow towards the die in other situations (Ceretti *et al.*, 2003). The die with the supporting frame and the robot are mounted on the same (thick) metal sheet: an automatic tool changing system was available beside the robot but it has not been used in the present experimentation.

### 3. Analysis of the whole production process

The design of the production process begins from the definition part's geometry, that is usually made by importing the CAD model of either the part or the die. Then the tool path is generated by a CAM program. The part program used to machine the die is useless and a specific path must be generated instead, to take into account that a plastic deformation is being induced and to satisfy the needs of realizing good quality parts. The CL file is then imported in FEM packages to evaluate the maximum forces that are required to complete the forming process (ANSYS®) and to simulate the operation (PAMSTAMP®) in order to forecast the final shape and the thickness distribution of the part. This is a fundamental task when studying the part feasibility.

A kineto-static model of the robot has been implemented in Matlab by the Authors therefore it is now possible to verify that tool path is entirely inside the workspace of the manipulator and that the forces required at tool tip can be actually developed by the motors at the actuated joints. If the check is not passed, it is necessary to change the punch (e.g. a smaller size one) or the relative position between the die and the robot (e.g. by means of a rotating table) or the kind of tool path (e.g. the tool can be differently oriented in such a way as to load it mainly with axial forces).

At this phase the availability of a commercial multibody simulator can be useful, e.g. to verify that the joints are not running out of their admissible stroke or that no impact with other machinery in the cell occurs. The IGRIP® package, that has been used to this aim, also allowed to generate robot's task in controller's own programming language, i.e. PDL in this case; then the preliminary version of the program has been directly uploaded to Tricept controller for the final tuning. The off-line programming is also enabled by an IGRIP® calibration utility, that has been used for the initial setting of cell's CAD model according to the real data measured in the laboratory.

Some modules of the recalled procedure have been previously outlined in (Callegari *et al.*, 2006) and will be explained in more details in the following sections.

#### 3.1 CAD/CAM module

The solid model of the die is based on the geometry of the part and corresponds either to convex or to concave die shapes. The tool path can be different in the two cases, since for positive die the tool usually deforms the blank starting from the inner part and moving towards the boundary, while the opposite approach is used for negative forming.

A CAD package has been used for modelling the part and the die and for the related CAM

processing: a fixed slicing of the part was used, with a step depth (or pitch) that has been varied from  $0.5\text{ mm}$  to  $1.0\text{ mm}$ . Both 3 axes (for both CNC machine and robot) and 5 axes (for robot) paths have been generated, see Fig. 3 and 4.

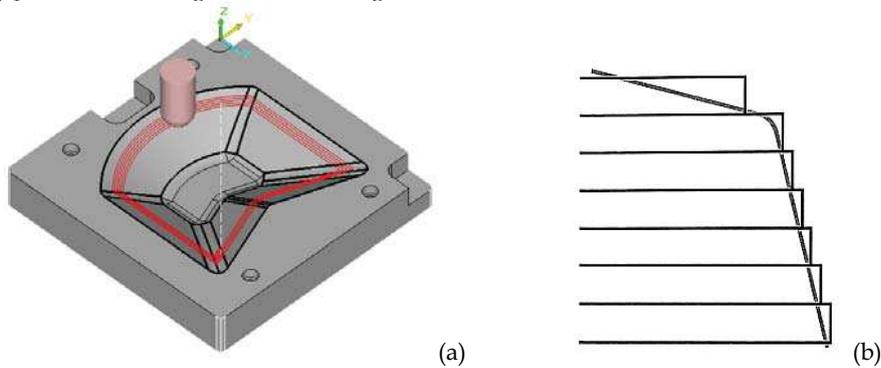


Fig. 3. Negative forming with concave die: 3 axes path (a) and fixed step slicing (b).

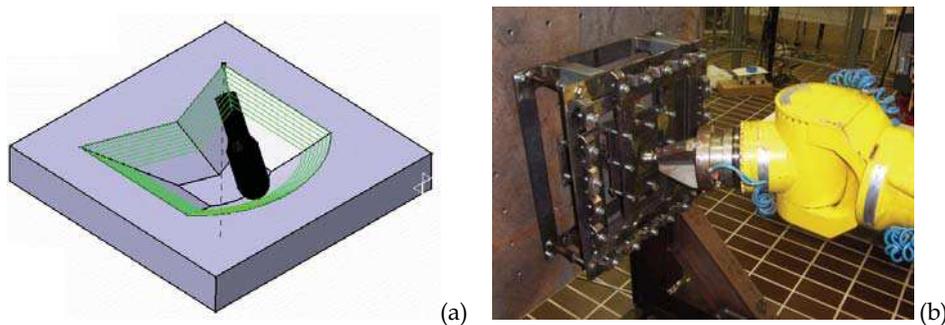


Fig. 4. Negative forming with concave die: 5 axes path (a) and robot wrist (b).

When the die is concave, different punch movement strategies can be used. In particular, one strategy starts the process from the part boundary and progressively deforms the sheet through trajectories drawn at constant  $Z$  levels (direct negative forming); the other strategy is characterised by a straight tool movement inside the blank till the maximum depth of the die is reached and then a spiral movement towards the part boundaries starts (inverse negative forming), see Fig. 5. This last approach can be used only with limited die depths and assures a better material flow from the boundary so guaranteeing a lower thinning of the part. Unfortunately, this strategy could not be applied with the robotised cell because the robot was not able to develop the high lateral thrusts that were required. To overcome this limit a progressive solution was tested: in this case the punch is moved as in inverse negative forming but it moves downwards up to the bottom of the die following progressive spiral paths with different geometrical dimensions whose effects were investigated.

The velocity of the tool together with the path variables (spiral width, pitch and so on) have a great relevance for the quality of the part and must be chosen according to the other parameters of the process, like sheet material and thickness, depth of deformation, etc.

If the surface finishing of the part is an important aspect of the process, the path conducted as a pocketing with constant step depth needs to be modified. In fact, this step down path from the top to the bottom of the pocket, in which the tool follows a series of consecutive contours with fixed step depth, is the simplest one but presents two disadvantages. In particular the sheet is marked at the transition point between consecutive layers and the quality of flat or near to flat surfaces is poor when high step depth or pitch (more than 0.5 mm) are used.

In this case to conduct pocketing with constant “scallop height” ( $S_c$ ) can give better results. This is a step down path from the top to the bottom of the pocket, in which the tool follows a series of consecutive contours with variable step depth (the maximum of which must be furnished) in order to keep constant the value of the scallop height (Fig. 5d). This kind of path reduces the disadvantages of the first type and, in particular, the flat surfaces show a better quality.

Step depth, scallop height and type of tool path influences were studied during the experimental tests, changing their values.

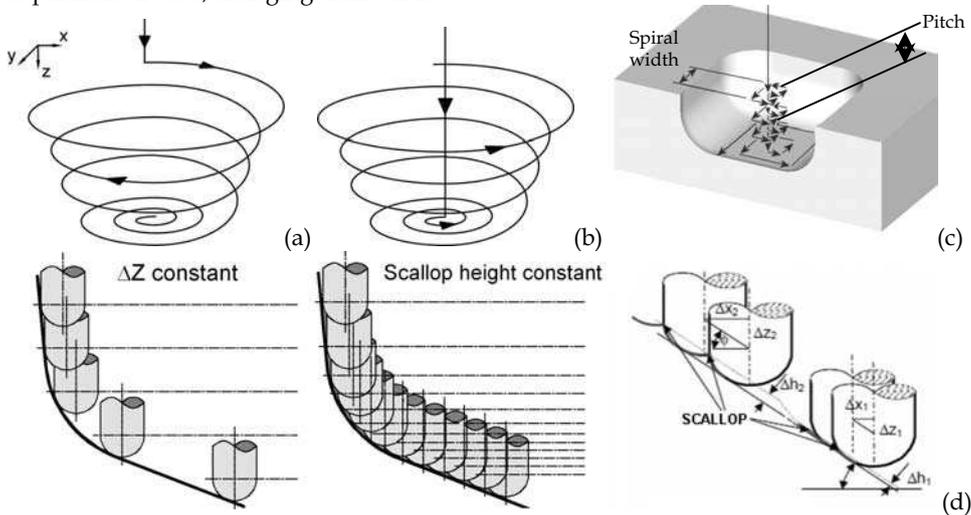


Fig. 5. Direct (a) and inverse (b) negative forming with progressive downward movement (c) at fixed step depth or fixed scallop height (d).

### 3.2 Analysis of the forming process

#### Analytical model

A rough estimation of the state of stress of the blank under deformation can be obtained by analytical models, while more detailed FEM simulations must be performed to go inside the matter and assess the influence of the main process parameters.

For sake of simplicity, it has been closely followed the approach of Iseki (2001), which refers to a planar state of deformation. This approximation can be rather well satisfied in case of spherical rollers, with good lubrication and relatively small curvature paths. Referring to the geometrical setting and notation of Fig. 6, representing a negative forming, the  $z$  axis is taken along the direction of the incremental depth steps, and the  $y$  axis along the current motion direction.

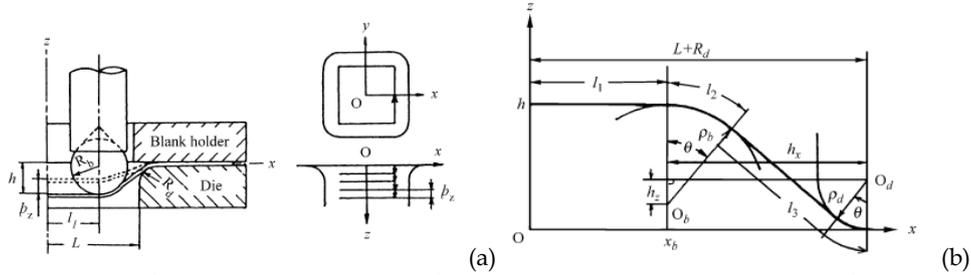


Fig. 6. Sketch of the negative incremental forming setting (a) and planar model of the arising state of deformation (b).

The contact angle  $\theta$  between tool and blank is:

$$\theta = \arcsin \left[ \frac{\rho_b + \rho_d}{\sqrt{h_x^2 + h_z^2}} \right] - \arctan \left( \frac{h_z}{h_x} \right) \tag{1}$$

It is noted that half of the initial thickness of the metal sheet,  $t_0$ , must be added to both curvature radiuses of tool and die,  $\rho_b$  and  $\rho_d$  respectively. The hypothesis of plain strain state leads to:

$$\epsilon_x = -\epsilon_z = \ln \left[ \frac{\ell_2}{L + R_d - \ell_1 - \ell_3} \right] = \left[ \frac{\ell_2}{h_x - \ell_3} \right] \tag{2}$$

where :  $\ell_2 = \rho_b \theta$  and  $\ell_3 = h_x \cos \theta - h_z \sin \theta + \rho_d \theta$ .

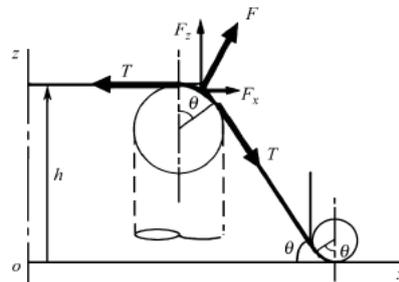


Fig. 7. Equilibrium of metal sheet during negative incremental forming.

With reference to Fig. 7, the total effort causing material deformation,  $F$ , can be well approximated being equal and opposite to the resultant of the 2 traction forces  $T$  at the borderline of contact surfaces. The tensile force  $T$  on the metal sheet is:

$$T = 2R_b t \sigma \tag{3}$$

If actual sheet thickness  $t$  is expressed as a function of the initial thickness  $t_0$  and of the deformation  $\epsilon$ , it can be obtained:

$$T = 2R_b \left( \frac{2}{\sqrt{3}} \right)^{n+1} K t_0 e^{(-\epsilon_x)} \epsilon_x^n \tag{4}$$

where the material hardening law  $\sigma = k \epsilon^n$  has been considered. The two Cartesian components of interaction force at the end effector can now be simply expressed as:

$$\begin{cases} F_x = T(1 - \cos \theta) \\ F_z = T \sin \theta \end{cases} \quad (5)$$

The simple inspection of (1-5) shows that, as expected, the lateral force to be developed at the tool increases with the contact angles  $\theta$  (and therefore with the depth  $h$ ) and decreases with the distance between the local centres of curvature of tool and die.

The results of the current model have been compared with the corresponding FEM simulations and experimental trials, whenever available: a good agreement has been proved in many situations, with results generally over-estimated and therefore conservative for the sake of process safety. On the other hand, the model is not able to emulate closely the actual thinning of the sheet (and therefore forecast the possible occurrence of tears or wrinkles) or the paths with small curvature radii, where clear three-axial states of deformation establish. If these cases must be investigated, a FEM simulation is unavoidable, while the analytical model still preserves its validity for a first assessment of the forces occurring at tool tip, that is an important input information for the kineto-static feasibility check that will be explained in detail in next section.

### Numerical process simulation

In order to verify the process ability in realizing the desired shape, that is the process feasibility, it is important to conduct FEM analyses of the sheet deformation. Once the FEM model has been validated by comparing the obtained results with the experimental ones, it is possible to use the model itself to forecast the process parameters influences on the final part shape and on sheet thinning which are relevant aspects in part quality evaluation. Moreover, different punch movement strategies can also be analysed and the best one can be identified prior to the experimental phase.

The simulations were conducted using both implicit (DEFORM®) and explicit (PAMSTAMP®) codes. This latter has the advantage of reducing the computational time with respect to the implicit code, in addition the explicit code results are closer than the implicit to the experimental thickness values. As a consequence, in the following of this paper, only the results of the explicit FE code will be presented. In both cases, the FE programs move the punch using as input the CL files obtained from the CAM module. The model components are the sheet (modelled as elastic-plastic element), the die, the punch and the blank-holder (considered as rigid bodies), see Fig. 8. The friction was modelled according to the Coulomb law.

A first set of simulations was run to identify the most suitable values for friction coefficient and blank-holder force by comparing the experimental thickness distribution along the piece section. Once the model was validated it was possible to use the model itself to forecast the feasibility of a given part shape and to evaluate the part quality, in correspondence of variations of tool path or other process parameters (e.g. tool diameter, feed rate).

To allow the simulation in 3D DEFORM® environment, a suitable program able to move the punch (treated as the upper die) along a defined trajectory as obtained from the CL file has been developed and implemented in a user subroutine. This module allows also to restart the simulation from an intermediate point of the trajectory as required when a remeshing occurs. Moreover, another module has been developed in order to allow the thickness calculation and representation using proper variables specifically defined in the pre-processing phase.

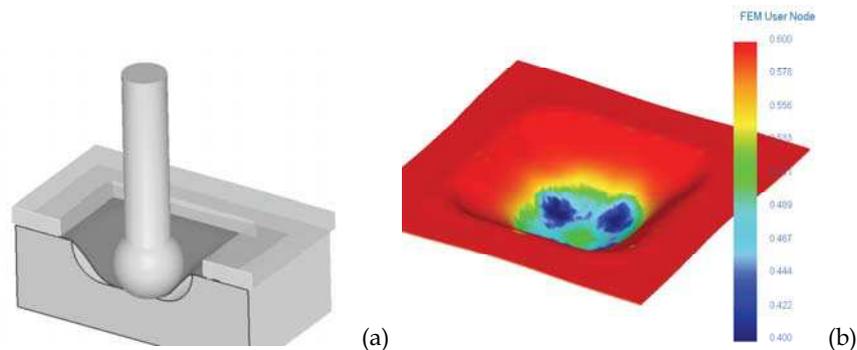


Fig. 8. FEM model objects: sheet, punch, die and blank-holder (a); the thickness representation (b).

### 3.3 Feasibility kineto-static checks

The only kind of robots presently able to develop the required thrusts at the tool are parallel kinematics machines, that are also characterised by high stiffness and good accuracy: unfortunately, the closed-loop architecture generally yields a workspace of complex shape and characterised by high anisotropy, which complicates the planning of effective operations (Merlet, 2005). On the other hand, the information provided by robot manufacturers are often too poor to enable an off-line assessment of the feasibility of the current incremental forming operation. Therefore more detailed simulations must be performed beforehand to check that all the generated 5-dimensional paths are included inside the 6-dimensional workspace of the manipulator and that, at every position, the motors torques required by the task can be actually developed. Since the velocities of the robot are usually quite low, a kineto-static model of the manipulator is sufficient to assess the kinematic feasibility of the required tool positions and to correlate workspace efforts to joint space torques. The Tricept HP1 used in the tests has a maximum thrust of  $15\text{ kN}$  in the axial direction when the tool is aligned along the same  $z$  axis but its static performances dramatically downgrade as the structure leaves such favourable configuration (see Fig. 9 for a qualitative representation). Therefore a complete kineto-static model of the robot has been developed and implemented in the Matlab programming language, as explained with details in (Callegari *et al.*, 2005) and summarised in the following sections.

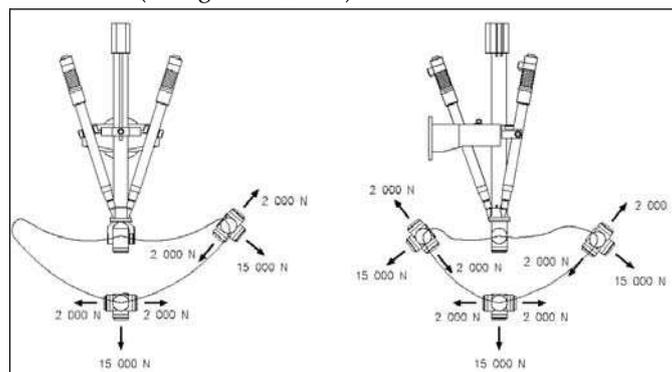


Fig. 9. Static performances of the robot Tricept HP1 (Comau, 1995 and 2001).

### Robot kinematic model

In order to develop the kineto-static model of the Tricept HP1, the conventional steps of direct and inverse kinematic analysis had to be performed. It is well known that the resolution of the position problem is always the most challenging phase of the work, usually ending up with a complex non-linear system of algebraic equations. In this case the approach suggested by Siciliano (1999) for the resolution of the (3 dof) parallel shoulder has been followed, by adapting it to the case of a 6 axes hybrid machine: due to the difficulty of the problem, direct kinematics has been solved numerically, while inverse kinematics admits closed-form solutions. Velocity kinematics, on the other hand, can be expressed in the usual linear form:

$$\begin{bmatrix} v_x \\ v_y \\ v_z \\ \omega_x \\ \omega_y \\ \omega_z \end{bmatrix} = J(\theta_1, \dots, \theta_6) \cdot \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \\ \dot{\theta}_4 \\ \dot{\theta}_5 \\ \dot{\theta}_6 \end{bmatrix} \quad (6)$$

where in the left hand side all the terms of tool linear and angular velocities are collected in a single vector, while  $\dot{\theta}_i, i=1, \dots, 6$  are motors speeds and  $J$  is a proper Jacobian matrix. It is noted that the Jacobian incorporates all the terms of the velocity mapping, up to ball screws pitches or gear reducers ratios.

### Manipulability ellipsoids

Let us consider the set of joint velocities  $\dot{\boldsymbol{\theta}}$  of constant unit norm:

$$\dot{\boldsymbol{\theta}}^T \cdot \dot{\boldsymbol{\theta}} = 1 \quad (7)$$

It is desired to describe the Cartesian space velocities of the end-effector that can be generated by such velocities at a given configuration in space. The image of the six-dimensional sphere (7) in the operational space of tool linear and angular velocities is called (*velocity*) *manipulability ellipsoid* and is given by the quadratic form:

$$\begin{bmatrix} \mathbf{v}^T & \boldsymbol{\omega}^T \end{bmatrix} \cdot \Gamma_v \cdot \begin{bmatrix} \mathbf{v} \\ \boldsymbol{\omega} \end{bmatrix} = 1 \quad (8)$$

where the  $6 \times 6$  square matrix  $\Gamma_v$  is defined by:

$$\Gamma_v(\boldsymbol{\theta}) = J^{-T}(\boldsymbol{\theta}) \cdot J^{-1}(\boldsymbol{\theta}) \quad (9)$$

Cartesian space velocities are high along the direction of the major axis of (9), while only low velocities are yielded along its minor axis: therefore an isotropic (kinematic) behaviour of the manipulator is manifested when the ellipsoid becomes a sphere. Just to visualise the matter, in case of a planar robot with two equal motors, the form (8-9) would represent an ellipse whose major and minor axes (the eigenvectors of  $\Gamma_v$ ) indicate the directions along which the tool can be moved with the maximum and minimum velocities respectively (that are given by the square roots of the eigenvalues of  $\Gamma_v$ ).

Due to the well-known duality between kinematics and statics, for every pose of the manipulator inside its workspace (position and attitude of the tool) the 6 joint torques  $\boldsymbol{\tau}$  balancing the external wrench of forces  $\mathbf{F}$  and moments  $\mathbf{M}$  applied at tool tip are given by:

$$\boldsymbol{\tau} = J^T \cdot \begin{bmatrix} \mathbf{F} \\ \mathbf{M} \end{bmatrix} \quad (10)$$

Following the same approach previously outlined for the characterisation of robot velocities, the ellipsoid representing all the Cartesian forces and moments that correspond to unit motors torques,  $\boldsymbol{\tau}^T \cdot \boldsymbol{\tau} = 1$ , can be derived. In the case of the present application the external moments at tool tip are null, therefore only the three-dimensional ellipsoid of end-effector forces is meaningful:

$$\mathbf{F}^T \cdot \Gamma_f \cdot \mathbf{F} = 1 \quad (11)$$

where  $\Gamma_f$  is the 3x3 upper left sub-matrix of  $J J^T$ .

The knowledge of matrix  $\Gamma_f$  clearly characterises the static performances of the manipulator and also represents an effective means to visualise them; it is noted that  $\Gamma_f$  depends on all the 6 coordinates of robot's pose. As an example, Fig. 10 shows in dark patterns the *force manipulability ellipsoids* at various points of Tricept workspace, when the tool is asked to lay parallel to the Cartesian axes of global frame. Of course to gain more insight into the performance of the actual robot under consideration, proper weights must take into account the different sizes of joints motors; moreover, due to the linearity of static relations, the application of higher forces/torques can be represented by simply re-scaling the resulting graphs.

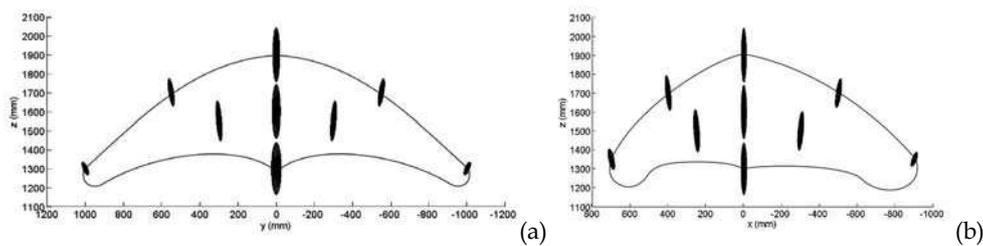


Fig. 10. Force manipulability ellipsoids of the robot Tricept HP1 in two Cartesian planes: upper (a) and side (b) view (end-effector parallel to global frame).

### Static performances

For every position of the manipulator inside its workspace (position and attitude of the tool) the 6 joint torques  $\boldsymbol{\tau}$  balancing the external wrench of forces  $\mathbf{F}$  and moments  $\mathbf{M}$  applied at tool tip are given by (10), where the 6x6 manipulator Jacobian matrix is highly varying with tool position in our case. Once a task has been assigned and the arising forces have been assessed, the feasibility checks can be easily performed: the joint torques that are computed by simulation must be compared with the actual rated torques of the motors driving shoulder and wrist axes, about 13 Nm and 3 Nm respectively, but of course the gear ratio of the Harmonic Drives and the efficiency of all the transmission has to be accounted for.

Figure 11 shows a sample analysis performed by means of the developed simulation package: tool tip spans a vertical plane at constant height ( $z=1600$  mm) with the tool perpendicular to the plane itself and charged by an axial load of 15 kN. The figure plots the value of the maximum torque requested to any one of shoulder motors: it is noted that the limit value of 13 Nm is easily overcome when the tool approaches workspace boundaries; wrist motors, on the other hand, are almost idle since the external force passes through the centre of the spherical wrist.

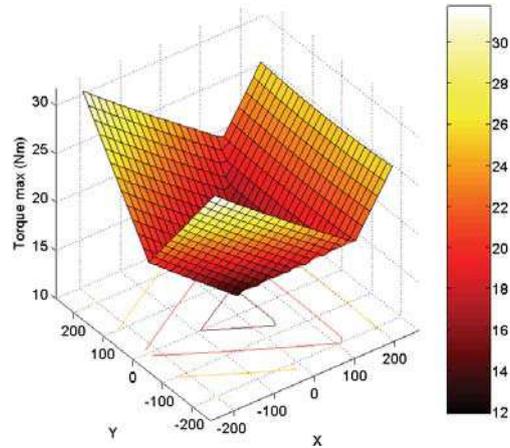


Fig. 11. Maximum torque delivered by shoulder motors ( $z=1600\text{ mm}$ ,  $F_z=15\text{ kN}$ ).

In the simulation of Fig. 12, instead, the configuration of the robot is still the same but an external force of  $500\text{ N}$  is vertically directed along the  $x$  axis: in this case shoulder motors are scarcely charged but wrist motors cannot sometimes deliver all the torque that should be required.

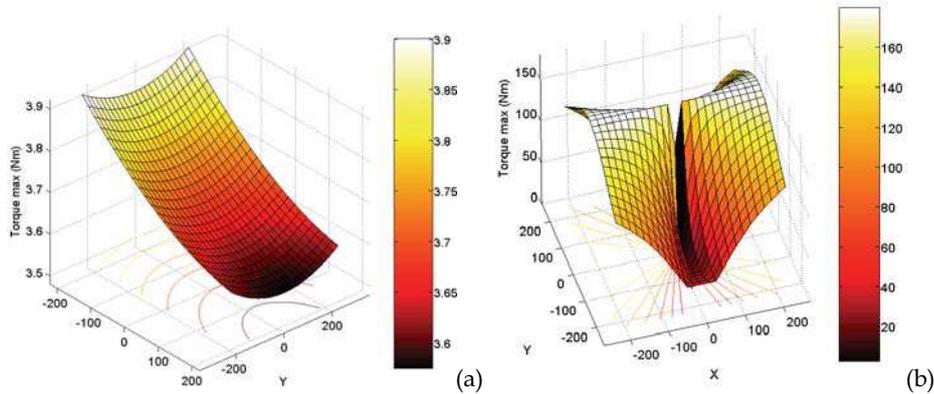


Fig. 12. Maximum torque delivered by shoulder (a) and wrist (b) motors ( $z=1600\text{ mm}$ ,  $F_z=0.5\text{ kN}$ ).

### 3.4. Cell simulation

The analysis of all the cell is performed by means of the IGRIP® package by Delmia, Fig. 13: it is a multibody simulation code for applications of industrial automation and its libraries already have all the information needed to simulate and program off-line the main industrial robots presently on the market. Its use is particularly important in case several intelligent pieces of equipment cooperate simultaneously in the cell, therefore needing a strict coordination of the tasks.

In our case, tool trajectory has been previously defined by means of CAD/CAM programs and then statically validated to be sure robot motors can actually push the punch against the blank with the required forces. Then, the path has been imported into the IGRIP®

environment to perform a multibody simulation, providing the kinematic feasibility of the task by taking into account actual joints strokes and possible impacts with obstacles or other equipment. For larger parts the use of a tilting table, synchronised with the robot and governed by the same robot controller, can be necessary, as well as for some operations, e.g. flanging, where the required line of action of tool force would not be close to the preferred thrust direction of the Tricept: in these cases a proper off-line programming reduces the set-up time of the operation and enhances the feasibility chances of the task.

Since IGRIP® data base codes all the kinematic data of the robot and is also aware of control characteristics, robot task can be generated in the proper programming language, i.e. PDL in our case, and directly uploaded to the controller: all production information like cycle-times, occupation of resources, etc. can be estimated off-line at this phase of the work. Of course the PDL program needs to be refined at robot side in any case, but a closer agreement between off-line program and the final code is obtained by exploiting the calibration module, that is purposely developed.

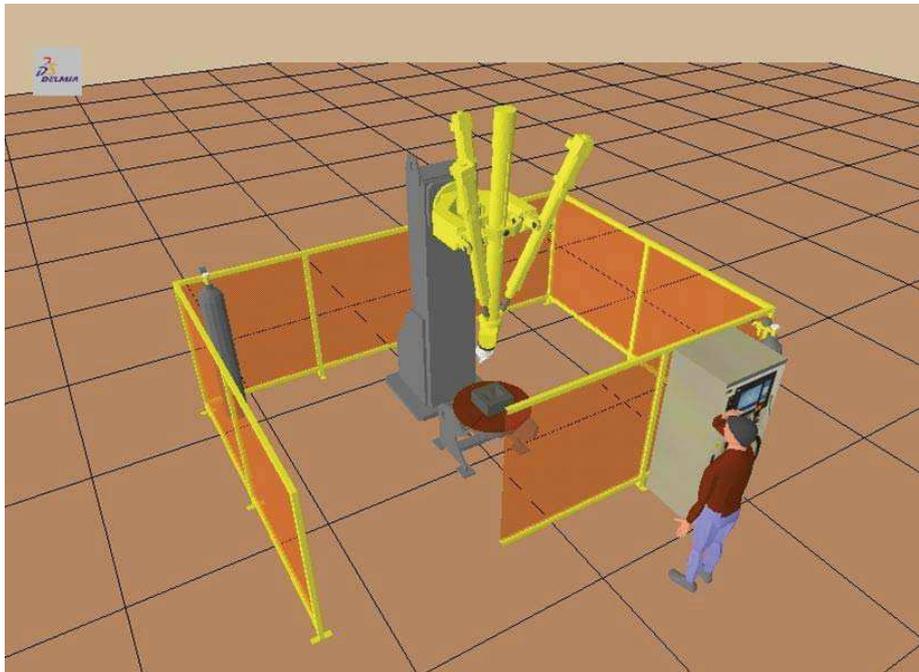


Fig. 13. Multibody simulation of the cell.

#### 4. Experimental and simulative results

The first laboratory tests have been performed on a square socket of small size,  $37\text{ mm} \times 37\text{ mm}$  side and a depth of  $21\text{ mm}$  in Ancona by using the robotised cell and  $40\text{ mm} \times 40\text{ mm}$  side and a depth of  $20\text{ mm}$  in Brescia, where the CNC machine was used. Figure 14 shows the metallic and wooden dies, the blank holder and all the fixtures mounted on a vertical frame.

This set of tests was difficult for the robot due to the particular shape of the die, whose lateral walls were almost vertical; in fact this geometry determines high reaction forces (due to the large contact surface between tool and blank) whose lines of action are almost perpendicular to the (preferential) axial direction, therefore often causing the block of the motors.

During these preliminary experiments it has been shown that, notwithstanding the relatively low velocities of the tool during the process, the velocity profile of the robot influences the quality of the product and even more the performances that can be obtained. In fact during accelerations the inertia forces are added to the elasto-plastic reactions coming from the blank under deformation, while the forming task is easier for the robot during deceleration ramps. Moreover, it resulted that the smaller the radii of the corners are, the higher torques are required to the motors for the impending state of three-axial deformation: better results and lower torques have been registered by using tools with smaller sphere diameters.

It must be emphasized that, when the CNC machine is used to perform the experimental tests, no limits can be identified for this simple geometry. In fact, the machine stiffness and the motor powers allow the deformation of the sheet since the working loads are low. In addition, increasing the feed rate gives the possibility of reducing the working time without affecting the part quality.

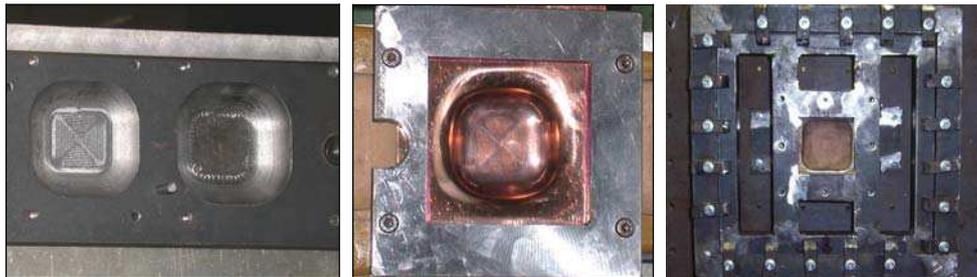


Fig. 14. Metallic and wooden dies with blank holder and clamping fixtures.

The first attempts of forming a steel blank have been performed by using 3 axes paths on a  $0.6\text{ mm}$  thick *AISI 304* stainless steel sheet; in this way it was possible to draw a comparison with the results obtained using both the robotised cell and the CNC machine. In the case of the robotized cell a maximum depth of about  $14\text{ mm}$  was reached in "direct" forming, while the motors blocked at the depth of only  $10\text{ mm}$  in inverse forming (see Fig. 15). In the first case a set of square paths at higher depths has been progressively realised, with a pitch of  $0.5\text{ mm}$  without working the bottom of the pocket; in the second case, after reaching the desired depth, a spiral path was traced with a spiral step of  $1\text{ mm}$ . The quality of surface finishing is quite different in the two cases, since the pocket bottom does not come into contact with the tool in direct forming, while in second case it is deformed by the tool. In this second case the quality is better, even if in the part bottom it is still visible the point corresponding to the straight path of the tool before starting the spiral path which deforms the bottom (Fig. 15). A very tight fixing of the blank holder is required in order to avoid the formation of wrinkles and the rotation of the sheet.

To reduce the working loads, it was necessary to lower the tool pitch to  $0.25\text{ mm}$  instead of  $1\text{ mm}$ . The consequence of this change was an increase of the total cycle time. A reduction of

total cycle time was obtained by using a different language primitive for the path interpolation. Instead of requiring the robot to pass exactly through the programmed points, and therefore to stop when cornering, a spline interpolation allowed the tool to pass “close” to the programmed points, without stopping every time. The quality of the part is still good, while cycle times have been strongly reduced.

In a second set of tests the capabilities of the 6 axes robotized cell were used to orient properly the tool with respect to the sheet local normal and to the feed direction. First of all, it must be made clear that in robot trajectory planning 3 degrees of freedom are constrained by the path to be followed by tool tip, while 2 more degrees of freedom can be used to orient the punch along a “suitable” direction in space; therefore, by having the availability of a 6 axes machine, infinite possible trajectories can still be specified after all.

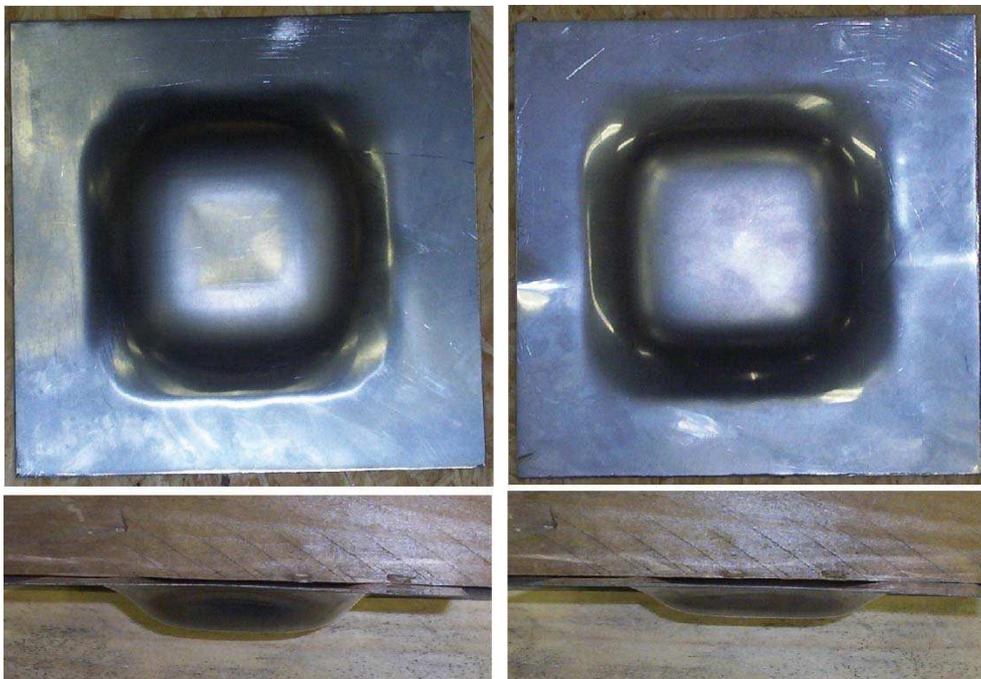


Fig. 15. Deformed steel parts for direct (left) and inverse (right) forming obtained with the robotized cell.

It must be pointed out that the kinematics of the robot is rather complex, therefore the “optimal” alignment of the tool does not necessarily mean that the tool itself is aligned along the direction of robot motion. In our trials, the tilting of the tool with respect to the feeding direction has been set so as to try to “minimise” the moments acting at wrist centre (by the way, the tool is charged by axial loads in this case). Moreover, due to wrist mechanical structure and to the limited winding of its joints, it was necessary to invert the sense of rotation of the motion around the die at every pass. This was also visible on the surface of the final part.

In future work, the redundancy of the robot with respect to the task could be used to:

- take automatically into consideration the constraints coming from the possible mutual collisions between blank/frame and tool/wrist;
- try to avoid the time consuming re-winding of wrist axes, therefore speeding up the process;
- align the whole robot structure along the main direction of the manipulability ellipsoids.

It must be said that the comparison with the 3 axes forming previously performed did not show major differences, apart from a slight higher quality and precision of the finished part mainly due to the smaller bending of the tool.

Considering the experiments conducted with the CNC machine, only the limit of the maximum reachable slot depth was found since it affects the sheet thinning (when thinning is too high the part breaks). Several tool paths of the “direct” forming type were tested by changing the spiral width and the spiral step according to Giardini *et al.* (2005a). The experiments conducted showed that roughness of the produced pieces was influenced only by spiral step and was not influenced by the tool path type. The thickness distribution, analysed along a part transversal section, is affected by the tool path and by the spiral step. In particular, summarising the results obtained in terms of part roughness, sheet thickness and maximum reachable punch depth it is possible to define the optimal Full Die IF process parameters, that is inverse negative forming with spiral step  $0.5\text{ mm}$ , tool pitch  $1\text{ mm}$  and feed rate  $400\text{ mm/min}$ .

The sheet thickness shows a minimum in correspondence of the bottom radius of the pocket, see Fig. 16. In one of the studied cases, the spiral step was so large that the final geometry of the part had a very low quality due to large wrinkles on the pocket bottom.



Fig. 16. Deformed steel obtained with the CNC machine.

Figure 17 shows an example of the comparison between simulations and experiments conducted on the CNC machine in terms of sheet thickness measured along a transversal cross-section. In particular the simulative results correspond to the PAMSTAMP® optimized model, that is the model with the most suitable values for friction coefficient ( $0.17$  between sheet and blank-holder and sheet and die,  $0.15$  between sheet and punch) and blank-holder force ( $50\text{ kN}$ ), referred to  $120\text{ mm} \times 120\text{ mm} \times 0.6\text{ mm}$  AISI 304 sheet with spiral step of  $0.5\text{ mm}$ , feed rate of  $400\text{ mm/min}$  and punch diameter of  $40\text{ mm}$ .

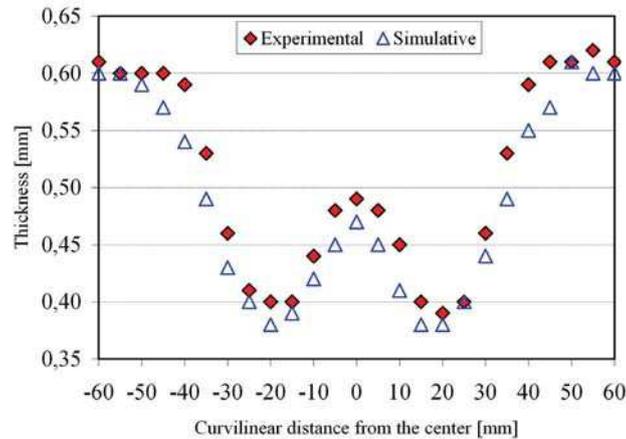


Fig. 17. Simulative and experimental thickness distributions along the transversal cross section of the realised part.

Finally some automotive components have been formed. Starting from CAD models of the parts, the resin dies were produced and then the part programs for the incremental forming have been developed. Figure 18 shows a component used in chair back assembly; two different kinds of steel blanks have been formed with this component: *AISI 304* and *DC04*. The results are satisfactory in both cases but the higher quality of the *AISI 304* part shows that this material can be worked better through the incremental forming technique.

During the working of the central slot, a certain compliance of the wrist became apparent, even if the overall quality of the part was good. Moreover, a little misalignment of the planes of the blank and the die caused the wrinkles that are visible outside the working area: a better realisation and tuning of the blank holder would certainly mitigate this problem.



Fig. 18. Formed chair backs: *AISI 304* (left) and *DC04* (right).

The research project analyzed also the feasibility study of some finishing operations just to show the potential versatility of an automated incremental forming cell: to this aim, the hatch of a multipurpose vehicle has been flanged by pressing the outer edge initially bent at 90°. The part was initially clamped between a punch and the die, then a specially designed tool, see Fig. 19a, rolled along all the outside border. The use of this rolling tool to deform locally the outer edge, allowed to flange the part without any problem and to avoid the expensive hydraulic presses generally used in this case or the manual operations that are time consuming and cost expensive but are necessary when the attention is focused on pre-series production. Similar application was studied using a roller mounted on a 3 axes CNC machine. The results are reported in Fig. 19b.

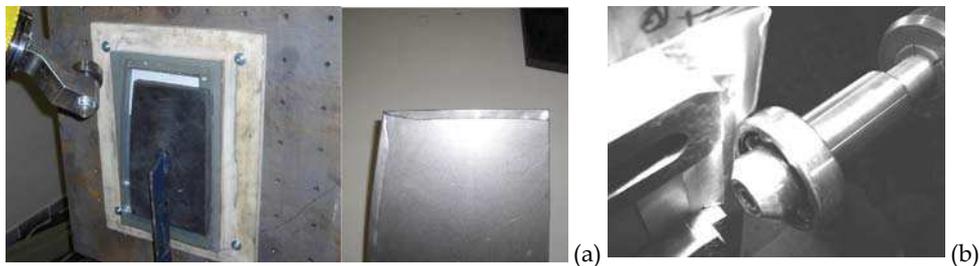


Fig. 19. Hemming of sheets in a robotised cell (a) and on a CNC machine (b).

## 5. Conclusions

The incremental forming of metal sheet parts can be an interesting alternative to manual forging of prototypes and pre-series blanks or to the manufacturing of shells for resin dies used for the production of small batches. Such characteristics of small-volume production would call for an increase in the level of flexibility and automation, possibly leading to the use of CNC machines or robotised cells able to produce or complete the parts. In particular, the use of robotised cells, with automatic tool change, can dramatically reduce the process time since on the same fixture it is possible to deform the part, cut the part, bend or flange the borders, load/unload the part, etc.

The present contribution has described the crossed experiments performed at the Polytechnic University of Marche in Ancona and at the Universities of Brescia and Bergamo to assess the feasibility of the automated processing by using both a traditional CNC machine and an industrial robot. It is noted that the research and industrial processes of incremental forming realised so far have ever used 3-axes CNC milling machines, apart from the hammering process patented by the Fraunhofer Institute for Manufacturing Engineering and Automation of Stuttgart (Shaefer & Schraft, 2005).

Unfortunately the conventional serial robots do not have the required stiffness and are not able to apply the necessary forces to deform incrementally the blank, but the rather new family of parallel robots has characteristics similar to CNC machining centres, while still keeping the versatility of a robot. The complex kinematics of the machine needed the development of a special purpose simulation environment to design beforehand the experiments and assess their feasibility. The necessary force at tool tip has been evaluated both analytically, with a simplified approach based on a plane strain state, and numerically,

by means of a commercial FEM code: different kinds of tool trajectories have been generated by CAM programs, based on actual part geometries. A final assessment of whole cell layout and working has been performed by means of the IGRIP® package, exploiting also the possibilities of the coordination with other external axes (e.g. a revolving table during flanging, a tool changing system, etc.) and its capability to generate the part program for the different commercial controllers.

Several experimental tests have been performed in order to validate the complex methodology for system design and prototyping and to study the several parameters playing a significant role in the process, as for instance: the different types of materials (e.g. *AISI 304* and *DC04* steel, copper), the number of axes of the task (3 or 5), the kind of interpolation between the points, the path imposed to the tool (e.g. depth first or breadth first), the size of punch end, etc. Many tests have been performed on a die specifically developed in-house for the execution system trials, then a few tests have been performed on commercial components, on dies provided by a car manufacturer supplier, with the execution of simple flanging operations too.

At the end of the research a development environment has been set up, able to interface the different software tools in order to support the process designer in making the correct choices. It must be said that, even if the simulation environment proved to be powerful and reliable, the whole design process of an experiment seemed very complicated by the complexity of the used equipment: therefore the use of more powerful robots, with larger workspaces would be desirable. It's Authors' opinion that parallel robots can be a viable alternative to CNC machines for the execution of incremental forming processes, especially if it is possible to exploit the high versatility of the machine for further completing operations. More tests should be needed to completely assess the benefits of robotics, with the possible availability of more powerful machines, that are already available on the market. As for the system design and prototyping tool that has been developed, it proved to be effective and reliable, even if resulted to be quite complex and more integration would be needed between the single software modules.

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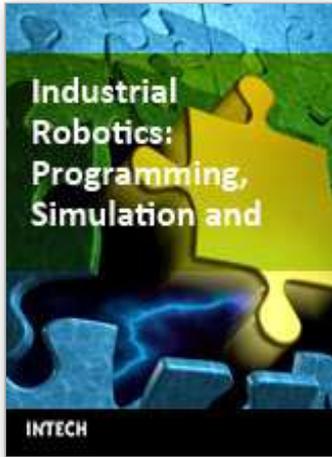
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## **Industrial Robotics: Programming, Simulation and Applications**

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This book covers a wide range of topics relating to advanced industrial robotics, sensors and automation technologies. Although being highly technical and complex in nature, the papers presented in this book represent some of the latest cutting edge technologies and advancements in industrial robotics technology. This book covers topics such as networking, properties of manipulators, forward and inverse robot arm kinematics, motion path-planning, machine vision and many other practical topics too numerous to list here. The authors and editor of this book wish to inspire people, especially young ones, to get involved with robotic and mechatronic engineering technology and to develop new and exciting practical applications, perhaps using the ideas and concepts presented herein.

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