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OPTIMISATION STRATEGIES TO DETERMINE PROCESS PARAMETERS IN TUBE HYDROFORMING

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Abstract

In tube hydroforming the concurrent actions of pressurized fluid and mechanical feeding allows to obtain tube shapes characterized by complex geometries such as different diameters sections and/or bulged zones. the main process parameters are material feeding history (i.e. the punches velocity history) and internal pressure path during the process. What is crucial in such processes is the proper design of operative parameters aimed to avoid defects (for instance underfilling or ductile fractures).

In this paper, the authors propose the results of a wide research project on hydroforming of aluminium alloy tubes based on the utilisation of different optimisation strategies and aimed to prevent the typical process defects (underfilling and bursting).

Key words: tube hydroforming, optimisation methods, FEM

1. INTRODUCTION

Hydroforming technologies allows to avoid the use of expensive dies by replacing them with the action of a pressurised fluid on sheets or tubes. Thus, hydroforming allows a strong reduction of tooling costs as well as an higher process flexibility since more complex shapes can be obtained with fewer forming steps with respect to traditional stamping. In particular, tube hydroforming allows to avoid the sequence of stamping and welding operations which characterizes the traditional tube production. Moreover, complex shape components characterized by good mechanical properties can be produced (Ahmetoglu and Altan, 2000).

The recent studies on tube hydroforming are focused on process mechanics investigation (Vollertsen et al., 1999; Schmoeckel, 1999), material formability issues (Filice et al., 2001), Sokolowski et al., 2000) and mostly on the optimisation of process parameters (Gelin, 2000; Gelin, 1998; Gelin and Labergere, 2002; Schmoeckel et al., 1992). In fact, the forming action in tube hydroforming derives from the combination of the material feeding (provided by the punch movement) and the internal pressure given by the fluid. In this way, the optimisation of the process strongly depends on the good calibration of the principal process parameters: the internal pressure of the fluid history and the punch velocity path. It was proved that a proper design of such variables allows the prevention of typical defects such as buckling, underfilling or bursting.

Many investigation on the above mentioned process parameters design and optimisation were presented based on different approaches. Some authors have focused on finite element simulation of tube hydroforming (Koc and Altan, 2002) also utilising FEM optimisation modules to determine loading paths (Imaninejad, 2005; Jirathearanat and Altan, 2005).

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Different approaches have been presented based on statistical tools such as Taguchi method (Li and Nye, 2006) or response surface methodology (Bonte et al., 2005).

In the last years, some researchers focused on artificial intelligence techniques to optimise loading paths, for instance integrating fuzzy control modules with finite element simulation (Ray and Mac Donald, 2005; Manabe et al., 2006).

Probably, the most effective results on loading paths optimisation were obtained by utilising gradient based optimisation methods (Fann and Hsiao, 2003; Labergere and Gelin, 2005) in particular when integrated with numerical simulations.

The authors have experienced different applications of optimisation tools in tube hydroforming trying to optimise not only the internal pressure paths but also the material feeding histories. The first step of such research project concerned the utilisation of an artificial intelligence procedure to design pressure and punch velocity paths (Di Lorenzo et al., 2004a; Di Lorenzo et al., 2004b), namely the application of fuzzy control procedures integrated with FEM simulation. The results obtained in such applications highlighted the main drawback of the approach: the controlled-design approach requires a strong computational effort since the process parameters histories are obtained running numerical simulations of the process at each control step.

More recently the authors developed some applications by utilising convex optimisation techniques (Boyd and Vandenberghe, 2004). In particular, different case studies were analysed trying to optimise pressure paths and punch velocity histories with the application of an integrated method FEM - Gradient based optimisation tools (Di Lorenzo et al., 2005; Di Lorenzo et al., 2006).

The application of such tools seems very promising even if the main drawback is that it is necessary to limit the number of optimised variables in order to reduce the computational effort in terms of necessary numerical simulations needed to reach the optimal values of the investigated variables.

In this paper, the results obtained with the application of a gradient methods are reported and a different control strategy is proposed to determine effective pressure paths and punch velocity histories.

The proposed control strategy is based on the experience acquired on the problem here addressed and allowed to reach process parameters histories which are very effective with a low computational effort. In fact, the proposed approach is based on the observation that a "safe wrinkling" effect can be utilised to reach good results in terms of product quality (Yuan et al., 2006; Yuan et al., 2007). Namely, the application of the proposed process parameters design procedure led to very effective results in terms of final shape of the part (no underfilling occurrence) and, what is more, in terms of bursting prevention.

2. THE OPTIMISATION PROBLEM

The optimisation process taken into account is applied on tube hydroforming of complex axisymmetrical shapes characterized by bulged zones. The process is carried out on a cylindrical tube by the application of an internal pressure, supplied by a pressurized fluid, and also by the action of one or two punches, that provides material feeding during the process. Figure 1 shows a model of the analysed operation with one side punch loading. The deformation process is driven by the internal pressure which expands the tube towards the expansion zones, the punch movement is necessary in order to supply new material to be formed so that excessive thinning should be avoided. A "process window" ensuring defects free products can be identified by the right combination of the two mentioned variables: in fact if excessive pressure is provided together with a scarce material feeding then thinning may increase with consequent fracture occurrence; on the other hand an inadequate pressure combined with high material feeding may lead to wrinkling (in figure 2 experimental test results are shown with defects occurrence derived from a wrong calibration of process variables).

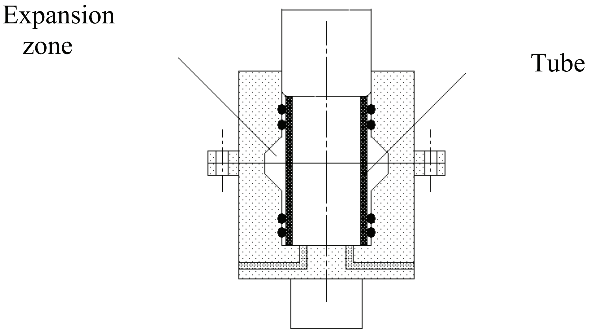


Fig. 1. A sketch of the tube hydroforming process.

The approaches aimed to design and optimise pressure and velocity paths, generally reach good solutions in terms of final part quality, by utilising pressure histories (i.e. internal fluid pressure vs. time) consisting of an increasing trend at the beginning of the process, a subsequent constant value and a final increase to a pressure peak aimed to calibrate the final shape.

Fig. 2. *Defects occurrence.*

Also, generally a trapezoidal curve shape is utilised for velocity paths (i.e. punch velocity vs. time) with a light increase at the beginning of the deformation followed by a constant value and a final decrease at the end of the process.

Such kind of histories are fully justified by the process mechanics; in fact as the process starts it is necessary to provide material feeding while pressure is acting on the tube. At the end of the process material feeding is not necessary anymore since the final shape calibration is given by the final pressure peak.

The authors have also investigated the possibility to optimise process variables following an adaptive approach based on a fuzzy system. The main drawback of a similar approach was the necessity of a wide numerical and experimental knowledge about the process. Moreover, in order to implement such optimisation procedure a strong computational effort (FEM simulations) was necessary.

Thus, a different approach was developed in order to reach a process variables correct design with the minimum experimental and numerical effort. In particular, gradient based methods were applied to optimise pressure paths in tube hydroforming taking into account as main goal the complete filling of the die cavities and also considering a constraint related to the control of excessive thinning of the tube.

In the former applications of the method (indicated as STEP1 in the following), the velocity paths were fixed a priori according to the available data about the analysed processes. Nevertheless, a validation of the obtained results was carried out by applying different velocity paths. The approach was applied to two different test cases as it will be described in the following.

The latter approach (indicated as STEP2 in the following) was also focused on the optimisation of the tube hydroforming of complex axi-symmetrical shapes characterized by bulged zones. In this step also by the action of two punches was considered. The design variables were defined as follows: the pressure and velocity curves were defined by some significant points whose coordinates identified the curves shapes. The optimal values of such coordinates correspond to the optimal operative parameters curves. In this application the objective function is a linear combination of two indicators: the former related to die filling and the latter related to tube wall thinning. The results of this latter investigation will be described in the following sections.

It has to be observed that the results obtained in the above described steps of the research project allowed a deep knowledge of the process evolutions and of the effects of pressure paths and material feeding histories.

Thus, such experience highlighted that the deformation paths guaranteeing the minimum thinning were characterised by a sort of "safe wrinkling" effect followed by a pressure peak leading to die filling. The basic idea derived from this experience was that the best process evolution consists on a preliminary strong material feeding, based on volume conservation principle, which results in a wrinkling effect and a subsequent pressure increase which has the role to guarantee filling. In fact, this latter phase develops by recovering the wrinkling zone thus excessive thinning is avoided since the deformation does not act on thickness.

On the basis of such consideration STEP3 of the research was developed whose implementation and results will be discussed in the following sections.

3. REMARKS ON GRADIENT METHODS

The optimisation problems in which the optimal values of some design variables is searched can be easily solved if the problem goal is expressed as a function of the design variables themselves. On the contrary, if the analytical links between problem objective and problem design variables are unknown, the gradient based approaches are very useful. The formulation of such problems generally, consists of: the definition of the set of design variables, the identification of an objective function, the solution of a certain number of direct problems (i.e. numerical simulations aimed to evaluate the values assumed by the objective function at the varying of the design variables) and finally the reaching of optimum values of the design variables.

The general formulation of a minimisation problem can be summarised as follows:

1. identify the design variables by a vector **x**;
2. choose the initial values: $x_k \in R^n$ with $k = 0$ (k denotes the method iteration number);
3. calculate the gradient of the objective function $\nabla f(x_0)$: if the convergence is reached the algorithm can be stopped;
4. else calculate an updated value of the design variables $x_{k+1} = x_k + \alpha_k d_k$ (where the scalar $\alpha_k \geq 0$ is called "step size" or "step length" at iteration k and indicates the entity of design variables adjustment at iteration k; d_k is the direction of movement i.e. the direction along which the objective function goes towards a minimum;
5. verify that $f(x_{k+1}) < f(x_k)$;
6. repeat step 4 and 5 until convergence is reached.

Such general approach can be refined according to different techniques with respect both to the gradient calculation and to the definition of step size and step direction.

Among the different possibilities available in the literature, the procedure proposed in the research project was the steepest descent method.

Such method is based on the hypothesis that if a minimum of the objective function is required then the search direction is given by the opposite of the function gradient; thus the following expression holds:

$$x_{k+1} = x_k - \alpha_k \nabla f(x_k) \quad (1)$$

A finite difference method was utilised in order to calculate the gradient; fixing a perturbation of the design variables ε it was possible to calculate the gradient as follows:

$$\nabla f\left(x_k\right) = \frac{1}{2\varepsilon}\left[f\left(x_k + \varepsilon\right) - f\left(x_k - \varepsilon\right)\right] \quad (2)$$

The calculation of the gradient required the evaluation of the objective function values for each value and for each perturbation of the design variables; in this way an integration with the numerical simulations was necessary: the FEM code provided the desired values of the objective function at each iteration of the applied method.

As the step size evaluation is concerned a line search procedure was utilised in order to determine the most performing value of α_k with respect to the minimization of the function. The method is stopped when the convergence is reached, i.e. when the function gradient is equal to zero and the objective function is minimized.

It has to be highlighted that this kind of method guarantees the reaching of a minimum (even a local one) for any initial values of the design variables. From a technological point of view this means that if the reached optimum is satisfying in terms of product quality, it can be considered a good solution for the given design problem.

4. STEP1 AND STEP2

In the former step of the research project here presented (STEP1), the gradient method was applied in order to optimise pressure vs. time curves in two different tube hydroforming operations on AA6060-T5 aluminium alloy (flow rule $\sigma = 330\varepsilon^{0,0925}$). Figure 3 a) and b) show respectively, the numerical models for the two cases: in case A the material feeding was provided by the action of a single punch while in case B two punches supply the feeding action (as it can be observed symmetry conditions were taken into account in both numerical models). Although the two side punch loading surely represents a more performing process configuration, the one side scheme was investigated too in order to verify the effectiveness of the proposed approach. In both cases, the cylindrical zone internal diameter was equal to 40 mm, while the maximum diameter of the expansion zone was 56 mm. Tube thickness is equal to 1,5 mm. The numerical simulations were carried out utilising DEFORM 2D 8.1 code; lubricating conditions were considered through a Coulomb friction model, with a value of the friction coefficient equal to 0,12.

In order to optimise pressure paths, in both cases four pressure values were taken into account in order to define pressure vs. time curves so that the design variables are represented by a vector whose components are the four pressure values. As the punch velocity vs. time curves are concerned, in the present application a trapezoidal shape was chosen in both cases characterised by a constant trend in the first phase of the process and a descending ramp during the second phase. In the operations here analysed the most important goal concern the obtainment of the desired final shape, thus the objective function to be minimised was related to the underfilling occurrence. Furthermore the main constraint regards the absence of ductile fracture, in this way such constraint was included into the objective function by taking into account the entity of thinning on tube walls.

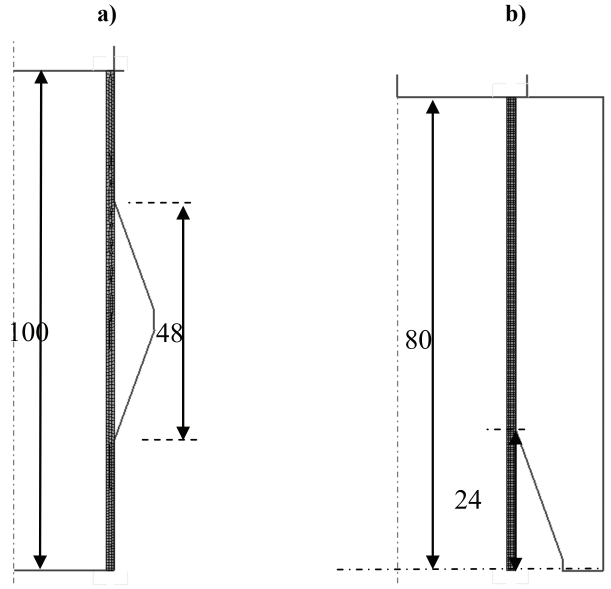


Fig. 3. a) Test case A; b) Test case B (dimensions in mm).

The optimisation procedure described in the previous section was applied in both the analysed cases. In Case A, a very satisfying solution was obtained after four iterations of the procedure (see figure 4). As it can be noticed, a good result is obtained after the first iteration: actually, the following iterations allow an improvement of the objective function even if as pressure curves are concerned a fine tuning of the pressure values is reached. As the objective function is concerned the method proved its effectiveness in taking into account both underfilling (a complete filling was reached) and thinning minimisation (final thinning is lower than 13%).

As it can be observed the algorithm significantly modified the pressure curve with respect to the initial one providing higher initial values followed by a pressure decrease and a final peak.

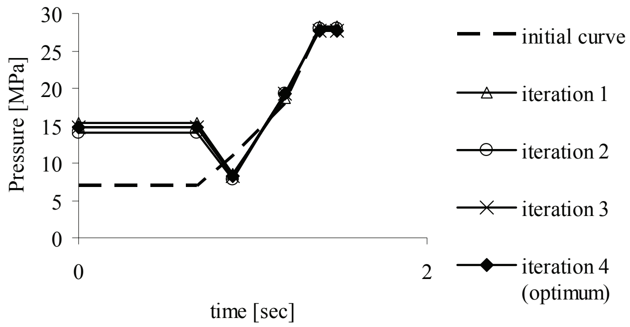


Fig. 4. Pressure curves at each iteration in case A.

Such evolution is coherent with process mechanics, actually the higher initial value are related to the calibration of initial material feeding while the pressure decrease is probably related to the minimisation of thinning. In fact, decreasing pressure while punch velocity is high allows a sort of "safe" wrinkling phenomenon which prevent fracture when pressure peak is applied. As expected the final pressure peak is suggested in order to guarantee filling.

As case B is regarded, the applied method reached the convergence after five iterations, the pressure curves evolution is reported in figure 5.

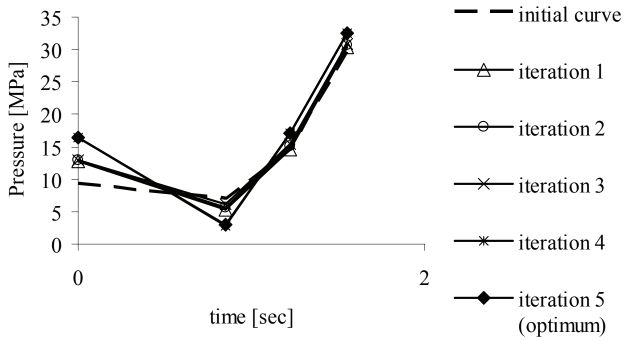
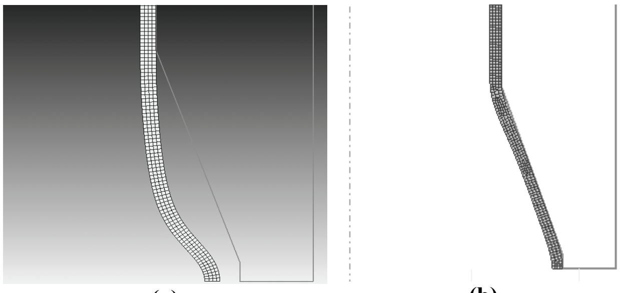


Fig. 5. Pressure curves at each iteration in case B.

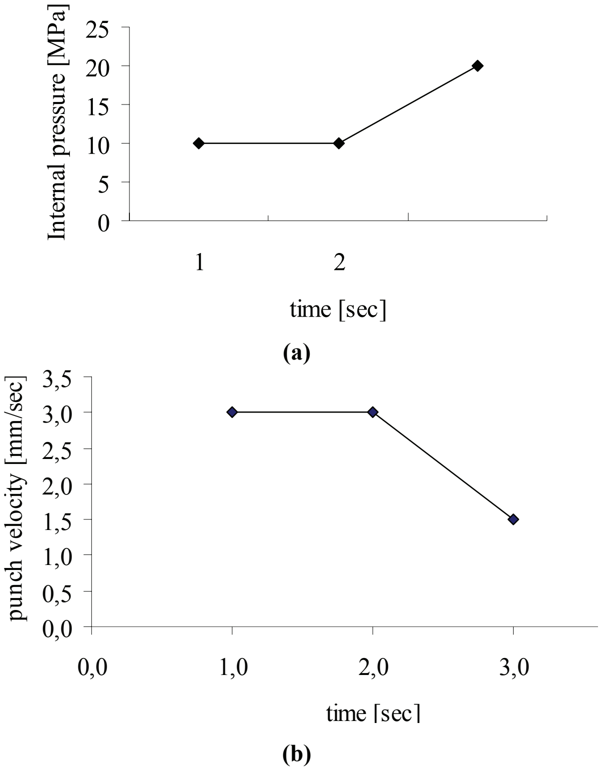
As it can be observed the method strongly modifies the curve in the former iteration while the latter steps only provide a fine tuning of the solution. In fact, in the application of the method smaller step sizes have to be utilised during the final iterations to update the variables, since near the optimum the procedure has a greater sensitivity. The final results of Case B are illustrated in the following figure 6: the ”safe wrinkling effect” can be observed as well as the complete filling; moreover thinning is limited to 12% which is very sound. It is worth outlining, in fact that maximum thinning of 20% is generally accepted in automotive production.



(a) (b)

Fig. 6. Case B: "safe wrinkling" (a) and complete filling (b).

In the latter step of the research project here presented (STEP2) a process similar to the one analysed in Case B of STEP1 was analysed. The main upgrading performed in this step of the research was the optimisation not only of the pressure paths but also of the material feeding histories. The steepest descent method was again applied; in the problem taken into account the variables vector has four components: the former two components correspond to the pressure values of the hypothesised pressure vs. time curve while the latter two refer to the punch velocity values of hypothesised velocity vs. time curve. Again, the objective function to be minimised is as a linear combination of two indicators: the former related to die filling and the latter related to tube wall thinning. Pressure and velocity curves corresponding to the initial values of the design variables are reported in figure 7; as it can be observed the time value corresponding to the curves slope variation and the total process time length are fixed a priori and time variables are not included in the optimisation. Such assumption is due to the necessity to reduce the number of variables and, as a consequence the computational effort to reach the solution. The initial curve shapes were chosen on the basis of previous experience in such kind of process optimisation.



(a)

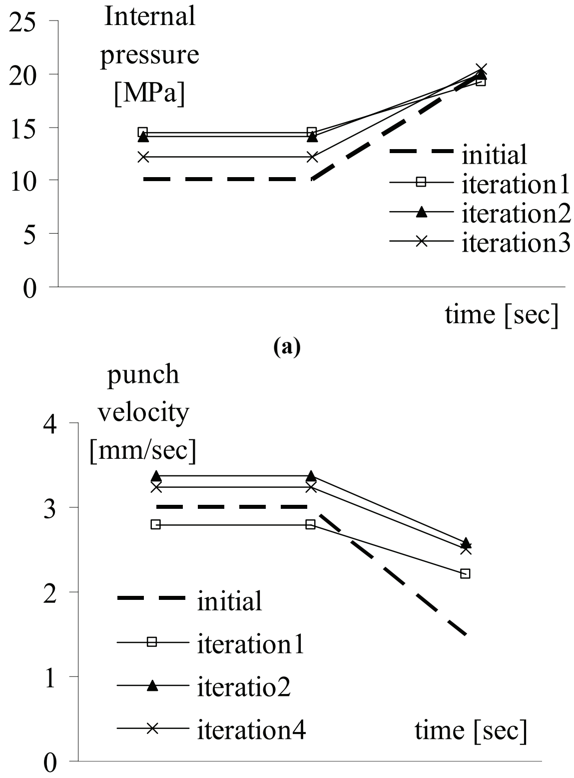
(b)

***Fig. 7.** The initial pressure vs. time curve (a) and velocity vs. time curve (b).*

The application of the above discussed optimisation procedure led to obtain in few iterations of the method very satisfactory results in terms of die filling and of fracture avoidance.

Figure 8 (a) and (b) shows respectively the pressure and velocity curves evolutions during the iterations. After only three iterations of the gradient method, the convergence is reached with a final underfilling lower than 3% (measured with respect to the total volume of the expansion zone) and a thinning lower than 9%.

A development of these results was performed by carrying a further optimisation procedure focused on time. In particular, the time value corresponding to the curves slope variation was optimised both for pressure (t_p) and velocity (t_v) curves. The basic idea of this step of optimisation is that the optimised pressure and velocity curve could be improved by modifying time intervals without an excessive computational effort. This further optimisation is carried out in two iterations and the pressure and velocity curves were modified with respect to the ones obtained from the first optimisation as follows the total punch stroke is higher and the material feeding is increased which is well justified by the process mechanics. As well the pressure peak is given earlier, and a lower underfilling is in fact obtained (underfilling is lower than 2% while the maximum thinning is lower than 7,5%).



(a)

(b)

***Fig. 8.** Pressure (a) and velocity curves (b) optimisation.*

5. THE PROPOSED TWO PHASE APPROACH (STEP3)

The basic idea of the proposed approach is the utilisation of the analysed “safe wrinkling” effect. The tube hydroforming operation is divided into two phases: in the former phase the main goal is the gathering of a proper amount of material in the expansion zone of the dies; in the latter phase the filling of the dies is reached by a calibration action given by a pressure peak without further material feeding. The material gathered in the first phase is accumulated in a wrinkling formation which is not a defect but a sort of useful effect which is recovered in the second phase by the pressure effect.

In this way, the optimisation strategy consisted of a preliminary action of constant pressure and constant punch velocity and a latter forming action given only by a linear pressure path reaching a maximum value when the complete filling was obtained while the punch movement was arrested. In fact, the material feeding in the second phase it not necessary since enough material was gathered in the first phase to fill the expansion zone with not excessive thinning. Thus, only in the first phase of the process an optimisation of the parameters is necessary, in order to determine the optimal values of the constant pressure and punch velocity to be applied. In fact, the pressure peak to be reached in the second phase was easily determined once the numerical simulation of the process showed the complete filling of the die cavities.

It has to be noticed that, with such approach only two design variables have to be optimised and, as a consequence, a low computational effort is required to develop the gradient based optimisation procedure. Once the optimisation strategy was chosen different steps of the optimisation procedure were followed. The first step consisted in the calculation of the punch stroke to be utilised in the first phase of the process; thus different values of the punch stroke were tested in order to determine the most performing one: it was observed that a too low value of the stroke led to excessive thinning in the final component while a too high one led to unrecoverable wrinkling defects. As the objective function is concerned the main goal of the optimisation procedure was the minimisation of thinning in order to prevent bursting at the end of the process. Once the punch stroke was fixed, a gathering of material was observed in the cylindrical walls of the tube in particular in the zone directly in contact with the punch depending on the combination of pressure and punch velocity values. Thus, if such gathering is excessive, it means that not enough material is accumulated in the expansion zone as "safe wrinkles", and, as a consequence, an early die filling is obtained and the final thinning will be excessive (see figure 9 (a) referring to one of the analysed operation). On the contrary, if such thickening of the tube walls in properly calibrated a beneficial wrinkling effect is obtained (see figure 9 (b)) and the final part will not reach excessive thinning.

According to the above considerations, an indirect measurement of thinning was utilised as objective function to be minimised, namely the total volume of the cylindrical tube walls in the former phase of the operation.

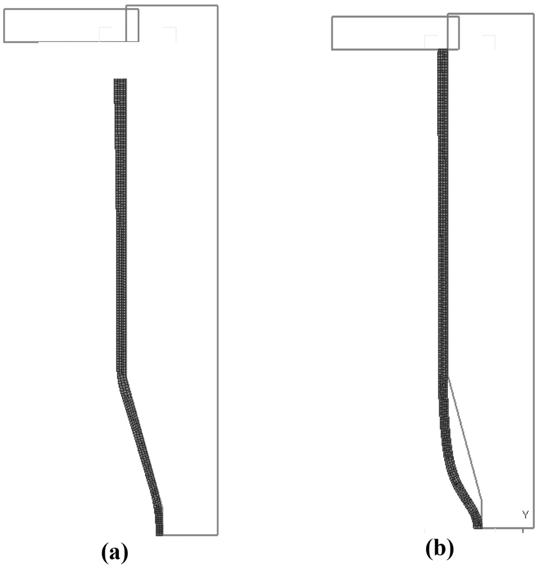


Fig. 9. *The effect of thickening of the cylindrical tube walls.*

The proposed approach was implemented on three different case studies:

Case 1: it is the operation analysed in Case B of the STEP1 of the research project mentioned in the previous sections;

- Case 2: it is the operation analysed in the STEP2 of the research project mentioned in the previous sections
- Case 3: it is a tube hydroforming operation analysed in the technical literature (Koc and Altan, 2002).

The first application was developed as follows:

Case1 Phase 1:

- the initial pressure value (p = 10MPa) was fixed as well as the punch velocity value (v = 3 mm/sec);
- the gradient optimisation procedure was applied and required two iterations to determine the optimal values of the process parameters. The obtained optimal values were p = 12,1 MPa and v = 2,15 mm/sec.

The final configuration of this first phase of the process is reported in figure 10. As it can be observed a proper material gathering is reached and "safe wrinkling" is obtained.

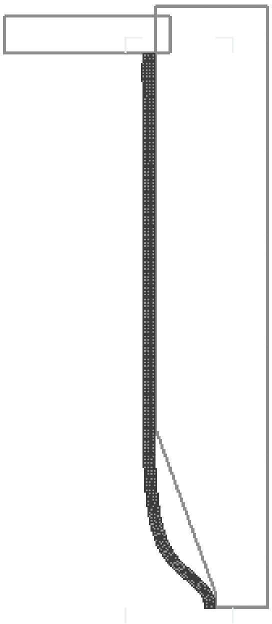


Fig. 10. The "safe wrinkling effect" in Case study 1.

Case1 Phase 2

A linear pressure path was applied increasing pressure to a maximum value of 40 MPa which ensured a complete die filling without excessive thinning; in fact the maximum thinning was about 9% which is a very sound results with respect to the optimisation performed in STEP1 leading to a final thinning of 12%. Moreover, the proposed approach allowed to reduce consistently the number of direct problems to be solved (i.e. numerical simulations) to reach the optimum; in fact both the number of the design variables and the necessary iterations of the method were reduced.

As the second application is concerned, similar improvements were obtained as described in the following.

Case2 Phase 1:

- the initial pressure value (p = 8MPa) was fixed as well as the punch velocity value (v = 1,5mm/sec);
- the gradient optimisation procedure was applied and required two iterations to determine the optimal values of the process parameters. The obtained optimal values were p = 10,25 MPa and v = 1,8mm/sec.

Case2 Phase 2

A linear pressure path was applied increasing pressure to a maximum value of 40 MPa which ensured a complete die filling without excessive thinning; in fact the maximum thinning was about 3% while in STEP2 of the research a thinning of 7.5% was reached. The final component obtained is shown in figure 11.

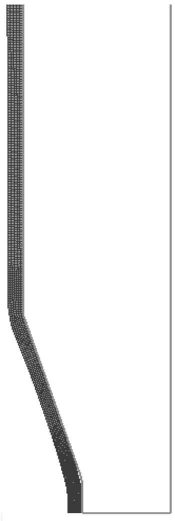


Fig. 11. The final part in Case study 2.

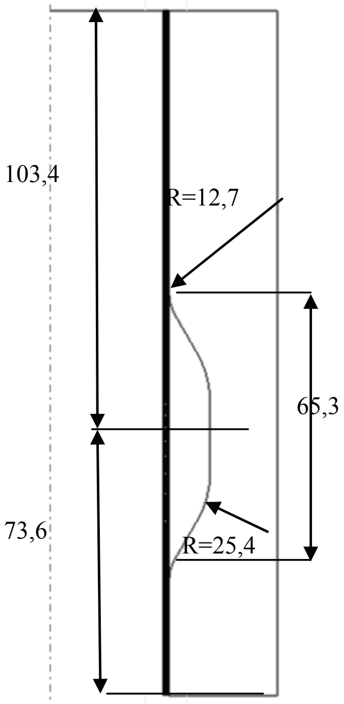


Fig. 12. Case study 3 (dimensions in mm).

As the third case study is concerned the process shown in figure 12 was investigated; the cylindrical zone internal diameter was equal to 64 mm, while the maximum diameter of the expansion zone was 95,1 mm. The two phase approach was applied: in particular, in phase 1 the gradient based optimisation procedure led to optimal values of pressure and punch velocity through a single iteration of the method. The optimal value obtained were: p = 21,575 MPa and v = 2,49mm/sec. In phase 2 of the procedure the maximum pressure was equal to 160

MPa. The results of phase 1 and phase 2 are reported in figures 13 (a) and (b) respectively. The final thinning was about 10% which is a very satisfactory results taking into account the values obtained in literature in similar cases (Koc and Altan, 2002). As it can be observed in figure 13 the "safe wrinkling" effect is very evident (a) and the final shape of the component was effectively reached (b) preventing bursting as well.

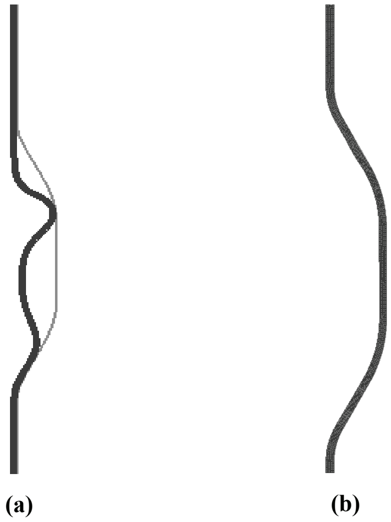


Fig. 13. *Results in Case study 3.*

6. CONCLUSIONS

A wide research project on 2D tube hydroforming was presented regarding the application of gradient based optimisation techniques to determine the most performing process parameters, namely internal fluid pressure paths and punch velocity providing material feeding during the process. The most effective optimisation strategy seems to be the one based on the idea that a "safe wrinkling" effect in an early step of the operation, can lead to very satisfactory results in terms of bursting prevention and final shape accuracy. The investigated case studies proved the effectiveness of the proposed procedure. Further developments of the proposed approach will concern the utilisation of optimisation strategies on more complex 3D tube hydroforming processes such as the ones utilised to obtain T-shape or Y-shapes.

REFERENCES

Ahmetoglu, M., Altan, T., 2000, Tube Hydroforming: State-of-the-art and Future Trends, *J. Mat. Proc. Techn.*, 98, 25-33.

Bonte, M.H.A., Van den Boogaard, A. H., Huètink,J., 2005, Metamodelling techniques for the optimisation of metal forming processes, *Proc. 8th Esaform Conf.,* ed., Banabic, D., Cluj-Napoca, 155-158.

Boyd, S., Vandenberghe, L., 2004. Convex Optimisation, Cambridge University Press.

Di Lorenzo, R., Filice L., Umbrello, D., Micari, F., 2004(a), Optimal design of tube hydroforming processes: a fuzzy-logic-based approach, *J. Engineering Manufacture – Part B*, 218 - 6, 599-606.

Di Lorenzo, R., L. Filice, D. Umbrello, F. Micari, 2004(b), An integrated approach to the design of tube hydroforming processes: artificial intelligence, numerical analysis and experimental investigation, *Proc. 8th NUMIFORM Conf.*, eds, Ghosh, S., Castro, J.M., Lee, J.K., Columbus, 1118-1123.

Di Lorenzo R., Corona V., Ingarao G. and Micari, F., 2005, Optimisation of a tube hydroforming process by gradient techniques, *Proc. VII AITEM Conference.*

Di Lorenzo R., Ingarao G., Micari F., 2006, Internal pressure and material feeding optimisation in tube hydroforming, *Proc. 9th Esaform Conf.*, eds, Juster, N., Rosochowski, A., Glasgow, 383-386.

Fann, K., Hsiao, P., 2003, Optimisation of loading condition for tube hydroforming, *J. Mat. Proc. Techn.*, 140, 520 -524.

Filice, L., Fratini, L., Micari, F., 2001. A simple experiment to characterise material formability in tube hydroforming, *Annals of CIRP*, 50, 181-184.

Gelin, J.C., Ghouati, O., Labergère, C., 2000, From Optimal Design to Control of Process in Sheet Forming and Tube Hydroforming, *Proc. ECCOMAS Conf.*

Gelin, J.C., Ghouati, O., Paquier, P., 1998, Modelling and Control of Hydroforming Processes for Flanges Forming, *Annals of CIRP*, 47, 213-216.

Gelin J.C., Labergère C., 2002, Application of optimal design and control strategies to the hydroforming of thin walled metallic tubes, *Proc. 5th Esaform Conf.*, eds, Pietrzyk M., Mitura Z., Kaczmar J., Kraków, 699-702.

Imaninejad, M., Subhash, G., Lokus, A., 2005, Loading path optimization of tube hydroforming process, *Int. J. Machine Tools & Manufacturing,* 45, 1504-1514.

Jirathearanat, S., Altan, T., 2005, Optimization of loading paths for tube hydroforming, *Proc. 8th ICTP,* Verona (CD ROM).

Koc, M., Altan, T., 2002, Application of two dimensional (2D) FEA for the tube hydroforming process, *Int. J. Machine Tools & Manufacturing,* 42, 1285-1295.

Labergere, C., Gelin J.C.,2005, New strategies for optimal control of command laws for tube hydroforming processes, *Proc. of 8th ICTP,* Verona (CD ROM).

Li, B., Nye, T.Y., 2006, Multi-objective optimization of forming parameter for tube hydroforming process based on the Taguchi method, *Int. J. Manuf. Techn.*, 28 23-30.

Manabe, K., Suetake, M., Koyama, H., Yang, M., 2006, Hydroforming process optimization of aluminium alloy tube using intelligent control technique. *Int. J. Machine Tools & Manufacturing,* 46 1207-1211.

Ray, P., Mac Donald, B.J.,2005, Intelligent control of tube hydroforming processes using finite element analysis, *Proceedings of 8th ICTP,* Verona (CD ROM).

Schmoeckel, D., Geiger, M., Hielscher, C., Huber, R., 1999, Metal Forming of Tubes and Sheets with Liquid and Other Flexible Media, *Annals of CIRP*, 48, 497-513.

Schmoeckel, D., Hessler, C., Engel, B., 1992, Pressure control in hydraulic tube forming, *Annals of CIRP*, 41, 311-314.

Sokolowski, T., Gerke, K., Ahmetoglu, M., Altan, T., 2000, Evaluation of Tube Formability and Material

Characteristics: Hydraulic Bulge Testing of Tubes, *J. Mat. Proc. Techn.*, 98, 34-40.

Vollertsen, F., Prange, T., Sander, M., 1999, Hydroforming: Needs, Developments and Perspectives, *Proc. 6th ICTP,* 1197-1210.

Yang, J. Jeon, B., Oh, S., 2001, Design sensitivity analysis and optimization of hydroforming process, *J. Mat. Proc. Techn.,* 113, 666-672.

Yuan, S., Yuan, W., Wang X.,2006, Effect of wrinkling behaviour on formability and thickness distribution in tube hydroforming. *J. Mat. Proc. Techn.*, 177, 668-671.

Yuan S., Wang X., G Liu G., Wang Z.R., 2007, Control and use of wrinkles in tube hydroforming, *J. Mat. Proc. Techn.*, 182, 6–11.

STRATEGIE OPTYMALIZACJI DLA WYZNACZENIA PARAMETRÓW PROCESU HYDROFORMINGU RUR

Streszczenie

W procesie wytwarzania rur metodą hydroformingu przeciwstawne działania płynu pod ciśnieniem i obciążenia mechanicznego pozwalają na wytwarzanie rur charakteryzujących się skomplikowanym kształtem, na przykład różne średnice poszczególnych przekrojów i/lub lokalne strefy wybrzuszenia. Historia ruchu stempla oraz wewnętrzne ciśnienie cieczy są głównymi parametrami procesu. Prawidłowe zaprojektowanie tego procesu, przyjmując za cel wyeliminowanie defektów (takich jak np. niewypełnienie wykroju lub pęknięcie plastyczne), jest kluczowym zadaniem. W artykule przedstawiono wyniki szeroko zakrojonych badań hydroformowania rur ze stopów aluminium, opierającego się na zastosowaniu różnych strategii optymalizacji dla wyeliminowania różnego rodzaju defektów (wspomniane niewypełnienie lub pękanie).

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