Hydroforming of sheet metal pairs for the production of hollow bodies*

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The hydroforming technology is well-known since several years and undergoes an extremely dynamic development in automotive applications, especially in Germany and the United States. The hydroforming of sheet metal pairs is still at an pre-industrial stage. This publication presents the process and draws attention to some particular results of research work. Principal working directions for investigations, regarding the transfer of the hydroforming process for sheet metal pairs to industry are mentioned.

■ INTRODUCTION

The hydroforming mainly of tubular parts is well known since several years as a technique that runs through an extremely dynamic development, especially in applications for the automotive industry, in Germany and the United States. The high pressure caused by environmental laws and the market lead to new concepts in the automotive development. Reducing the fuel consumption can be done by an optimization of the power train and the mass reduction of the chassis and the body.

Examples of new lightweight body concepts are given in *figure 1*. The space frame technology is an answer for lightweight design that uses aluminium as profile extrusions, casted knots and blanks. Automated assembly of body structures longs for small tolerances. Therefore, the used straight and bent profiles are often calibrated by high internal pressure to meet the specifications. On the other side, the ULSAB study showed that essential weight savings can be reached by the use of new steel materials and new production technologies like hydroforming and laser welding. Although the intensive use of hydroformed components did not meet the requirements because of well-known assembly problems, the ULSAB body contains two hydroformed rails. These two examples show that hydroforming plays an important role in the realization of lightweight design.

Up to now hydroforming is used mainly to process tubular products, but new variants are applied. The use of tailored tubes for example can adapt the part in a flexible way to different loads along the longitudinal axis. Profiles could not only be calibrated, but also used for the production of branches. Moreover, the use of sheet metal pairs as semi-finished product widens the field of hydroforming to a new range of geometries that can be realized by this technique.

The growing market of hydroforming and the appearance of new variants induced the Verein der Deutschen Ingenieure (VDI) to propose a summarizing guideline to classify the process like shown in *figure 2*. The forming of tubes, profiles and blanks can be found in the general classification that takes into consideration the possibilities of punching, cutting and joining by internal pressure. For example, the cams and the shaft of a camshaft can be joined with the hydroforming process.

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Étude du procédé d'hydroformage de flans doubles pour la production de corps creux

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L'hydroformage connaît depuis quelques années un développement extrêmement dynamique dans le domaine de l'automobile, en particulier en Allemagne et aux États-Unis. Cette technologie présente un certain nombre d'avantages liés aux possibilités de réduction du nombre de pièces et à l'allégement des composants.

Présentation de l'hydroformage de flans

L'hydroformage de flans doubles est un procédé pour la production de corps creux. Il fait actuellement l'objet d'intenses travaux de recherche qui ont pour but d'examiner le potentiel de ce procédé en vue d'une industrialisation.

L'extension du principe de la déformation sous l'effet d'une pression interne à partir de l'hydroformage de tubes vers l'utilisation de flans résulte principalement de deux observations. Tout d'abord, l'utilisation de tubes restreint l'application de l'hydroformage à des pièces ayant une géométrie avec des rapports d'expansion nécessairement limités. De plus, le spectre de matériaux et de gammes dimensionnelles nécessaires sous forme de tubes n'est pas encore assez large pour pouvoir réaliser toutes les applications potentielles.

Le maintien de l'étanchéité du corps creux formé par les deux flans est également un point crucial. Des premières études effectuées en injectant un fluide sous pression entre deux flans préalablement soudés au laser le long de leur contour ont montré la faisabilité du procédé. Néanmoins, il s'est avéré que le couplage rigide entre les deux flans limite le degré d'asymétrie que l'on peut réaliser entre les deux demi-coques de la pièce.

La gamme de fabrication étudiée à l'université d'Erlangen-Nuremberg (Allemagne) utilise l'hydroformage de flans doubles non soudés pour permettre un mouvement relatif entre les flans et ainsi éviter un couplage forcé des déformations dans les deux demi-coques. Les essais ont montré qu'il est possible de maintenir le volume entre les flans étanche grâce à une pression de serre-flan suffisante tout en autorisant un avalement de matériau et un glissement d'un flan sur l'autre. Après cette opération de préformage, les flans sont détourés, puis soudés au laser avant d'être calibrés par pression interne. Ces différentes opérations ont tout d'abord été réalisées dans des outils séparés, puis intégrées à l'intérieur d'un système d'outillage combinant une presse d'hydroformage à triple action et un laser Nd:YAG.

Applications potentielles

L'hydroformage de flans doubles trouve des applications potentielles privilégiées dans le domaine des composants automobiles creux, spécialement dans la structure portante (longerons, traverses, montants, etc.) et le châssis (berceau moteur, triangle de suspension, etc.). Il s'agit ici de pièces complexes, hautement sollicitées et devant satisfaire des exigences d'économie de masse sévères. L'utilisation de flans permet ici de réaliser des variations importantes de la section de la pièce le long de son axe longitudinal.

Contrôle du procédé

Les principaux paramètres du procédé sont la pression à l'intérieur de la pièce et la force de serre-flan qui influe directement sur le frottement sous le serre-flan. Les limites du procédé définies par la perte d'étanchéité (pression de serre-flan insuffisante pour éviter la séparation des flans) et la rupture du matériau sont montrées.

Les essais réalisés montrent qu'il existe un optimum du procédé défini par un compromis entre une force de serre-flan suffisamment élevée pour maintenir l'étanchéité, mais suffisamment faible pour permettre un écoulement radial de matériau sous le serre-flan.

Axes de développement

Du point de vue technologique, le contrôle de l'écoulement de matière sous le serre-flan est un point délicat, qui peut néanmoins être maîtrisé par exemple grâce à un contrôle des pressions de serre-flan. Par ailleurs, l'utilisation d'un fluide à la place d'un poinçon rigide peut induire la formation de plis au début de l'hydroformage. Des solutions visant à éviter la formation de ces plis ou à les résorber grâce au développement de tensions dans la tôle ont été développées. Par ailleurs, pour des applications particulières et des matériaux difficilement déformables (aluminium, magnésium), l'utilisation d'un fluide chauffé peut s'avérer judicieuse.

Les considérations économiques montrent l'intérêt de machines d'hydroformage nouvelles combinant les avantages des presses hydrauliques et des systèmes à verrouillage mécanique. Le raccourcissement des temps de cycle impose de même des stratégies d'injection du fluide par points multiples. L'intégration d'opérations *de débouchure et d'assemblage des flans dans l'outil d'hydroformage vise également à la rationalisation de la production.*

Conclusions

L'hydroformage de flans doubles est un procédé qui se trouve encore au stade préindustriel. Un certain nombre d'études allant jusqu'à la phase de prototypage ont été conduites. Les particularités du procédé ont été mises en lumière et son potentiel est en train d'être démontré.

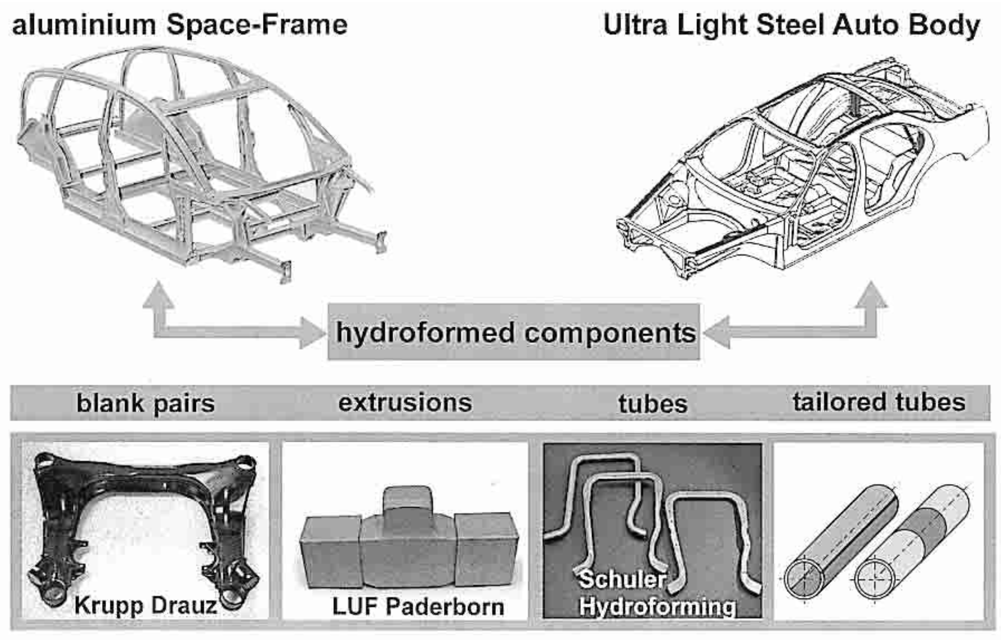

Fig. 1 – Lightweight design by hydroforming.

Fig. 1 – Construction légère par hydroformage.

■ HYDROFORMING OF SHEET METAL PAIRS

The hydroforming of sheet metal pairs is a process for the production of hollow bodies and was presented by different authors (1 to 3). Now topical research work deals with investigations concerning the potential of that process regarding industrial applications.

In principle, two main reasons motivate the change of raw products for the processing with high internal pressure from tubes to the use of blanks. First, the use of tubes limits the possible products to longitudinaly oriented structures with limited possibilities for expansion. The other reason can be found in the limited material range and quality for tubes in comparison to blanks so that not all possible applications can be realized with these materials.

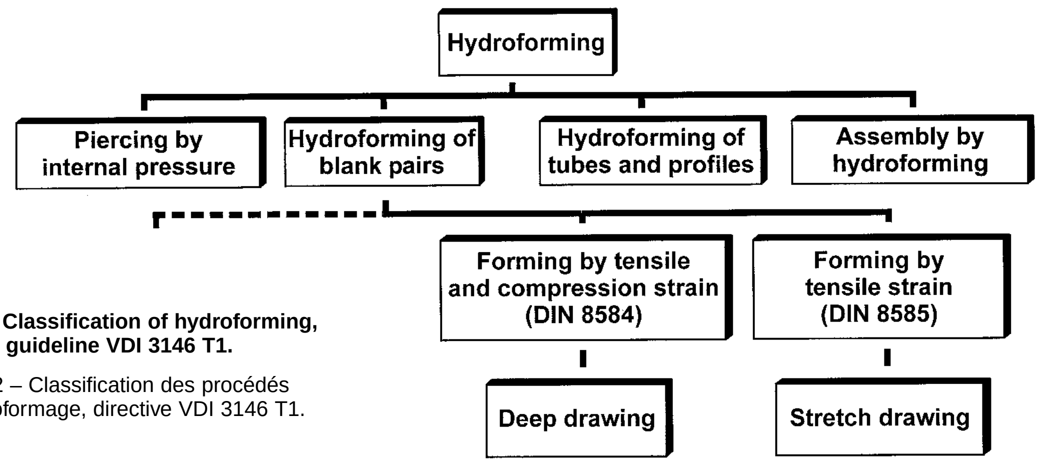

Fig. 2 – Classification of hydroforming, guideline VDI 3146 T1.

Fig. 2 – Classification des procédés d'hydroformage, directive VDI 3146 T1.

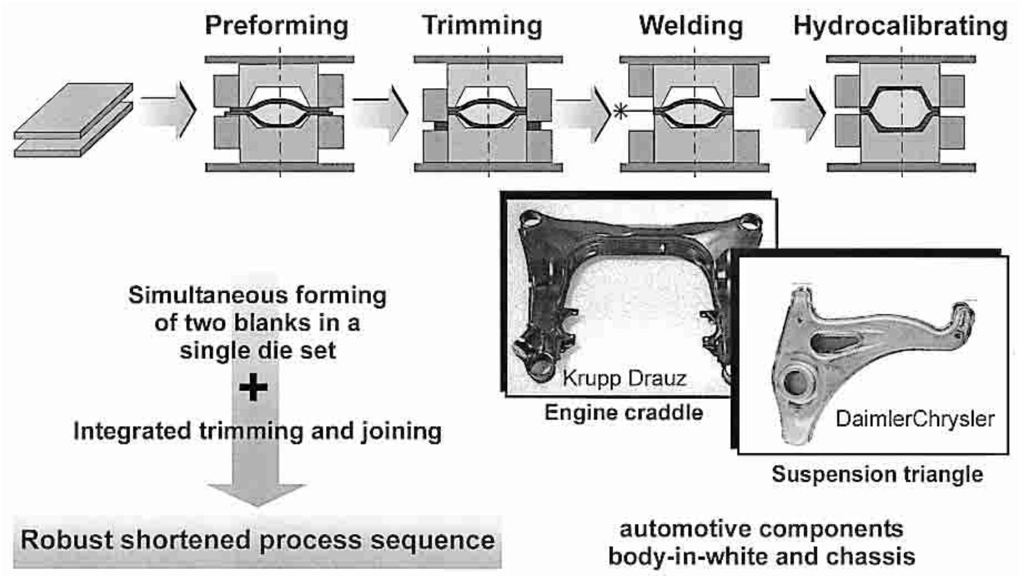

Fig. 3 – Operations for the production of hollow bodies based on non welded blank pairs.

Fig. 3 – Opérations pour la production d'un corps creux à partir de flans non soudés.

The comparison with the classical deep drawing process shows that the hydroforming of double sheets can lead to reductions in tooling costs, as the use of a punch is not necessary anymore. In addition, the correct positioning of the deformed blanks to each other in the tool after the forming process allows to assemble the sheets directly in the tool. This can lead to cost savings because fewer operations are necessary for transport and trimming. On the other hand, the cycle time of the forming process itself is longer than that of the classical deep drawing, so that the main use of this technology can be expected for small and middle series production.

One main aspect in the development of the hydroforming of sheet metal pairs is the use of the element that introduces the fluid between the blanks. Here different technical variants were developed and are still under investigation.

The sealing of the hollow bodies formed by two sheets is still critical. First studies that dealt with the injection of fluid pressure between two blanks were made with blank pairs that were welded along their rim. This method showed the feasibility of the process for the first time (4). Nevertheless, the rigid connection of the two blanks limits the geometric potential that can be realized by the two blank shells. If the blank fills completely the lower cavity of the tool, the movement of material from the flange area stops. This means for the deeper tool cavity that there is a lack of material from outside and the strain rises up to the rupture of the material.

The process chain that is under investigation at the University of Erlangen realizes the hydroforming of unwelded blank pairs to permit a movement of the blanks relative to each other. This avoids the direct coupling of the shells and their deformations *(fig. 3)*.

The experiments showed that it is possible to keep the volume between the blanks sealed by a sufficient blank-holder force, whereas the movement of each blank relative to the other is not hindered by this action (5).

After the free preforming operation, the flange area is trimmed and welded, before the calibration with high pressure starts to fill the whole cavity. These different operations are now realized separately, but will be integrated in future in a complete production system consisting of a triple action press and a Nd:YAG laser.

■ POTENTIAL APPLICATIONS

The hydroforming of doubled blanks will find its potential applications in the production of hollow bodies for automotive components *(fig. 4)*, especially for structures (e.g. frames, beams, pillars) or the chassis (e.g. engine craddle, suspension triangle). Highly complex parts that bear high loads and fulfil the economic requirements can be expected. The use of blanks allows a widespread range of different cross section geometries along the longitudinal axis of the part. Operations for the assembly of the formed parts will be comparable to the classic assembly line for deep drawn structures, because flange areas can be found as well.

Another chance of application appears in the growing trend for metal fuel tanks. Environmental laws regarding the emission of hydrocarbon gas and the demands of crash safety will be tightened up more and more, so that steel materials become more important compared to plastics.

■ PROCESS CONTROL

For a success of the process, it is necessary to control the draw-in behaviour from the flange in the cavity and this describes as a consequence the physical limitations of that

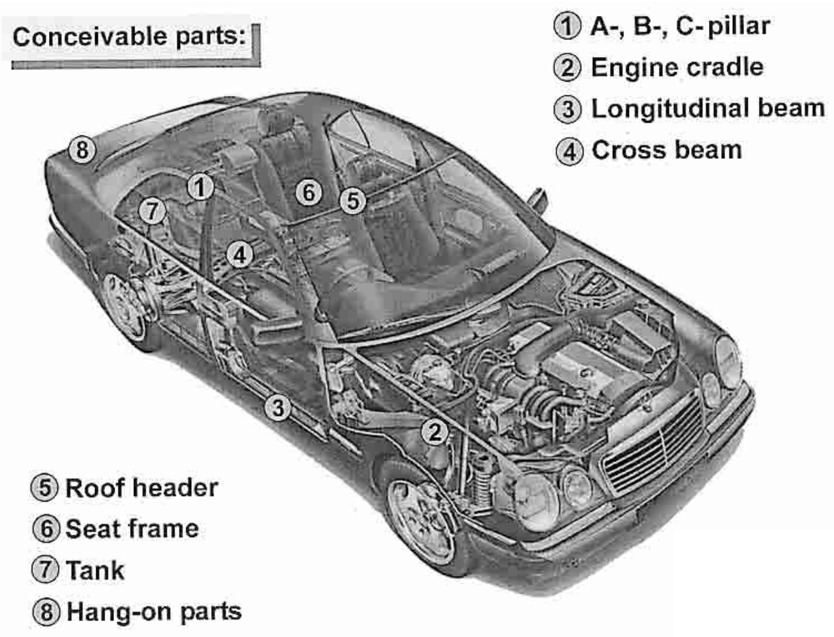

Fig. 4 – Potential applications.

Fig. 4 – Applications potentielles.

process. The draw-in rate during the increase of internal pressure influences directly the strain distribution in the part. Therefore, the blankholder force is the main control parameter for the process control of bodies presenting rotational symmetry *(fig. 5)*.

Working range

Figure 5 shows the process limits defined by the leaking (blankholder pressure is insufficient to seal between the two blanks) and rupture of the material. It is to mention that the geometry of the tool is rectangular between the bottom of the die and the border. This geometry was chosen to be able to determine a relation between the control parameters and the minimal radius reachable, without rupture at the bottom of the die cavity. The higher the bursting limit is, the smaller radii and better accuracy of shape can be reached. The blankholder force is kept constant during the raising of the pressure level of the fluid.

The application of small blankholder forces leads to a limitation of the process by leakage, because the pressure between the blanks is then insufficient to realize the sealing against the fluid. After reaching this limit in the preforming process, it is possible to apply a very high blankholder force to seal the leaks, which stops in the same manner the draw-in of material. The forming can be continued up to the rupture of the part.

Elevated blankholder forces at the preforming stage lead to rupture before leakage occurs. In this region of the diagram, the forming is realized by pure stretching of the material without draw-in. If a sufficient fluid pressure is reached, the draw-in starts. This has an remarkable influence on the bursting pressure and as well on the accuracy of shape. The more draw-in can be realized, that is to say the lower the chosen blankholder force is, the higher bursting limits can be reached.

The curves in *figure 5* show that there exists an optimum for the process control. This optimum can be defined by a compromise between an elevated blankholder force to keep the

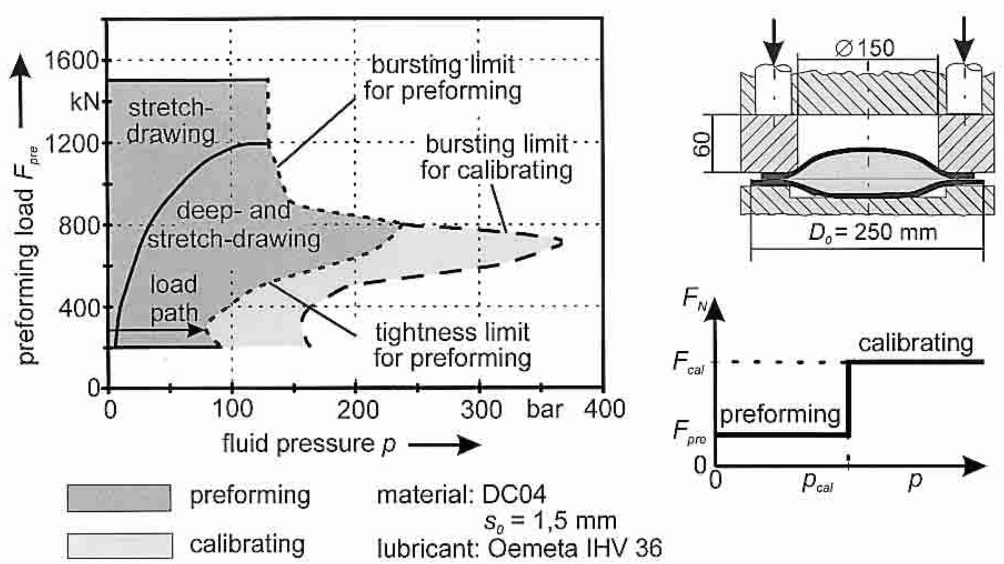

Fig. 5 – Process window for hydroforming of unwelded sheet metal pairs.

Fig. 5 – Latitude de réglage pour l'hydroformage de flans doubles non soudés.

sealing function and a lower level to allow a draw-in of material from the flange.

The process layout for more complex structures can be found by using the finite element method. This tool is very suitable for finding the correct process parameters and the needed blank contour (6).

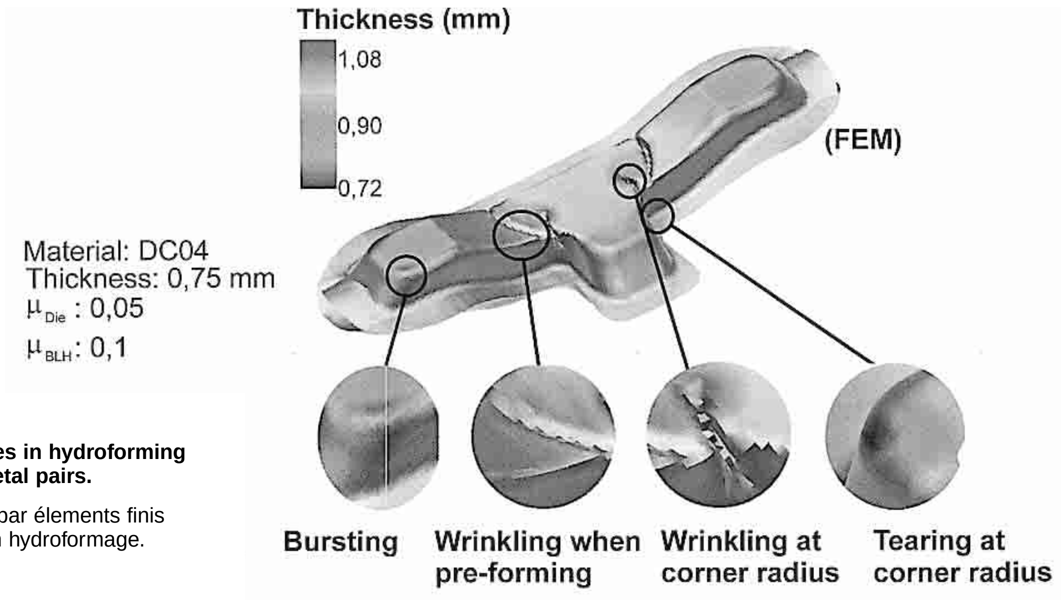

Fig. 6 – Failure modes in hydroforming of sheet metal pairs.

Fig. 6 – Simulation par élements finis des instabilités en hydroformage.

Process adjustments

Figure 6 shows an example of the problems that occur during the hydroforming of more complex parts. The rupture is caused by a strain exceeding the FLC (forming limit curve) because of an insufficient draw-in of material. This failure mode can be avoided by a better process control and therefore a better strain distribution in the structure. Wrinkling is another failure mode that should be avoided. It is characteristic for the processes working with a fluid pressure.

The mechanism of wrinkling was investigated in detail to find adequate means for the prevention of these wrinkles. *Figure 7* shows the cross section of three forming steps for the part mentioned before. Each step represents a different level of internal pressure between the blanks.

Since parts for frames often have a non-plane flange, a 3D design of the flange area was realized as well in this demonstrator part. The preforming caused by the closure of the tool at the beginning of the

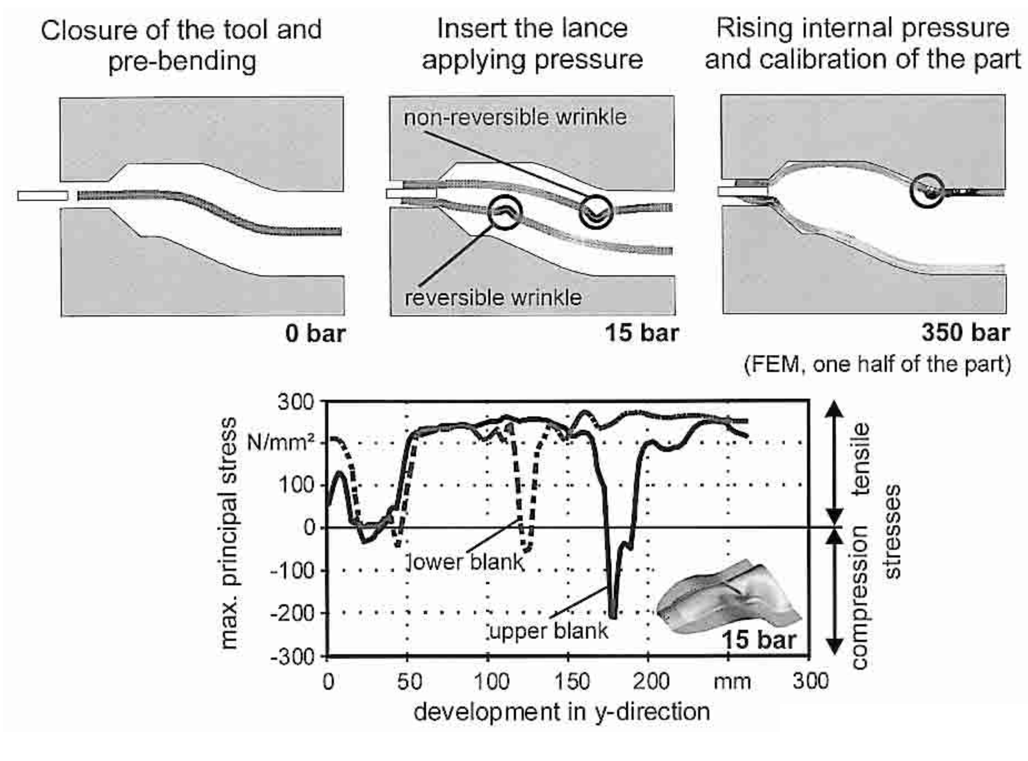

Fig. 7 – Wrinkling mechanism.

Fig. 7 – Formation de plis.

process leads to wrinkles during the following hydroforming operation.

The applied internal pressure load causes compressive stresses in the blanks plane so that the material forms the wrinkles. At this stage of the hydroforming process, it is difficult to determine if the wrinkles are reversible or not. After the calibration, it is clear that enough tensile stresses are induced in the lower blank to remove the wrinkle. In the upper blank, the wrinkles cannot be traced back by rising the pressure and the wrinkles get more compressed.

To avoid the wrinkling, different strategies were developed and verified by running different FE-simulations *(fig. 8)*.

As mentioned before, tensile stresses at an adequate level can lead to the reduction or even removal of wrinkles. The following strategy was tested and led to satisfying results. As shown on the left side of *figure 8*, the blankholder force control puts a means at our disposal to apply tensile stresses at the level needed. At the beginning of the process, the elevated blankholder force causes the necessary stresses for the reduction of wrinkles. Afterwards, the force is lowered to realize a draw-in of blank material into the cavity to realize a satisfying accuracy of shape.

On the other hand, the use of a counter punch can lead to nearly similar results and is shown on the right side of *figure 8*. Here the positive effect is caused by a limitation of the blank geometry at different process stages. Several different simulations showed that only a large punch geometry at the position of the wrinkling danger is suitable. In addition to that, the control of the additional tool (punch) is a complex and delicate task as well.

These strategies are under experimental investigation. Besides an improved process control, avoiding wrinkles is more or less a task that has to find answers primarily in the field of adapted part design produceable by sheet metal hydroforming, adapted design of 3D-flange surfaces (especially regarding the curvature) and if necessary, definitions of adequate intermediate geometries during the process.

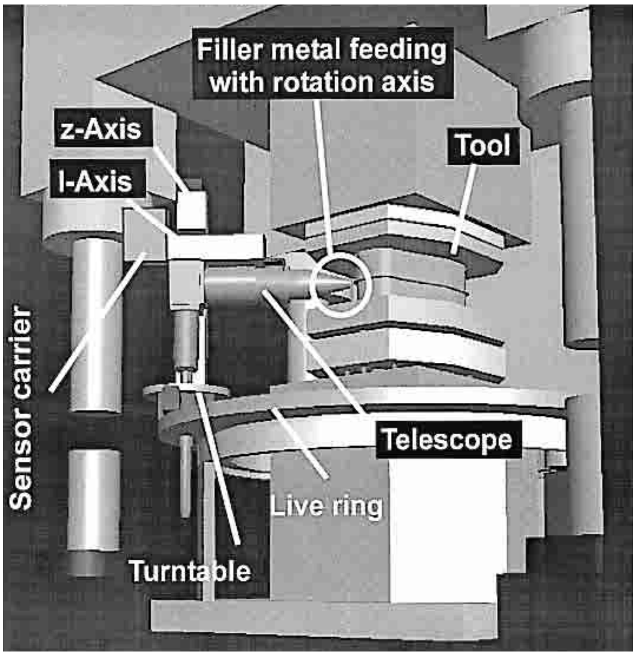

Fig. 9 – Welding robot integrated in the hydroforming tool.

Fig. 9 – Robot de soudure intégré à l'outil d'hydroformage.

■ DIRECTIONS OF DEVELOPMENT

One main aspect for the economic production by hydroforming is the integration of several processes into one tool system, like mentioned before. The processes can contain operational steps that would be done as pre- and post-treatment of the produced parts in a conventional process chain. Operations like trimming, piercing and welding can be integrated. A system that integrates the trimming and welding in one tool system is shown in *figure 9*.

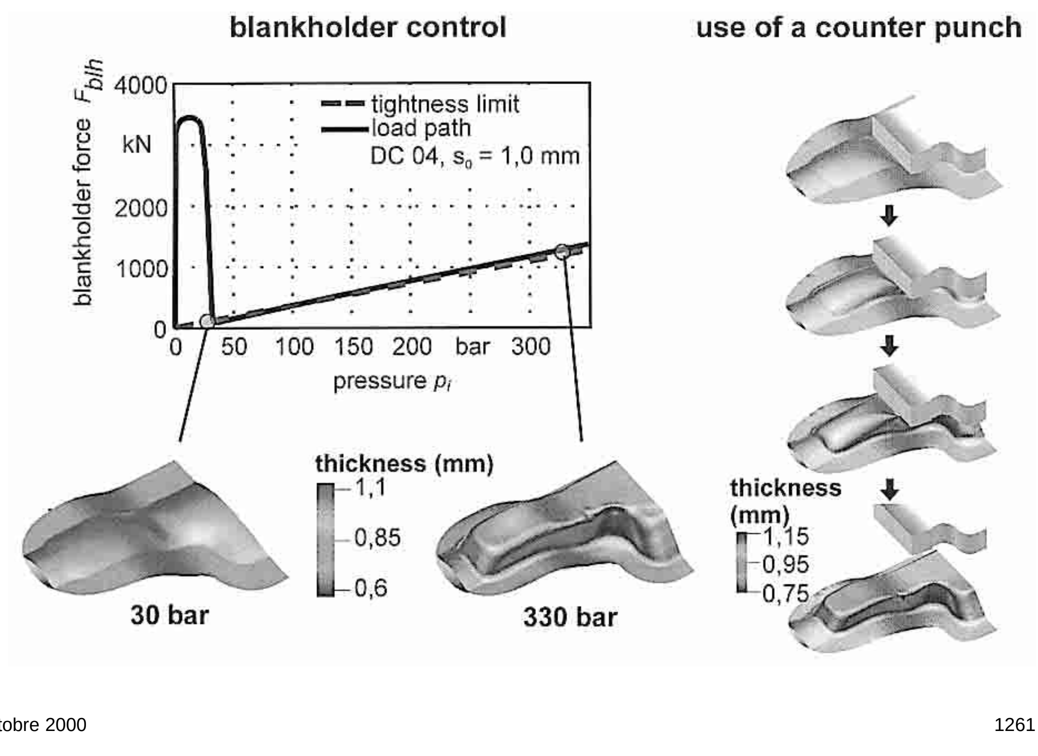

Fig. 8 – Strategies to avoid wrinkling.

Fig. 8 – Stratégies pour éviter la formation de plis.

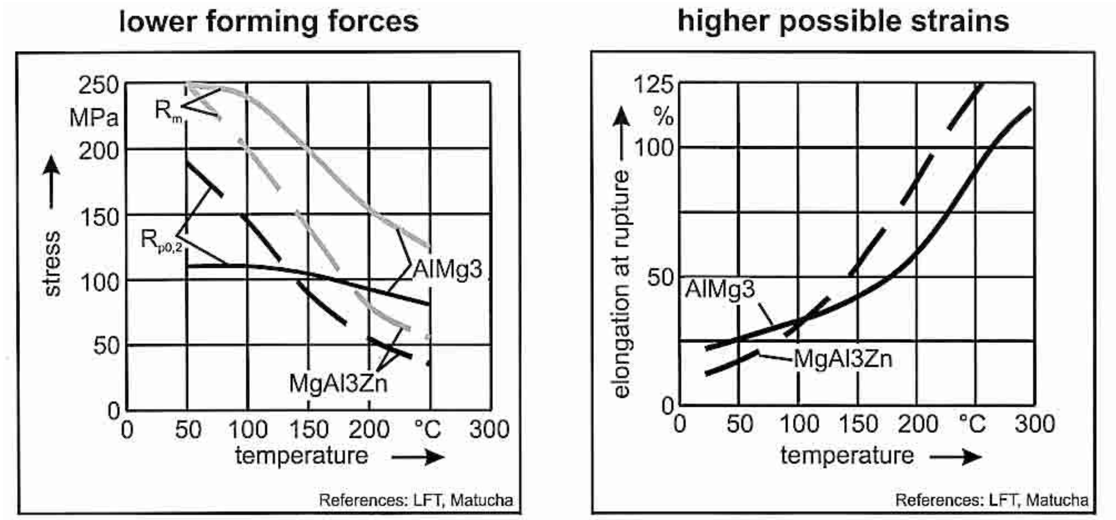

Fig. 10 – Benefits of an elevated process temperature for the lightweight alloys AlMg3 and MgAl3Zn.

Fig. 10 – Influence de la température sur la formabilité d'alliages d'aluminium (AlMg3) et de magnesium (MgAl3Zn).

It consists of a hydroforming tool and a welding robot that was especially developed to face the requirements of the narrow space in the hydraulic press. It is possible to weld the pre-formed and still positioned parts with a Nd:YAG laser just before the calibration step. The trimming of the flange before the welding operation is realized by a movement of an integrated cutting plate for the upper and lower blank.

The work done in the research on the hydroforming process showed the potential of that process and examined the developing axes of that technology. From the technological point of view, the control of the material flow under the blankholder is a delicate point that can be influenced in most cases by the control of the blankholder forces. The use of multi-point drawing cushions, including a powerful control device is therefore necessary, especially when non

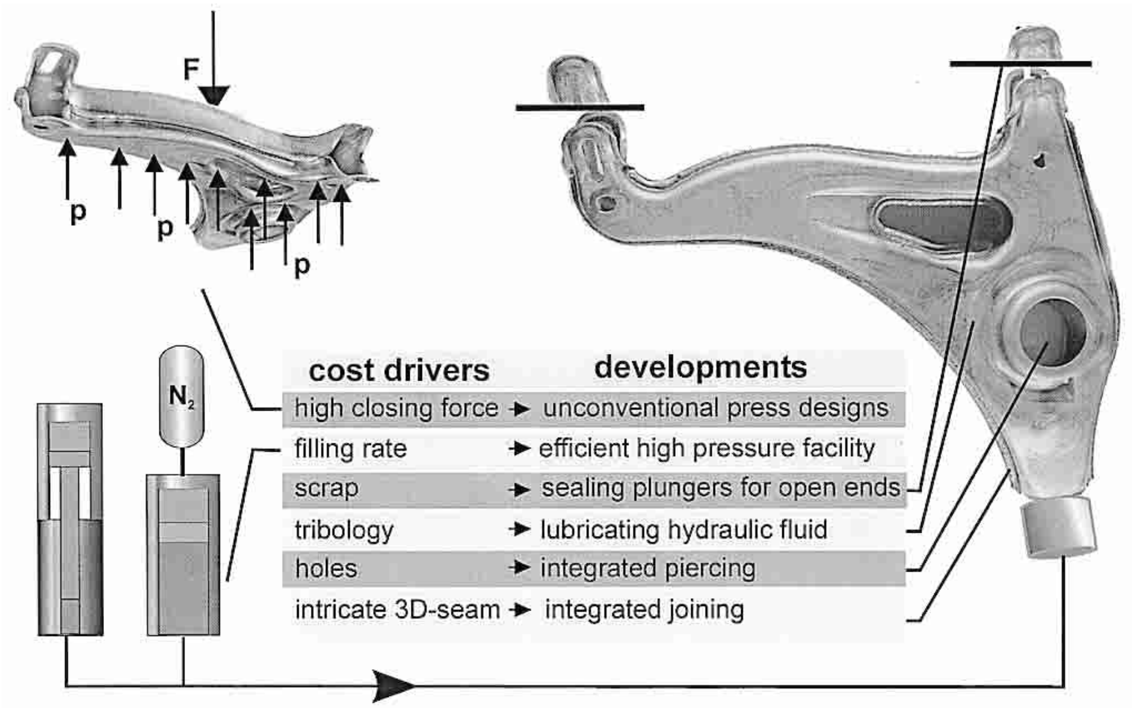

Fig. 11 – Expected axes of development.

Fig. 11 – Axes de développement possibles.

rotationally-symmetrical structures should be realized. The use of a fluid for forming instead of a rigid punch can induce wrinkles, especially in structures that have a three-dimensional flange surface. Solutions that influence the stress state by building up tensile stresses during the forming operation were developed for particular applications. For other part geometries, that do not meet certain limitations in part design, new strategies for the process have to be developed. Here an extensive definition of design rules has to be developed to give a guideline for the correct design of hydroforming parts.

Besides the process integration, the enhancement of the formability, especially for lightweight materials, is another important research field. The use of aluminium and magnesium, for example in the automotive industry, grows and the temperature dependency of the formability is an aspect that can lead to new process variants. Different material testing experiments and first applications to manufacturing processes demonstrated the benefits and first concepts for an increase of the forming temperature (7) (8). *Figure 10* shows the effect of an elevated process temperature for two chosen lightweight materials.

The lower forming forces and higher reachable strains show the potential of this process variant. As a consequence of these effects, current engineering work is carried out to develop an equipment design with which hydroforming processes at elevated temperature can be conducted.

The whole process of hydroforming of sheet metal pairs is still at a pre-industrial state and the technological and economical potential of this new manufacturing process cannot yet be finally assessed. Regarding the application to complex components, there is still a lack of basic knowledge concerning the control and robustness. Analyses of risks and chances and preliminary economic calculations (9) have been performed to give indications on the fields in which efforts have to be made for a successful introduction into an industrial environment *(fig. 11)*.

A new press design with a combination of a hydraulic press with a mechanical locking unit and shorter cycle times (powerful hydraulic units and multiple injection points) can be the improvement needed for further industrial application. The integration of up-stream and down-stream operations such as trimming, joining and punching was already pointed out, but additional work needs to be done on this topic.

■ CONCLUSIONS

The hydroforming of sheet metal pairs is a process that is still at a pre-industrial state. A certain number of investigations up to a prototyping stage are under research. The special characteristics of this process were examined and the potentials will be demonstrated in the near future. This article presented the process, drew attention to some important results of research work and gave additional informations concerning the principal working directions that prepare the implementation of the technology in an industrial environment.

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