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MODERN SIMULATION AND OPTIMIZATION OF PEEN FORMING PROCESSES

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ABSTRACT

The extremely flexible shot peen forming process permits difficult uni-axial or multi-axial curved sheet metal geometries which would require high machine effort if they are processed by conventional methods like bending or stretch forming. In the initial phase of shot peen forming, knowledge of the process was purely empirical, but considerable effort has recently been devoted to researching the technological and materials phenomena involved, developing models, and building plant and machinery capable of using computer control systems to achieve increasing component accuracy.

The present contribution reports on these recent developments and on a number of investigations currently in progress at the *Institut für Bildsame Formgebung* (IBF) of the RWTH Aachen.

KEYWORDS

Peen Forming, Computer Aided Planning and Simulation of Coverage, Optimization of Shot Peening Processes, FEM-Analyses, Multi-Axial Peened Products

The *Institut für Bildsame Formgebung* (IBF) has been concerned with the peen forming process since the beginning of the nineteen-seventies /1/. As reported in detail in earlier publications, a variety of different production strategies for different components in the ARIANE and AIRBUS programmes have been developed to the series production stage on the IBF shot peening plant, in close collaboration with the aerospace industry /2,3/. More than four hundred Airbus A 310 and almost two hundred Ariane 4 tank segments have meanwhile been peen formed by industrial users. The IBF develops the production parameters and helps industry to implement these data in series production.

Current developments concentrate on multi-axial curved sheet components of varying thicknesses, e.g. tank domes and parabolic antennas. As part of a development programme commissioned by *Cryospace*, Les Mureaux (France) and carried out jointly by *Dornier*, Friedrichshafen/Munich, the IBF and *Engineering Consulting Metal Forming* (ECMF, Aachen), some thirty multi-axial curved tank bulkheads of non uniform size and contour for the future Ariane 5 European rocket were peen formed on the IBF shot peening facility, the first time this process had been used to produce components of this size in Europe /4,5/. Production development for these components has been completed successfully. A new shot peening plant with automatic path control required specially for continuation of this development programme was commissioned by industry and installed at *Dornier Luftfahrt GmbH* in Munich /6/.

OBJECTIVES AND CONCEPTS

Aerospace vehicles require weight- and load-optimized structures, sometimes entailing extremely complex component shapes. In addition, economic considerations often require the components to be constructed from the largest single sections possible (integral components), to save weight by eliminating riveted joints (*Fig. 1*).

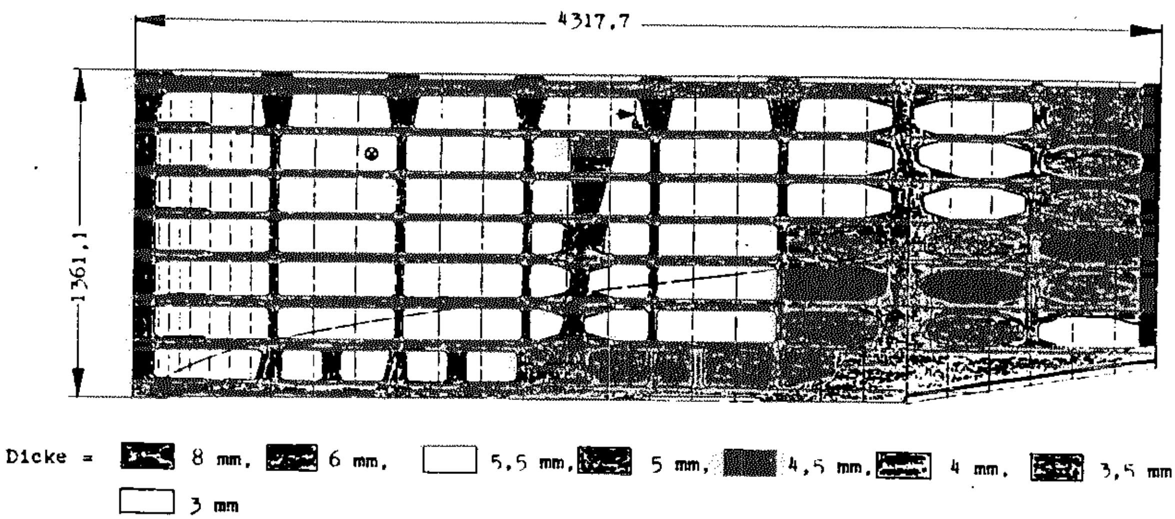

Fig. 1 Zones of Equal Thickness on an Integral Component (Fuselage Side Shell) of the Airbus 310

It is often impossible to produce components of this type economically by means of conventional processes such as bending or stretch-forming. The high standards required for series production of aerospace components present the companies

... with a substantial additional challenge. It is here that universities can make a contribution, both in the field of fundamental research and in the optimization of production processes. For peen forming, it is particularly important to improve knowledge of technological and material science phenomena and to develop both models and plant/machinery enabling increasing component precision to be achieved with the aid of computer techniques.

Computer-aided dosing and nozzle positioning and adaptive process models already permit production of extremely precise, near-net-shape components on the IBF injector shot peening facility (*Fig. 2*). Production of these components using comparable manufacturing processes would entail very much higher machine and labour costs /7,8/. A newly installed software package for computer-aided planning and simulation of abrasive coverage in peen forming processes (*Section 3*) and FEM calculations allowing increasingly precise estimation of expansions beneath a shot indentation (*Section 4*) will provide additional planning and optimization tools for future users of this technology.

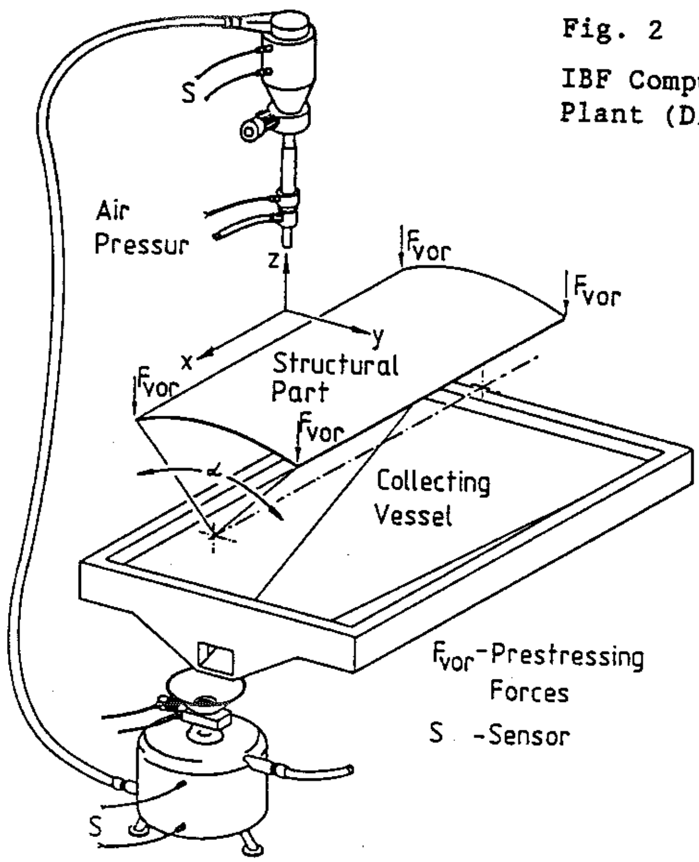

Fig. 2

IBF Computer-Controlled Injector Plant (Diagram)

COMPUTER-AIDED PLANNING AND SIMULATION OF THE ABRASIVE COVERAGE IN PEEN FORMING

The abrasive coverage, designated the A* coverage, is defined as the percentage of a peened area in which abrasive actually impinges during peening. 100 % represents a nominal limit which in practice can neither be achieved nor measured.

According to /9/, coverage can be described mathematically using the basic statistical equation:

$$C^*_n = 1 - (1 - C^*_1)^n \qquad (3.1)$$

[C^*_n = total coverage after n peening passes, C^*_1 = coverage after 1 peening pass, n = number of peening passes]

This basic equation is inferred from a simple statistical consideration:

If an event possesses a probability *p* in a random experiment, the probability *q* that this event will not occur will be $q = 1 - p$.

The coverage C^*_1 is thus equal to the probability p_1 of hitting a chosen point on the workpiece surface with any shot during the first peening pass (SG = 1). The probability q_1 that the point will not be hit during the first peening pass SG = 1 will accordingly be:

SG=1 $$q_1 = 1 - p_1 = (1 - C^*_1).$$

Analogously, if this procedure is applied to a series of peening passes, then

SG=2 $$q_2 = (1 - C^*_1) \cdot q_1 = (1 - C^*_1) \cdot (1 - C^*_1)$$

SG=3 $$q_3 = (1 - C^*_1) \cdot q_2 = (1 - C^*_1) \cdot (1 - C^*_1)^2$$

⋮

SG=n $$q_n = (1 - C^*_1) \cdot q_{n-1} = (1 - C^*_1) \cdot (1 - C^*_1)^{n-1}$$

The first factor in each case describes the probability of not being hit during the current peening pass, the second the probability of not having been hit during any of the preceding passes. The total coverage C^*_n after *n* peening passes is therefore equivalent to the probability p_n, of being hit during any of the *n* peening passes. This results in the basic equation given above, $p_n = 1 - q_n$ (3.1).

A significant disadvantage of this equation is, however, that the coverage C^*_1 must first be determined at the cost of considerable effort, for example by planimetry.

According to /10/, much more rapid estimation of the abrasive coverage can be achieved by formulating the same relationship with changed coefficients:

$$A^*_n = 1 - (1 - A^*_1)^n \qquad (3.2)$$

[A^*_n = total coverage, A^*_1 = coverage of one shot related to a reference area, n = number of all impinging shots]

A^*_1 and *n* may be determined as follows:

$$A_1 = A_{dE} / A_{Ref} = (\pi \cdot d_E^2 / 4) / A_{Ref}$$
$$n = A_{Ref} \cdot m_A / m_K$$

[A_{dE} = shot indentation area of a shot, A_{Ref} = reference area, m_A = abrasive quantity per unit area, m_K = mass of a shot, d_E = shot indentation diameter]

Complex planimetric determination of coverage after the first peening pass is replaced by the ratio between a single shot indentation area produced by a single shot impact and on a predetermined reference area. The exponent *n* represents the total number of impacting shots, which can easily be determined.

The shot mass and shot indentation diameter are likewise easily determined variables. The abrasive quantity per unit area is, however, again dependent on various peening parameters, according to the peening strategy selected. This dependence should be examined more closely for the "line peening" strategy: in line peening, the nozzle is moved horizontally across the immobile workpiece surface in the direction of the peening path once or a number of times (factor *x*) at a constant rate of travel v_D, so that a strip-shaped peening pattern with a width S_B (referred to below as the spread) is formed. In this case, the abrasive quantity per unit area may be calculated as:

$$m_A = x \cdot m_t \;/\; (S_B \cdot v_D)$$

[m_A = abrasive quantity per unit area, x = number of peening paths per peening pass, m_t = abrasive quantity per unit time, S_B = spread, v_D = rate of travel of the nozzle]

A further modification is advisable for modelling the abrasive coverage. If all other parameters in the basic equation 3.2 remain constant, $A_n^* = f(A_{Ref})$ yields the curve shown in *Fig. 3* /11/.

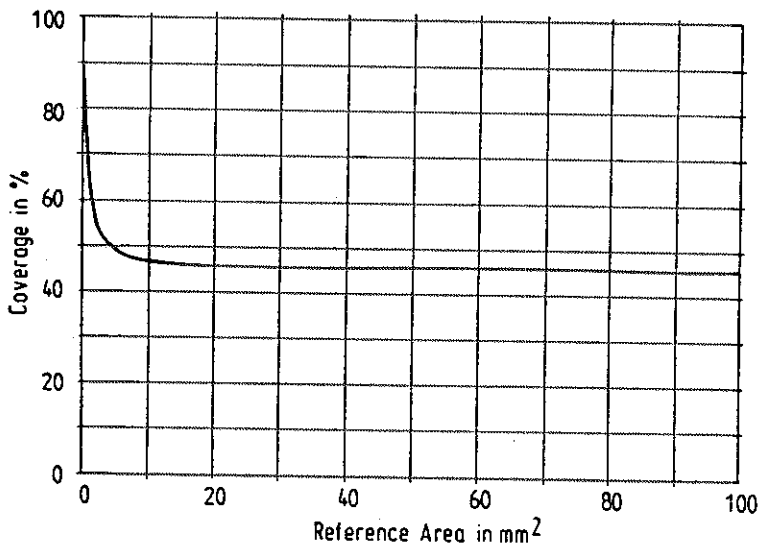

Fig 3

Abrasive Coverage A^*_n as $f(A_{Ref})$ according to Equation 3.2

Forming the limiting value lim A* for $A_{Ref} \rightarrow \infty$, a more global consideration of the abrasive coverage, i.e. for reference areas 20 mm² (cf. *Fig. 3*), results in the likewise mathematically exact but less complex formulation

$$A^* = 1 - \exp\,[-A_{dE} \cdot m_A \;/\; m_K] \qquad (3.3)$$

which produces the same calculated results /11/.

Other basic mathematical components of the coverage model installed at the IBF (software package for the planning and simulation of abrasive coverage in shot peening) are the "mathematics of the Gaussian normal distribution" and the "addition statement for random events" for overlapping between two normal distributions /12/.

The input variables are the shot diameter, the shot indentation diameter and the spread. Depending on the peening strategy employed (line peening, circular

... are required for the plant parameters volume flow (shots per unit time), rate of travel of the nozzle, etc.

The abrasive coverage depicted in Fig. 4 was generated at the IBF using the line peening strategy with four peening passes SG = 4 (without displacement) and the following plant parameters:

Shot diameter	d_K = 6.35 mm
Peening pressure	p = 4 bar
Nozzle height	h_D = 200 mm
Rate of travel of nozzle	v_D = 77 mm/s
Volume flow	m_t = 16,4 kg/min

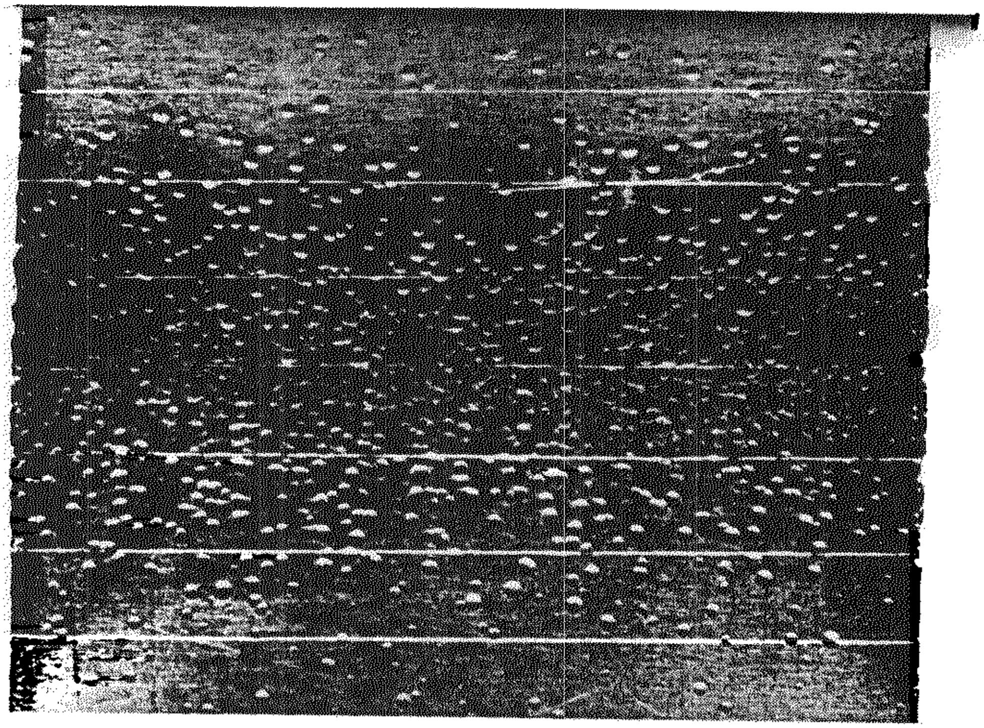

Fig. 4

Coverage after Four Peening Passes (SG=4)

The shot indentation diameter (cathetometer) and spread (measuring grid) were determined as:

Shot indentation diameter	d_E = 1.8 mm
Spread	S_B = 87 mm

The software package first calculates the mean coverage A* from the peening parameters given above, using basic equation 3.3, and corrects this value by means of an experimentally determined corrective function to the mean value for the normally distributed coverage $\bar{A}^*_k$ /11/. The standard deviation σ of the normal distribution and, depending on the nozzle position μ , the local bell curve, are then inferred (*Fig. 5*).

Using an overlap curve for the total coverage A^*_{ges}, the required coverage distribution per peening path A^*_i can also be inferred (*Fig. 6*).

The results are displayed as tables and/or graphics. The programme has been validated by reference to experimental studies /13/. Results indicate that description, planning and simulation of peen forming coverage are possible.

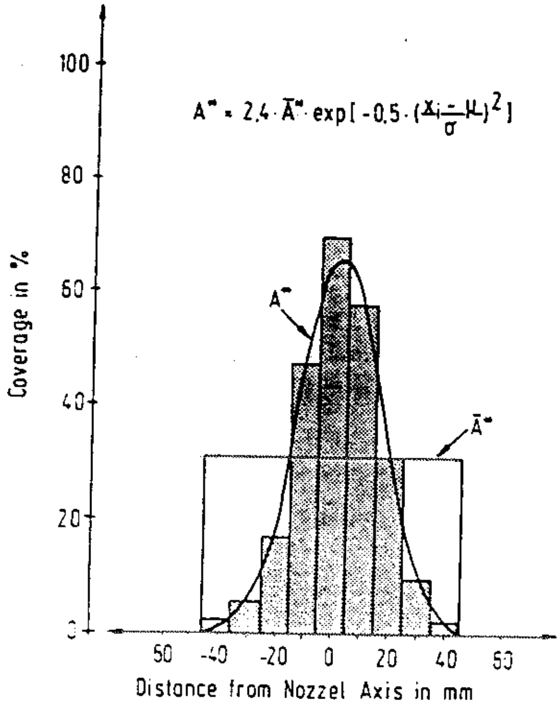

Fig. 5

Discrete Coverage from Fig. 4, Mean Coverage $\bar{A}^*$ (here $\bar{A}^* = \bar{A}^*_k$) and Calculated Local Normal Distribution A*

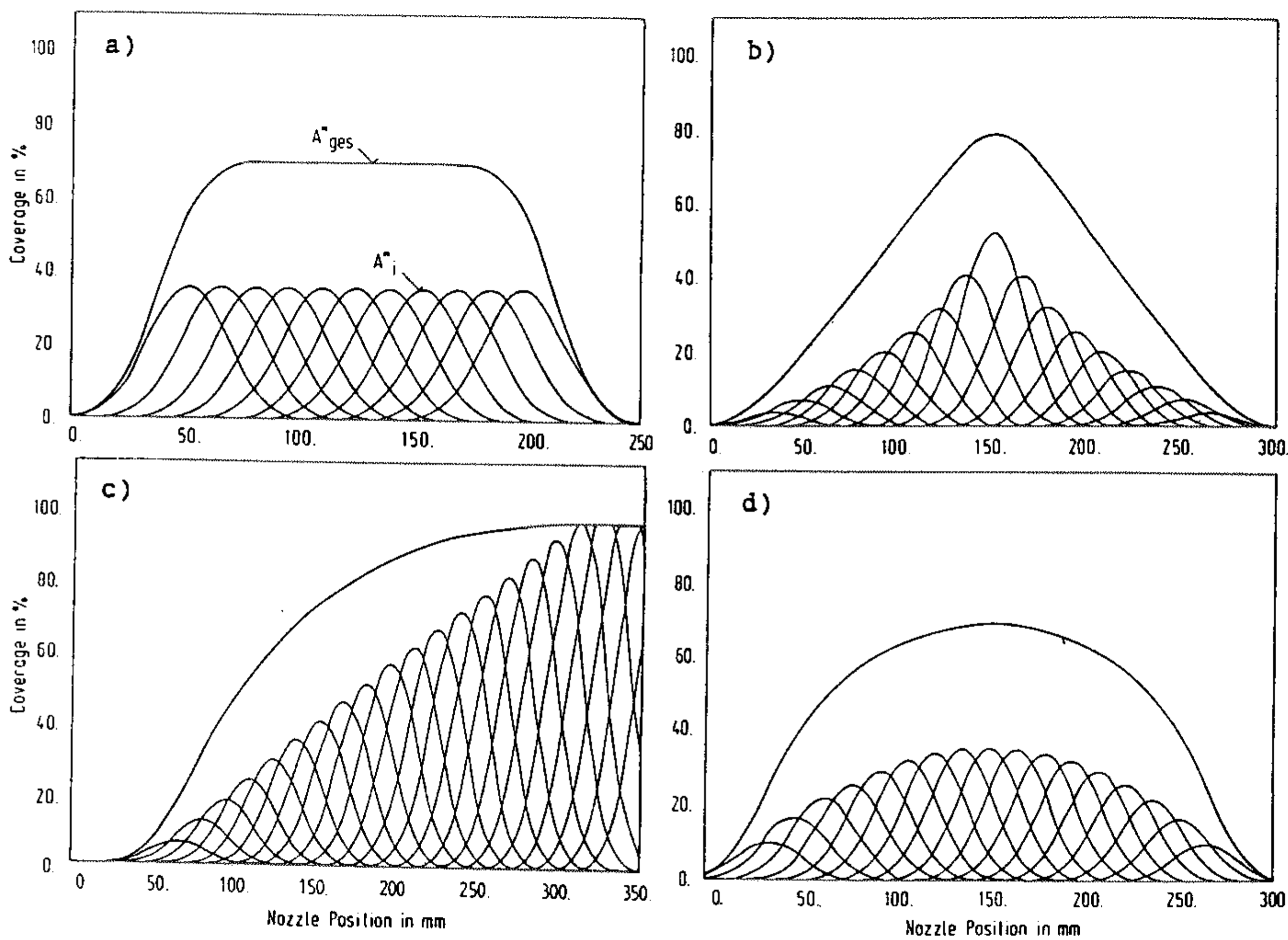

Fig. 6: Planning and Calculation Examples $(A^*_{ges} = 1 - [\prod_{n=1}^{m} (1 - A^*_i)])$

a) Simulation of a constant coverage curve, b) Linear total coverage curve
c) Degressive total coverage curve, d) Semicircular total coverage curve

A number of process constraints can be usefully simulated by FEM techniques. Current studies at the IBF have for the first time achieved dynamic simulation of a single shot impact /14/. Apart from friction on the shot/workpiece contact zone and differing shot impact velocities, the dynamic analysis takes into account inertial effects and the vibrational behaviour of the workpiece.

Fig. 7 shows the FE mesh used for these calculations. The figure depicts the right half of the symmetrical model. A shot with a diameter of 6.5 mm impinges on a round blank with a field size of 2.4 mm and a diameter of 20 mm.

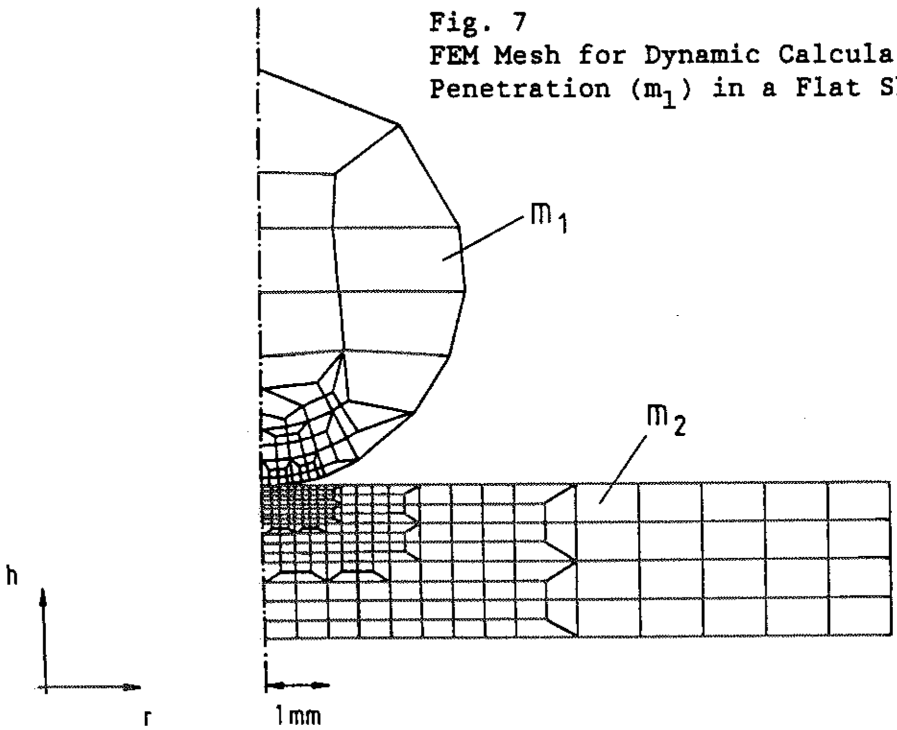

Fig. 7
FEM Mesh for Dynamic Calculation of Single-Shot Penetration (m_1) in a Flat Sheet (m_2)

The workpiece is very finely discretized in the expected shot indentation zone. To economize on continuum elements and thus on computing time, a coarser mesh structure has been selected as the distance from the contact zone increases. Similar considerations apply to the structure of the FE mesh for the shot. The Coulomb coefficient of friction between the shot and the workpiece is initially set at 0.2 for all the results illustrated here. The selected stress-strain curve is the cold stress-strain curve for aluminium alloy 2219T87.

Figure 8 a) and b) show the influence of abrasive velocity on radial strain and residual stresses during peen forming along the symmetrical axis beneath the shot indentation.

Fig. 8 a) indicates the influence of abrasive velocity on radial strain distribution: the radial strain maximum shifts upwards as the velocity increases, and is displaced away from the indentation surface to the interior of the workpiece. From 20 m/s tool velocity onwards a saturation limit is reached; thereafter, the influence of the velocity on strain distribution decreases sharply. This behaviour may be attributed to the transition from convex to concave forming, i.e. from partial to complete plastification, which occurs at this limit. As soon as the entire cross-section has been completely plastified, an increase in the imparted deformation energy causes no further change in the shape of the strain distribution, but only a general rise in strain level.

a)

b)

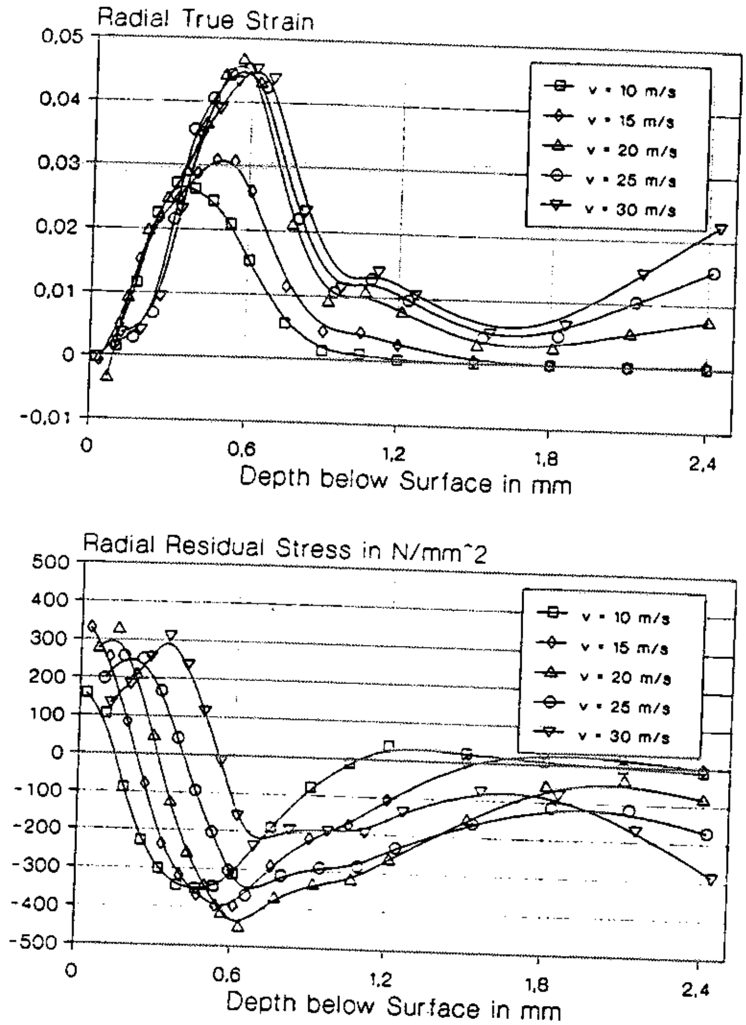

Fig. 8: Calculated Influence of Shot Velocity on
a) Radial Strain Distribution, b) Residual Radial Stress Distribution

The corresponding radial residual stress distribution is depicted in *Fig. 8*b): the curves are increasingly displaced towards the interior of the workpiece as the velocity rises. The residual stress maximum directly beneath the shot indentation observable at low velocities falls to lower values as the tool velocity increases; the calculated tensile stresses beneath the surface are thus dissipated as shot velocity rises. The position of the resulting compressive stress maximum in the central component zone remains relatively stable, increasing slightly in amount as the tool velocity rises. Starting from virtually neutral behaviour at low tool velocities, a compressive residual stress state forms on the underside of the component as tool velocity increases, completely converting the residual tensile stresses for the convex forming case still observable in the lower half of the component at low tool velocities into residual compressive stresses for the concave forming case as tool velocity rises.

Further FEM studies are intended to clarify the influence of the selected constraints on these calculated results. The predictive power of the present results is, however, already comparable to that of results in the literature /10/. In particular, practical tests also show high residual radial tensile stresses immediately beneath the surface of a single shot indentation, changing to residual compressive stresses for multiple indentations. Moreover, the measured strains in practical tests also shift towards higher values and are displaced away from the indentation surface.

TANK BULKHEAD FOR THE ARIANE 5 ROCKET

The following section presents the development of a peen forming process for Ariane 5 tank bulkheads recently completed on the IBF shot peening plant.

Present plans envisage construction of the cryogenic H150 middle stage of this European rocket, whose first launch is planned for 1995, as a cylindrical section with a diameter of 5.4 m and three spherically curved tank bulkheads. Owing to the required dimensions, and for design reasons, each tank bulkhead has to be constructed in a number of segments. A total of eight segments are assembled to form one tank dome (*Fig.* 9).

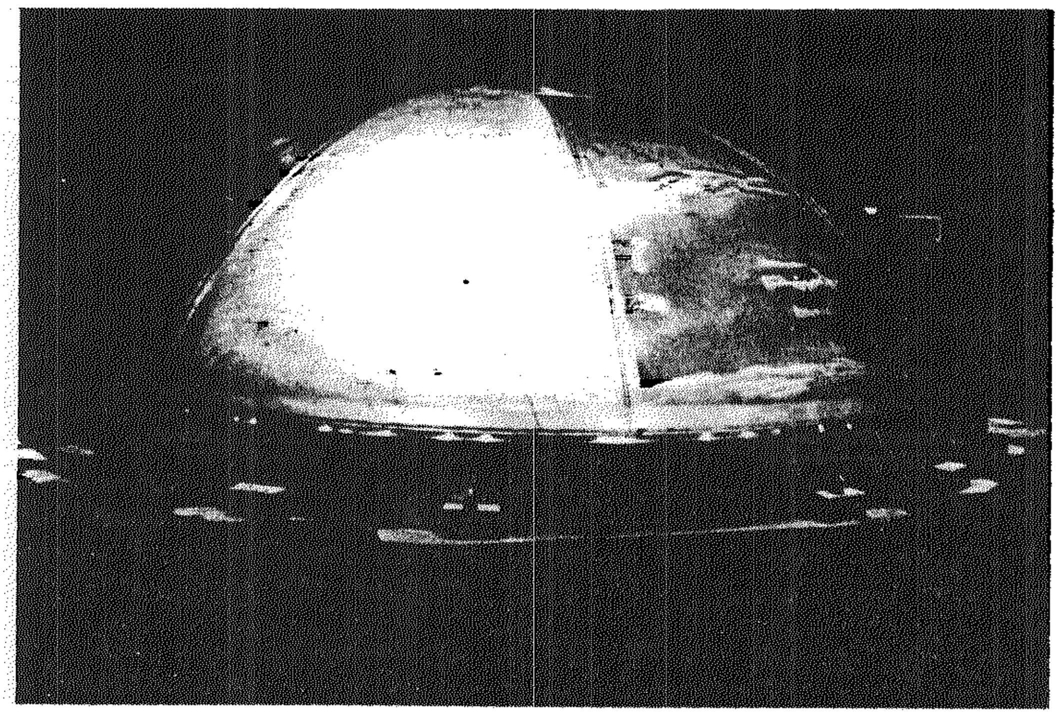

Fig. 9: First Tank Dome Peen Formed on the IBF Plant (Photo: *Dornier*)

A number of forming processes were considered for construction of the tank bulkheads. Stretch-forming, already familiar in the aircraft construction field, was rejected owing to the lack of suitable plant with a capacity adequate for parts of this size in Europe. Flow turning proved unsuitable, as cracks formed in the subsequent welding seam zone on the edges of the component before the necessary degree of deformation had been attained. The third process considered, peen forming, proved successful /6/.

The IBF dimensioned the necessary peening parameters jointly with a number of participating companies, so that as part of a feasibility study on the IBF plant configuration, which currently supports only linear path guidance and a maximum of six peening pressure stages, the desired part contour could be verified with the aid of masks (*Fig. 10a*).

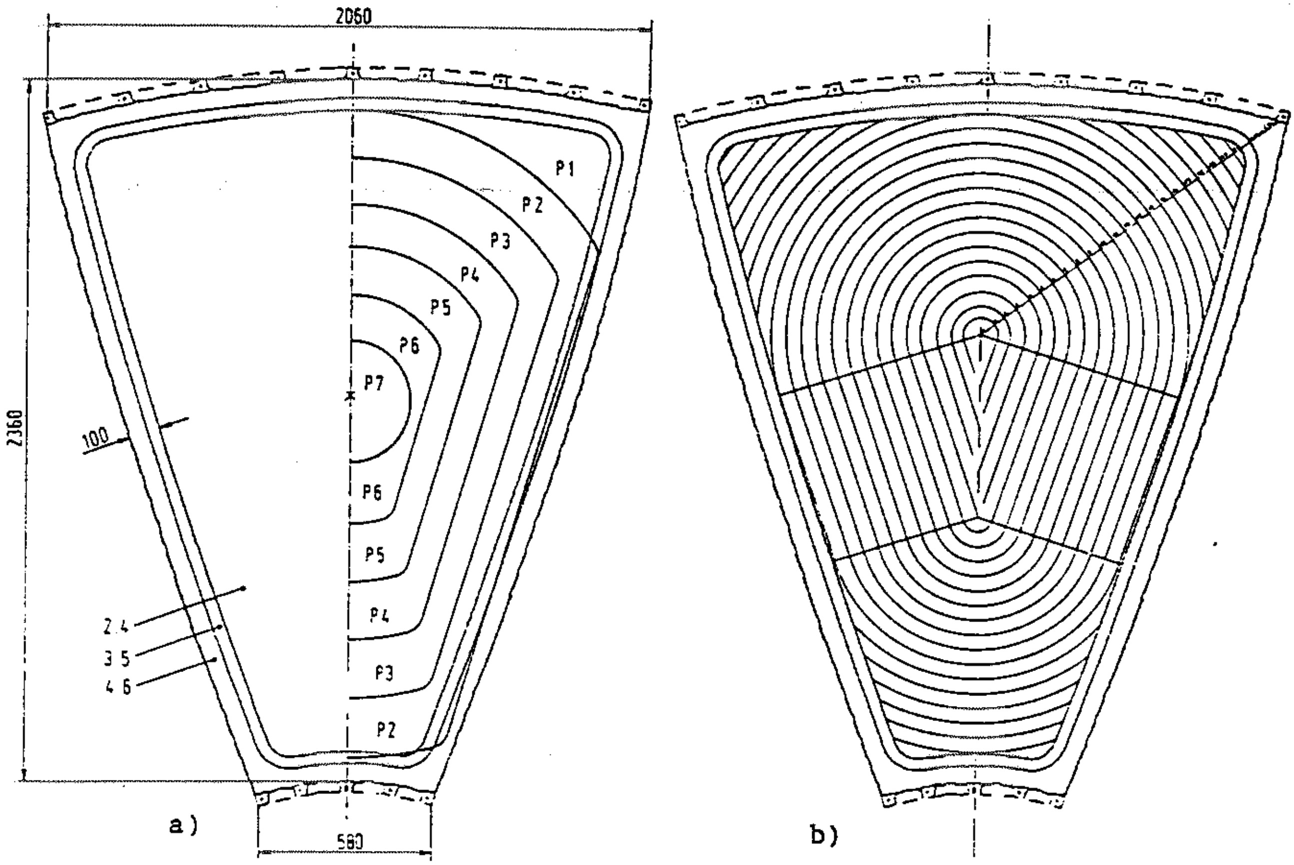

Fig. 10: Various Possible Manufacturing Strategies for the Production of Tank Segments by Peen Forming;
a) Mask technology,
b) Triaxial path control

Taking theoretical considerations into account and using a reference component from the feasibility programme (the first dome, depicted in *Fig. 9*, was produced during this phase), an initial proposal for nozzle movements and plant settings on a new shot peening plant with path control was developed (*Fig. 10b*).

Polishing shot with a diameter of 6.35 mm was used as the forming tool. The required tank dome contour can now be achieved by either of the two production strategies (in *Fig. 10*) through extremely symmetrical peening of the inside of the dome, accompanied by bending-type prestressing of the as yet untreated edge zones with their different thicknesses, and a series of edge and compensation steps from the convex outer side of the dome /15/.

Future production of the tank segments, envisaged at a rate of eight per year, i.e. 24 tank domes with eight segments each, will be carried out at *Dornier* in Munich.

The IBF has developed the production parameters and will provide consultancy for the company during series production.

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