

Computer simulation of laser cutting for the limiting-value-oriented development of robust processes

The CALCut (computer-aided laser cutting) computer-simulation program was developed on the basis of a physical model for laser cutting and is capable of calculating the three-dimensional steady-state cutting front as a function of technical process parameters and of portraying it graphically together with the resulting process variables and result parameters. In a closed formulation, the model links the sub-processes of the laser-beam propagation and the laser-beam focusing, the compressible cutting-gas flow and the shear-stress transfer as well as, if necessary, exothermic reaction contributions in the kerf, the Fresnel absorption at the cutting front, the thermal conduction, the phase transformation in the molten and vaporous states and the expression of the molten and vaporous flows. The reliability of CALCut, e.g. with regard to the predicted geometry of the kerf and to the attainable cutting speed, has now been examined and confirmed over a period of more than ten years in numerous cutting projects for structural steel, stainless steel and aluminium materials.

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1 Introduction

In order to support development, application and training tasks, modern laser-aided fabrication engineering is increasingly asking for suitable process simulations. This interest is based, amongst other factors, on the obvious wish to be able to forecast the process-specific physical process limits in the most efficient and cost-favourable way possible and to recognise and understand process rules at an early stage so that the technological and economic chances of optimised process and system design can thus be exploited to the full. Today, this approach is paraphrased with the term of „limiting-value-oriented“ process development.

Already because of the time-consuming and cost-intensive binding of personnel and plant capacities, purely empirical optimisation experiments are not appropriate for the ever shorter innovation cycles of modern processes and products. In addition, empirical parameter optimisation fails due to the large number of influencing quantities. As a rule, the development and application of fractional factorial orthogonal designs of experiment, e.g. according to Taguchi or Shainin, is only successful if the parameter dependences and process rules are already known to a sufficiently precise extent as a result of existing expert knowledge or on the basis of simulation calculations. A similar case applies to the utilisation of the quality-assuring methods of quality function deployment (QFD) and failure mode and effects analysis (FMEA) which reliably support the knowledge-based control of the fabrication process to a substantial degree but cannot replace it. Expert knowledge is spread around individuals and is frequently characterised by experience, subjective and difficult to access or retrieve. A switch to the interpolations or extrapolations of discrete, experimentally established sets of parameters from databases of

ten entails risking an impermissible generalisation of special cases or going beyond ranges of validity which may be wide but are almost always restricted.

Instead, the complexity of the effective connections of the laser-cutting process itself and of its integration into the complete fabrication system suggests that computer-aided optimisation on the basis of process simulations should be carried out during the development, investment planning and application of laser cutting. The starting point for any process simulation is formed by the physical modelling of the sub-processes which make dominant contributions and of their interactions. The closed formulation of the overall process ultimately leads to an equation system which is solved analytically, semi-analytically or numerically.

Important criteria for the characterisation of a process model and of the simulation program based on it are:

- the dimensionality of the model,
- the significance and number of the sub-processes taken into consideration, including the relevant process variables as well as the incorporated process and result parameters,
- the degree of self-consistency with regard to the calculation of the process variables,
- the extent of the proven coincidence with the real process sequence and result,
- the width of its proven range of validity,
- the necessary computer power and the calculating time,
- the clarity and practical applicability of the input and output contents and formats as well as
- the user friendliness of the program.

At the end of this article, reference is made to these criteria in order to assess the laser-cutting model described in greater detail below and the CALCut (computer-aided laser cutting) computer simulation based on it.

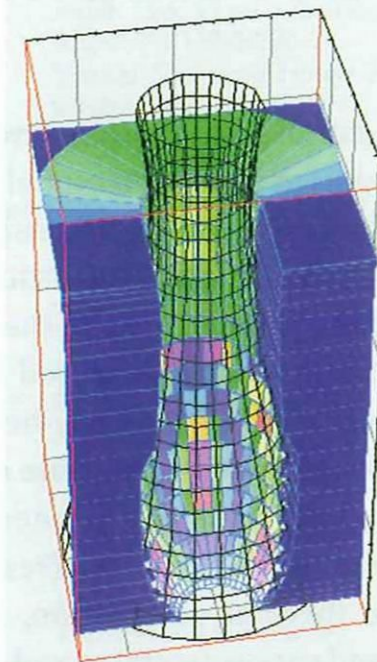
2 Cutting-front model

In view of the numerous corresponding processes which are involved in the cutting operation, a closed, purely analytical solution for the three-dimensional cutting-front geometry cannot be formulated while paying attention to all the fundamental process parameters and variables as well as their interactions. Towards the solid base material, the cutting front is limited by the melting front, i.e. by the solid/liquid phase boundary. The focused laser radiation strikes the cutting-front surface facing the open kerf with a certain intensity distribution and is partly absorbed and partly reflected. The calculation of the free shape of these two boundary surfaces necessitates the three-dimensional description of the interactions between the beam propagation in the kerf, the angle-dependent energy input at the absorption front, the thermal conduction in the solid and the molten material and the dynamics of the gas flow and the molten material [1], Fig. 1.

In the model, the propagation and focusing of the laser radiation are described in an idealising form for the single-mode case and in paraxial approximation. Any intensity distributions and

Input:

- Workpiece parameters
 - Approx. 20 constants per material
 - Thickness
- Laser-beam parameters
 - Wavelength
 - Polarisation
 - Intensity distribution
 - Beam quality
 - Raw-beam diameter
 - Power
- Focusing parameters
 - Optics type
 - Focal length
 - Focus position
- Cutting-gas parameters
 - Type
 - Pressure
- Machine parameters
 - Feedrate



Sub-processes and interactions taken into consideration:

- Laser-beam propagation and focusing
- Fresnel absorption
- Multiple reflection (optional)
- Thermal conduction
- Phase transformation and exothermic reaction
- Supersonic cutting-gas flow
- Molten-material flow
- Capillary forces
- Vapour-pressure gradients

Output:

- Max. cutting speed
- Geometry of kerf
- Heat-flow distribution
- Temperature distribution
- Various process quantities
- Graphic visualisation

Fig. 1. Sub-processes and parameters taken into consideration as well as an example of a three-dimensional cutting-front representation by the CALCut process simulation with a superimposed focus caustic and heat-flow distribution.

beam qualities can be used. The beam propagation and the angle-dependent and polarisation-dependent energy input into the kerf are calculated with local resolution according to the known laws of geometrical optics (raytracing without taking account of diffractive effects) and by applying the Fresnel formalism. In order to determine the refractive index which depends on the material, the wavelength and the temperature, the dominant interaction with the free conduction electrons according to Drude is assumed in the case of molten metals. In this respect, consideration is also given to quantum-mechanical effects by applying the „effective electron density“ indicated in sets of physical tables [1].

In the steady-state equilibrium, the cutting front arises in such a way that the absorbed radiation intensity corresponds to the local heat-flow requirement. In the case of oxygen as the cutting gas, the exothermic reaction and the resulting oxide layer are taken into account additionally. The assumption of a molten-material film with an azimuthally uniform distribution facilitates the parameterisation of the balance equations and permits their analytical formulation, Fig. 2. Their self-consistent linking is carried out numerically. The thermal conduction in the molten material is calculated at the vertex of the cutting-front segments in one-dimensional approximation and at the edge in boundary-layer approximation [1]. The thermal-conduction losses in the solid are established segment by segment in two-dimensional approximation. In addition, the power and heat-flow balances take account of the phase transformation in the form of the enthalpy of melting and evaporation to be applied and of the exothermic reaction contribution in the case of cutting with oxygen [2].

The cutting-gas flow is modelled as a function of the cutting-gas type and the cutting-gas pressure. Below the nozzle exit, the gas jet in the idealised model concept initially expands isentropically and, via a normal compression shock above the workpiece, experiences an increase in entropy which is efficiently interpreted as a static-pressure loss before the second isentropic expansion in the kerf [1]. The developed formalism allows the estimation of the absolute flow rate in the kerf. The hydrodynamic laws of a turbulent pipe flow are applied in order to calculate the shear stresses transferred to the molten material.

The combined mass and force balance of the material removal takes account of the shear-stress transfer from the cutting-gas flow to the molten material which leads to the axial expulsion of molten material. In the event of strong evaporation, the material transport is accelerated towards the cut edges, similar to the welding process. The evaporation rate and the ablation pressure are, in a simple way, computationally dependent on the surface temperature and the resulting saturation vapour pressure and interact with the capillary forces which depend on the surface tension and the curvature radius [1]. In the model, an almost completely azimuthal molten-material flow occurs when the process-gas pressures and gas flow rates are reduced to minimal values. This corresponds to the welding process with a flow around the capillary, as also arises in reality. Therefore, the self-consistent model is readily capable of describing the formation of a welding-capillary front as well.

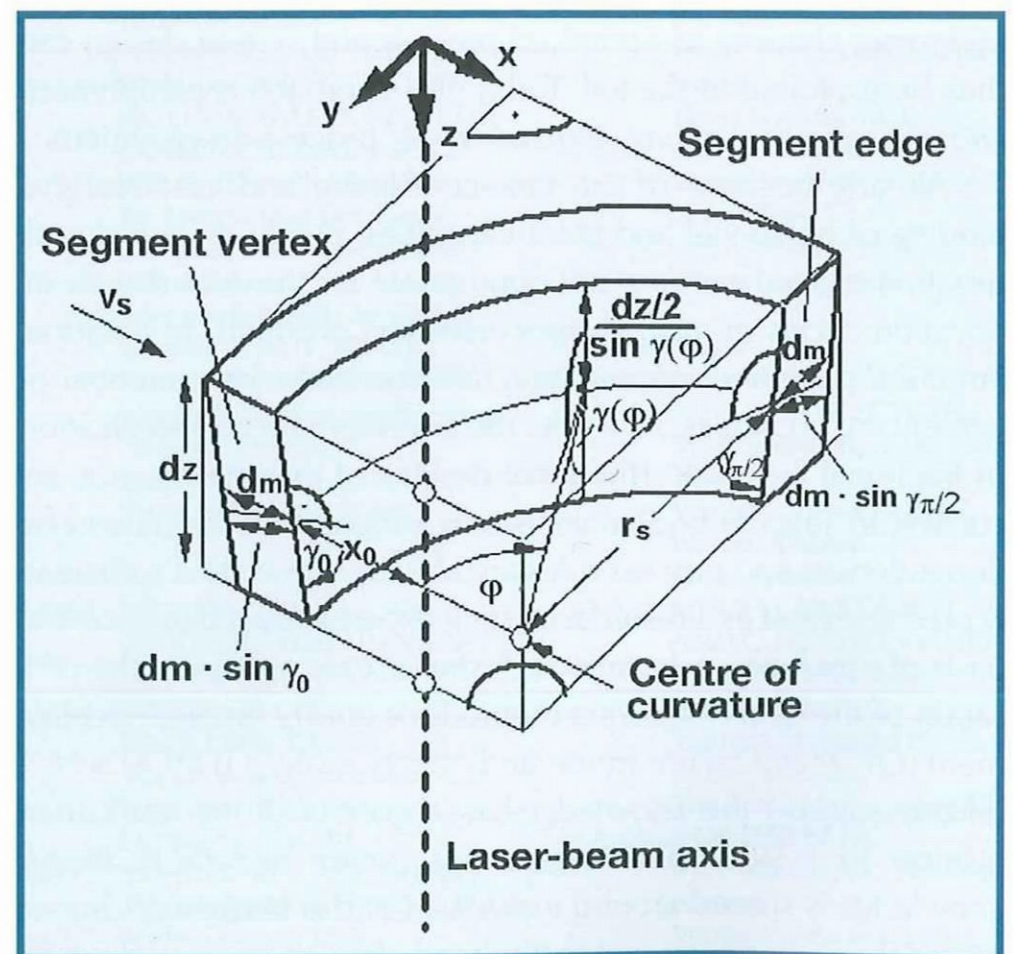


Fig. 2. Geometrical parameterisation of a cutting-front segment with regard to its shape and position [1].

3 CALCut simulation program

In order to reduce the mathematical scope to a justifiable extent, the cutting-front geometry is parameterised in an appropriate way. Layer by layer, the computer simulation develops the resulting cutting front from horizontal segments which are, in turn, divided into facets. The shape and position of every single segment is parameterised by the segment height dz , the curvature radius r_s , the molten-film thickness d_m , the vertex inclination γ_o , the vertex coordinate x_o and the edge inclination $\gamma_{\pi/2}$. Fig. 2. Three balance equations and three continuity conditions are available for the local calculation of these six variables [1]. This geometrical parameterisation permits a largely free three-dimensional calculation of all the possible process states and cutting-front shapes.

The process parameters which the simulation takes into consideration as input quantities are listed on Fig. 1. The laser-beam properties in the focus caustic, the temperature-dependent material and cutting-gas properties as well as the resulting process variables are calculated by the simulation program. Fig. 3 shows the relevant flow chart – for better clarity, in a simplified form. Inputs and outputs occur interactively on a graphic user interface. There is the possibility either of varying the cutting speed as an input parameter or of determining its maximum limiting value and the corresponding cutting result depending on the chosen set of parameters.

The cutting result is made available, amongst other ways, in the form of the three-dimensional cutting-front geometry, Fig. 1. In

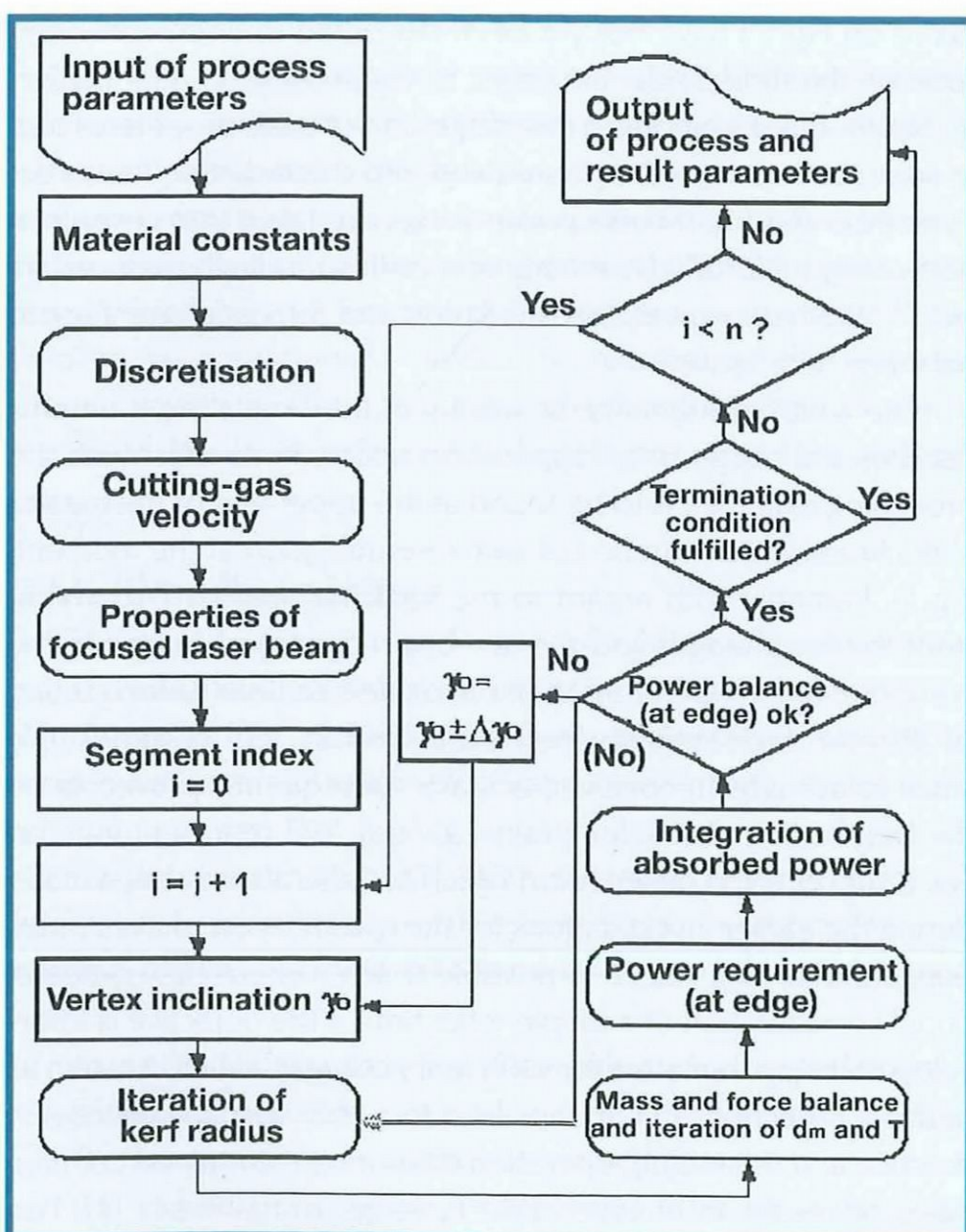


Fig. 3. Simplified flow chart of the CALCut simulation program [1].

addition, it is possible to inquire about all the process variables taken into consideration by the model. These include the resulting heat-flow and temperature distributions which, in the three-dimensional representation, are visualised by scaled false colours and colour saturations on the facets. Together with the variation of the molten-film thickness as a function of the cutting depth z , the contour of the cutting-front edge permits a statement about the resulting kerf geometry.

The CALCut process simulator takes account of all the process parameters apart from the geometrical parameters of the cutting-gas nozzle. Its application has led to the identification of three process types [1]:

- the thermal-conduction-controlled cutting process at low speeds,
- the melting-controlled cutting process in the medium speed range and
- the evaporation-controlled cutting process above a critical cutting speed.

On the basis of extensive simulation runs, it was also possible to derive analytical approximation formulae which are each applicable in restricted ranges of validity and, as algorithms, are suitable for incorporation into intelligent machine controllers [1].

The process simulator identifies the relative significance of the individual sub-processes, e.g. with regard to their contributions in the balance equations, and thus reveals the effective connections of the complex overall system. Fundamental input and output parameters of the simulation are documented in a simulation record [1]. Within the process development, this makes parameter dependences physically reconstructable and comprehensible. The CALCut simulation program was checked and confirmed on the basis of numerous series of practical tests in defined experimental conditions. To a great extent, the experimental results with variation of the laser-beam power, the focal length, the focus position, the cutting speed, the material thickness and the material type correspond to the simulation results – with regard not only to the maximum cutting speed but also to the geometrical kerf formation, Figs. 4 and 5. The discernible deviations are typically less than 10% and 20% at most and are thus within the error limits which are specified solely by the limited precision of the experimental beam diagnostics and the available material constants. To an increasing degree, the solutions developed in [1] are also being adopted by other international working groups for development and training tasks [3...5].

4 Examples of applications

In the field of process development, the model is used for the fundamental offline analysis and offline optimisation of the process since it establishes and explains parameter influences. The CALCut development platform permits the identification of system-induced process limits and the optimisation of process parameters, adapted to the technical boundary conditions and the demanded result parameters. The simulation supplies quick and detailed information about the cuttability of materials or material thicknesses, possible cutting speeds and kerf geometries as well as necessary laser powers and beam qualities.

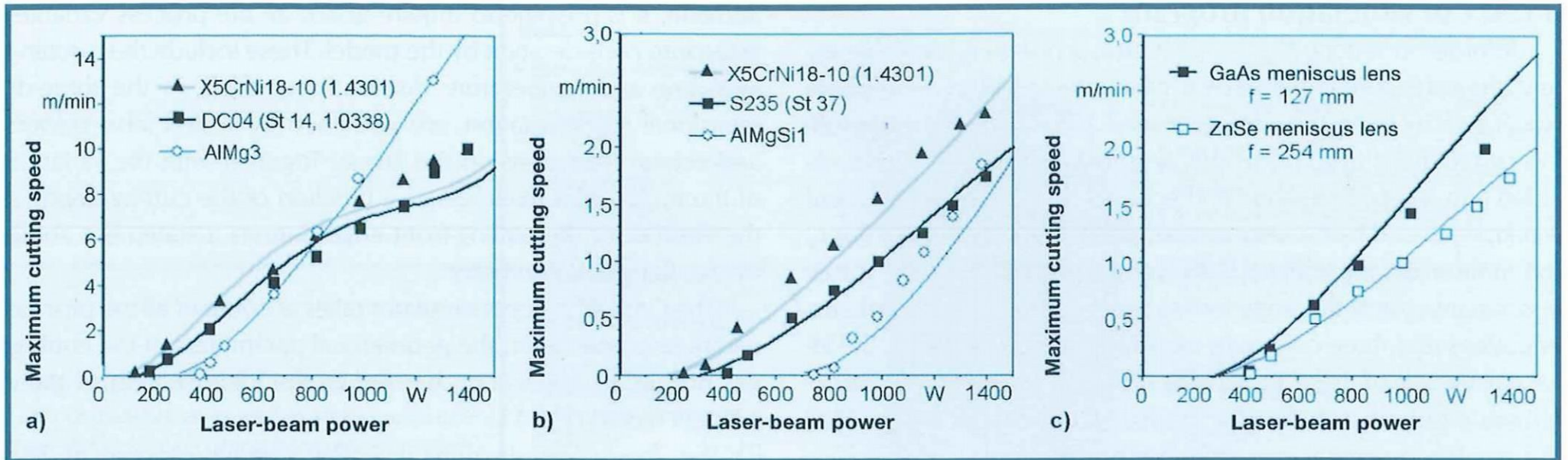


Fig. 4. Comparison of the theoretical and practical maximum cutting speeds as a function of the laser-beam power [1] (CO_2 laser, $\lambda = 10.6 \mu\text{m}$, TEM_{01}^* , beam-quality index $K = 0.5$, polarisation: circular, raw-beam diameter $D_L = 20 \text{ mm}$, cutting gas: nitrogen, cutting-gas pressure: 1.5 MPa, maximum cutting speed); a) different materials with a thickness of 1 mm (focusing optics: GaAs meniscus lens, focal length $f = 127 \text{ mm}$, focus position $\Delta z = -0.5 \text{ mm}$), b) different materials with a thickness of 3 mm (focusing optics: ZnSe meniscus lens, focal length $f = 254 \text{ mm}$, focus position $\Delta z = -1.5 \text{ mm}$), c) S235 structural steel with a thickness of 3 mm, different focal lengths (focus position $\Delta z = -1.5 \text{ mm}$).

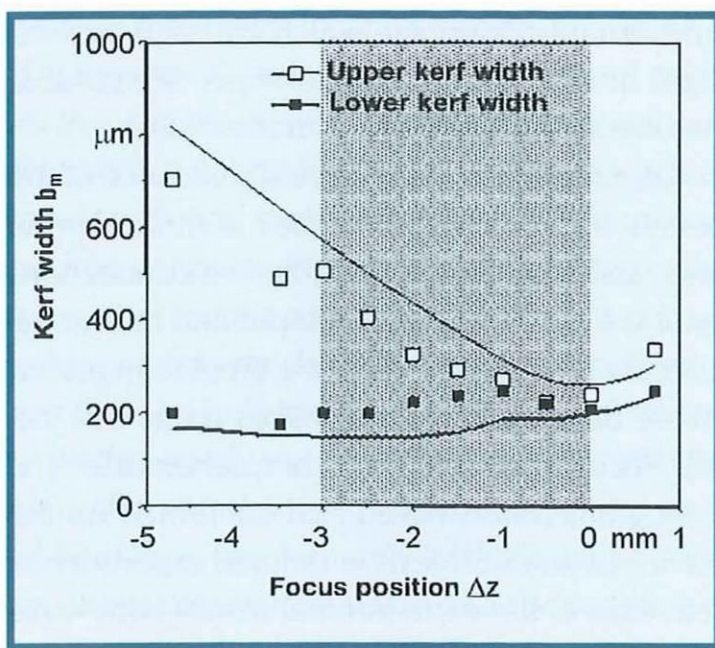


Fig. 5. Comparison of the theoretical and practical kerf widths (upper and lower) in 3 mm thick structural-steel sheets as a function of the focus position ($f = 127 \text{ mm}$, $P_L = 1,250 \text{ W}$, other parameters as on Fig. 4c) [1].

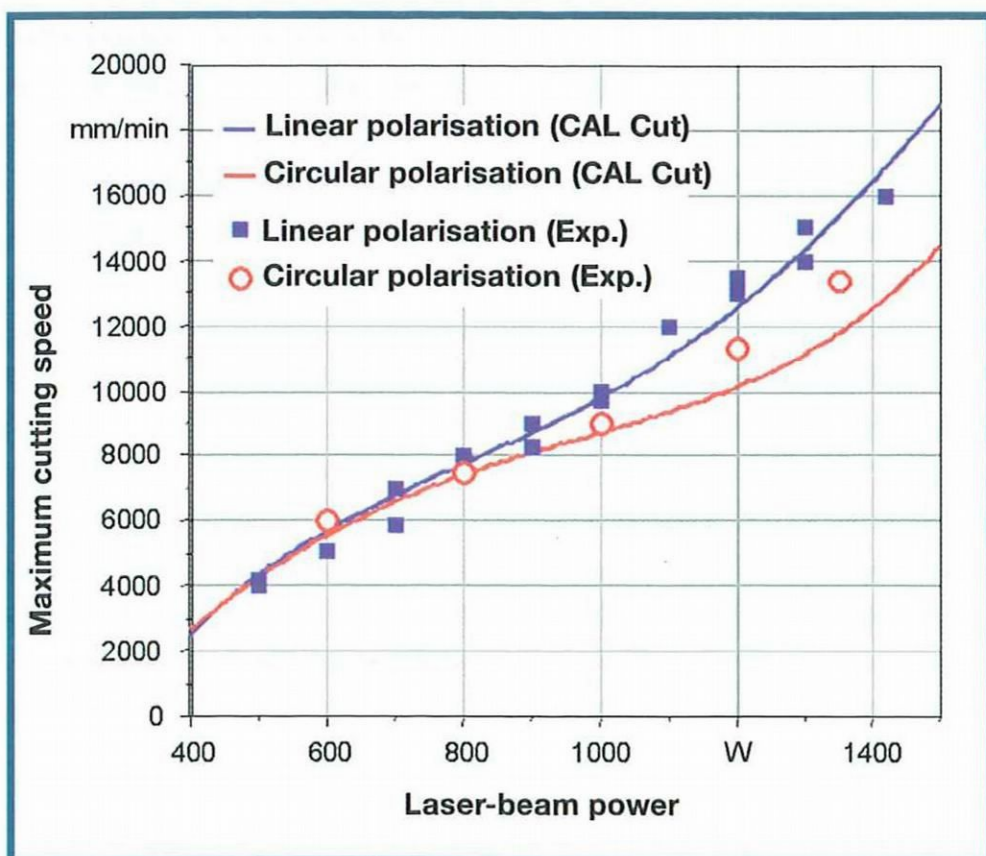


Fig. 6. Influence of the polarisation type on the theoretical and practical maximum cutting speeds in 1 mm thick structural-steel sheets as a function of the laser-beam power (CO_2 laser, cutting gas: nitrogen).

Figs. 6 and 7 show examples of simulation results and practically established cutting speeds which were elaborated in the course of the process analysis of the high-speed cutting of sheets. The influences not only of the polarisation type, Fig. 6, but also of the properties of the beam source (intensity distribution and beam quality, Fig. 7) on the cutting result are defined correctly by the simulation. Merely the speed-reducing influences of the cutting plasma arising at intensities as from approx. 10^7 W/cm^2 (blue curve on Fig. 7) have not yet been described in a self-consistent form on the model side. However, it was possible to quantitatively explain the deviations in this range on the basis of spectroscopic investigations into the plasma and into the radiation losses derived from this [6]. If these power losses are taken into consideration computationally by means of a correspondingly reduced input for the laser power, the simulation and the experiment are in harmony here as well.

The width of the range of validity of the simulation is emphasised by the results of an application which, in contrast with the preceding example, is to be found at the upper end of the material thickness which can be cut with laser radiation at the moment, Fig. 8. Primarily with regard to the focusing number F (quotient from the focal length and the raw-beam diameter) to be set, the computer-aided optimisation of the oxide-free laser fusion cutting of 40 mm thick stainless-steel plates initially led to surprisingly small values which, however, actually subsequently proved to be the best setting after experiments as well. The representation on Fig. 8 supports the observation which has also already been made during the earlier investigations for the qualification of the simulation, i.e. that, as a rule, it is possible to do without the computational consideration of multiple reflections if the objective is to develop cutting parameters for sufficient cutting qualities. As soon as multiple reflections occur, they lead to a very unstable process in practice and the cutting operation cannot be maintained continuously or results in unacceptable cut-edge roughnesses [1]. Furthermore, a lot of calculating time is saved by „switching off“ the multiple-reflection algorithms in CALCut.

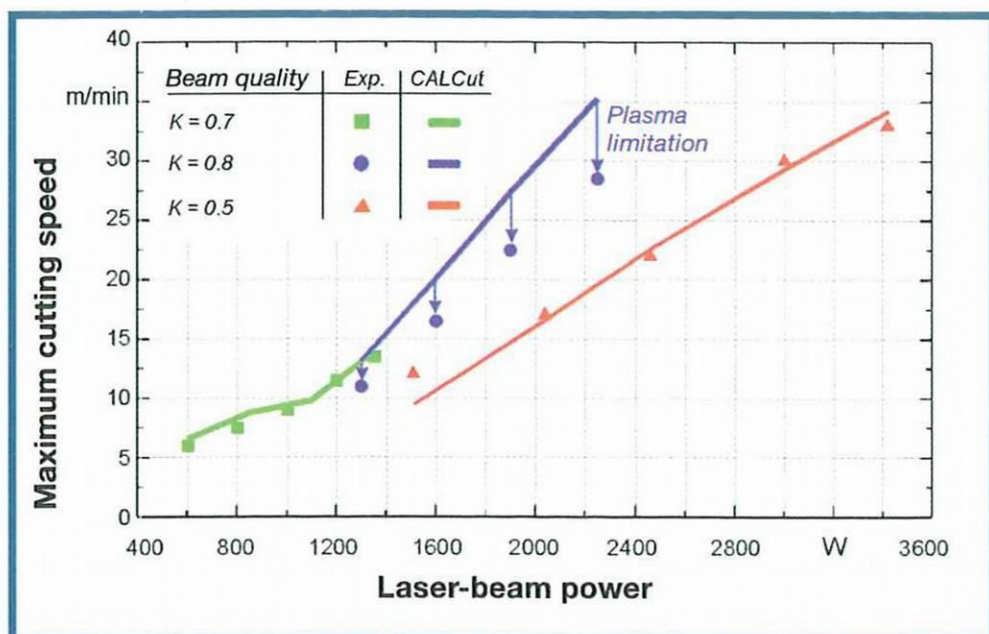


Fig. 7. Theoretical (CALCut) and practical (Exp.) maximum cutting speeds in 1 mm thick structural-steel sheets as a function of the laser-beam power (CO_2 laser with different intensity distributions and beam qualities; cutting gas: nitrogen).

In connection with preventive quality assurance, the determination of parameter tolerances for example is an important task of the simulation. Before a new laser system is purchased, the simulation also makes the investment decision considerably more efficient. Especially for forecasts about new types of process applications, the simulation supplies valuable key data, e.g. for calculations relating to economic viability. With regard to the trouble shooting on industrial fabrication installations, a simulation-aided process analysis permits quicker reactions.

The efforts made in recent years in the field of the monitoring and closed-loop control of laser-beam processes have shown that a frequent weak spot is the fact that process signals cannot be interpreted unambiguously. The process simulation makes the temperature distribution on the projection surface of the cutting front directly available as a function of the process parameters and can help to computationally predict or reconstruct the detected process signals. It is thus possible to check monitoring and control concepts. This leads to logical and intelligent process-control systems.

5 Multimedia training

The global economic and sociopolitical significance of training and advanced training is attracting ever more attention. „Life-long learning“ in a „global knowledge-based society“ requires the modernisation of the training tools and constant adjustment of the training contents. This applies, in particular, to high technologies such as laser technology [7]. With regard to passing on knowledge about the utilisation of the laser beam in fabrication engineering, it is necessary to take account of special boundary conditions:

- As a rule, the laser radiation is invisible and is focused down to minimal dimensions.
- The interaction zone cannot be viewed directly.
- The physical processes involved and their interactions are complex.
- The process conditions (temperature and pressure) and their

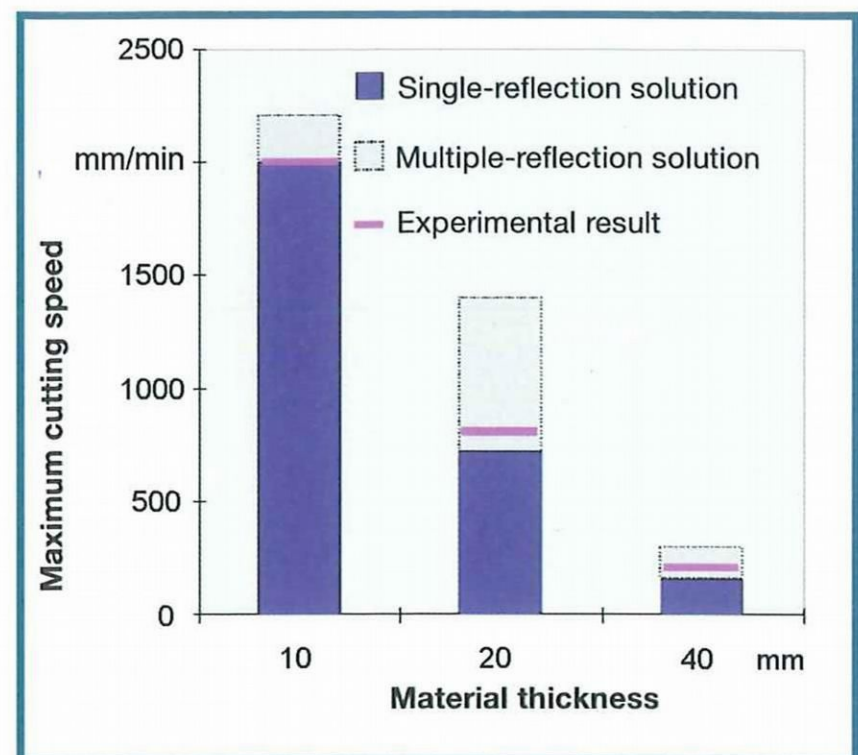


Fig. 8. Theoretical and practical maximum cutting speeds on 10, 20 and 40 mm thick stainless-steel plates (CO_2 -laser-beam power: 8 kW, cutting gas: nitrogen); the single-reflection solution from CALCut coincides best with the experimental results.

gradients deviate considerably from the usual world of experience.

- The procurement of laser installations is connected with high investment costs.
- As a rule, laser installations can only be operated in an economically viable form with a high utilisation factor.

By applying modern multimedia methods [7], the interactive LASIM CUTTING training program serves to substantially raise the efficiency of the training with regard to the clarity, the depth and width of the imparted knowledge, the flexibility as well as the personnel and machine capacities which must be used. With CALCut, not only texts, graphics, animations and video sequences but also simulations of the cutting process are an integral constituent of the software. As a seminar chairperson or for advanced training by means of self-education, the user can pass on or study the influence of parameters such as the material type, the material thickness, the cutting speed, the laser-beam power, the beam distribution, the beam quality, the focal length of the lens and the focus position on the cutting result on the basis of the three-dimensional cutting-front geometry, Fig. 9. For the training software, the fundamentals of the power balance for fusion and oxygen cutting were also graphically prepared in a simplified form. Aspects relating to systems engineering (such as the setting-up and functionality of various laser-beam sources and installations), to the CNC programming and to the avoidance of cutting errors are explained using interactive, realistic animations. Just like the LASIM WELDING software module which has already been commercially available for quite a long time, the LASIM CUTTING software module is now being used not only at universities, technical colleges, DVS training establishments and other training and advanced-training centres but also by manufacturers and users of laser-beam installations in order to prepare pupils, students, employees and customers effectively for practice.

6 Concluding remarks

Oriented to the criteria listed in the introduction, brief classification and assessment of the presented cutting model and of the corresponding simulation software result in the following properties:

- three-dimensional, steady-state model,
- consideration of all the important sub-processes and parameters apart from the gas-nozzle geometry and the gas-nozzle distance,
- largely self-consistent algorithms due to parameterisation appropriate for the process,
- very good coincidence between the simulations and practical results,
- wide range of validity proven,
- executable on a commercially available personal computer with calculating times of some seconds per cutting front due to largely analytical and semi-analytical solution routines,
- comprehensive and clear result output (can be utilised for training purposes) as well as
- user interfaces corresponding to the customary standard.

The CALCut simulation program permits the efficient and cost-favourable execution of laser-cutting experiments on the personal computer without any laser equipment and thus also allows a detailed process analysis within the framework of development pro-

jects and training media. In the meantime, simulation results from CALCut are also provided in the LASIM CUTTING training software in order to pass on a deeper understanding of the process by visualising the parameter dependences of the cutting front.

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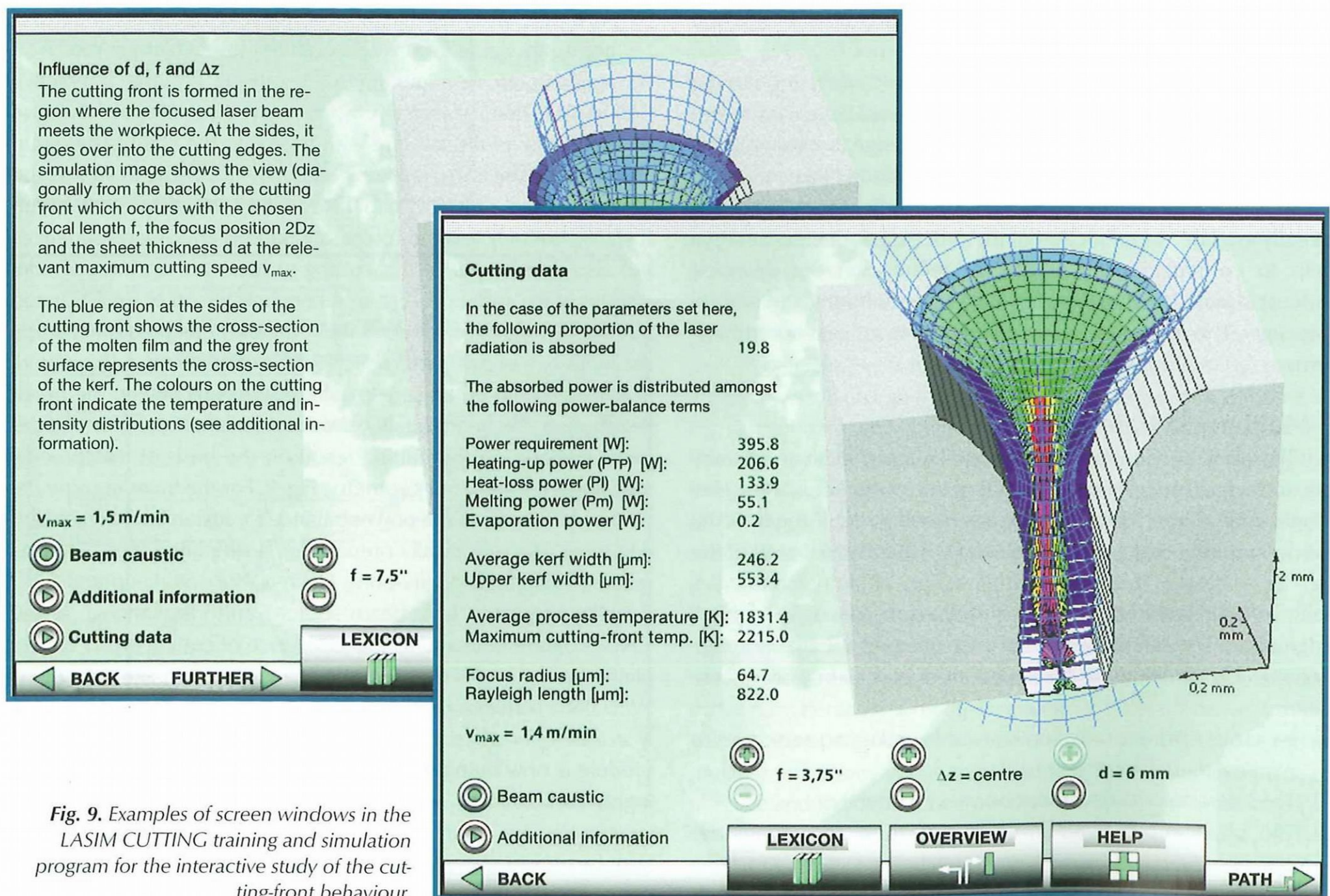


Fig. 9. Examples of screen windows in the LASIM CUTTING training and simulation program for the interactive study of the cutting-front behaviour.

WELDING AND CUTTING

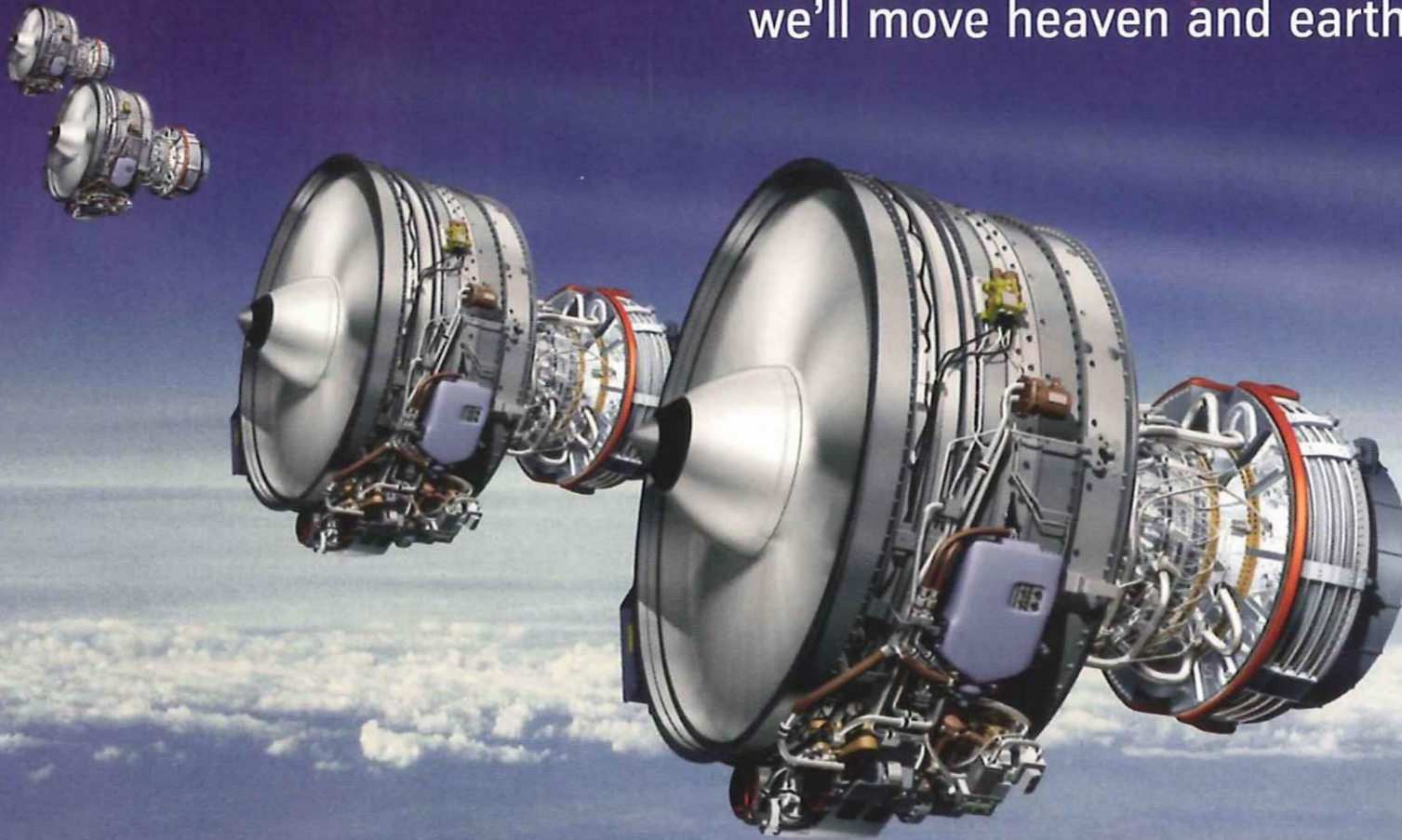


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