Sensitivity Studies
for the Development of Laser Machines

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Advanced Development TruLaser
TRUMPF Werkzeugmaschinen GmbH + Co. KG
Agenda

- TRUMPF
- Challenges for the development of laser cutting machines
  - Sensitivity studies
    - Laser & machine’s dynamic
    - Optical system
- Summary
About us

We are a high-tech company that focuses on manufacturing technology, laser technology and medical technology.

We offer our customers both innovative and high-quality products.

We are represented in all world markets, close to our customers with 58 subsidiaries.

We are a family business established in 1923 and our goal is to stay economically independent.
## At a glance

<table>
<thead>
<tr>
<th></th>
<th>2011/12</th>
<th>Change in percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sales (mil. EUR)</td>
<td>2,328.2</td>
<td>+15.0</td>
</tr>
<tr>
<td>Income before Taxes (mil. EUR)</td>
<td>210.9</td>
<td>+13.8</td>
</tr>
<tr>
<td>Expenditure on Fixed Assets (mil. EUR)</td>
<td>152,5</td>
<td>+151.2</td>
</tr>
<tr>
<td>R+D Expenditures (mil. EUR)</td>
<td>193.4</td>
<td>+ 22.4</td>
</tr>
<tr>
<td>Employees as of June 30 (number)</td>
<td>9,555</td>
<td>+11.8</td>
</tr>
</tbody>
</table>
## TRUMPF Group Business Divisions

<table>
<thead>
<tr>
<th>Machine Tools</th>
<th>Laser Technology/ Electronics</th>
<th>Medical Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Machine Tools</strong></td>
<td><strong>Laser Technology</strong></td>
<td><strong>Electronics</strong></td>
</tr>
<tr>
<td>- Machine tools for flexible sheet metal and tube processing, Power tools for sheet metal processing</td>
<td>- Lasers for production technology</td>
<td>- Power supplies for induction heating, plasma and CO₂ laser excitation</td>
</tr>
<tr>
<td>Sales (mil €)</td>
<td>1,890</td>
<td>727</td>
</tr>
<tr>
<td>Employees</td>
<td>5,918</td>
<td>2,330</td>
</tr>
</tbody>
</table>

End of fiscal year: June 30, 2012; consolidated within the business division; figures rounded
TRUMPF Historie – eine Innovationsgeschichte von der Komponente zum High-end System

1923

Christian TRUMPF acquires the mechanical shop Julius Geiger.
Flexible shafts for medical application and printers
TRUMPF – a success story from a single component to high-end systems

First manual operating motor-driven scissor for sheet metal cutting

1923
70 Employees

1934
TRUMPF – a success story from a single component to high-end systems

Patent application for a guide of coordinates by the young engineer Berthold Leibinger. First step towards numerical controlled motion
TRUMPF Historie – eine Innovationsgeschichte von der Komponente zum High-end System

Trumatic 20: first numerically controlled sheet metal processing machine. Pure automatic operation by „Lochstreifenspeicherung“.

1923: 70 Employees
1934: 145 Employees
1957: 325 Mitarbeiter
1968:
TRUMPF – a success story from a single component to high-end systems

First steps into laser technology - first punch and laser machine TRUMATIC 180 LASERPRESS
TRUMPF – a success story from a single component to high-end systems

TRUMPF is manufacturer of laser sources (CO2-Laser).

<table>
<thead>
<tr>
<th>Year</th>
<th>Employees</th>
</tr>
</thead>
<tbody>
<tr>
<td>1923</td>
<td>70 Employees</td>
</tr>
<tr>
<td>1934</td>
<td>145 Mitarbeiter</td>
</tr>
<tr>
<td>1957</td>
<td>325 Employees</td>
</tr>
<tr>
<td>1968</td>
<td>1500 Employees</td>
</tr>
<tr>
<td>1979</td>
<td></td>
</tr>
<tr>
<td>1985</td>
<td></td>
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</tbody>
</table>
TRUMPF – a success story from a single component to high-end systems

First 2D-laser cutting machine
TRUMATIC L3000

<table>
<thead>
<tr>
<th>Year</th>
<th>Employees</th>
</tr>
</thead>
<tbody>
<tr>
<td>1923</td>
<td>70</td>
</tr>
<tr>
<td>1934</td>
<td>145</td>
</tr>
<tr>
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<tr>
<td>1968</td>
<td></td>
</tr>
<tr>
<td>1979</td>
<td>1500</td>
</tr>
<tr>
<td>1985</td>
<td></td>
</tr>
<tr>
<td>1987</td>
<td></td>
</tr>
</tbody>
</table>
TRUMPF – a success story from a single component to high-end systems


70 Employees  145 Employees  325 Employees  1500 Employees  8500 Employees

20,000 TruFlow CO₂-Lasers sold
Cutting and laser technology define the performance progress

TruFlow CO2-Laser

TruDisk SS-Laser

Steel

Performance

1990

2000

2010

2000 Watt
9 m/min@1mm
4 mm

2600 Watt
11 m/min@1mm
10 mm

4000 Watt
11 m/min@1mm
15 mm

3000 Watt
34 m/min@1mm
4 (12) mm

6000 Watt
11 m/min@1mm
25 mm

8000 Watt
11 m/min@1mm
32 mm

5000 Watt
50 m/min@1mm
5 (20) mm

WOST 2012 - 30.11.2012
Sensitivity Studies of Laser Machines © TRUMPF
Solid state lasers almost doubled the portfolio

- TruLaser 7000 Series
- TruLaser 5000 Series
- TruLaser 3000 Series
- TruLaser 1000 Series
- TruFlow CO₂-Laser
- TruDisk SS-Laser
Sensitivity studies help to find efficient laser - machine combinations

- Input parameter laser
  - Forward feed
- Input parameter of the machine’s dynamic
  - Acceleration
  - Jerk
- Output
  - Average velocity
  - Duration of production
- Test case
  - Sheet metal 2.500x1.250 mm²
  - 169 parts
  - TruLaser 3030 → 33 minutes
Virtual control unit as basic model
VNCK “virtueller NC-Kern” by Siemens
Results (1)
Results (2)

<table>
<thead>
<tr>
<th>Power (W)</th>
<th>Speed (m/min@1mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3000</td>
<td>34</td>
</tr>
<tr>
<td>5000</td>
<td>50</td>
</tr>
</tbody>
</table>

efficient combination
High quality laser cutting requires several parameters in a certain range
Basic optical design calculated with ZEMAX

For both beam diameters, the beam waist is placed be in the centre of the machine.
Optical components and it’s parameters for sensitivity study

- Laser
  - waist diameter, waist position, power, ...
- Mirror (plane)
- Mirror (plane)
- Adaptive mirror 1
  - pressure
- Adaptive mirror 2
  - pressure
- Adaptive mirror 3
  - pressure
- Mirror
  - focal length
- Lens
  - focal length
Results

Coefficient of Importance (linear)
full model: adjusted $R^2 = 99\%$

INPUT: Linsenbrennweite
-0 %

INPUT: Brennweite_fester_Toroid
-0 %

INPUT: Abweichung_vom_Grunddruck_Spiegel1
0 %

INPUT: Abweichung_vom_Grunddruck_Spiegel2
0 %

INPUT: k_Zahl_des_Lasers
1 %

INPUT: Taillenlage_des_Lasers
1 %

INPUT: Spiegeldruck3
8 %

INPUT: Strahlendurchmesser_in_der_Taille_des_Lasers
9 %

INPUT: y_Position
15 %

INPUT: x_Position
65 %

adjusted CoI [%] of OUTPUT: Fokuslage_in_Bezug_zum_Werkstueck_mm

Coefficient of Importance (linear)
full model: adjusted $R^2 = 89\%$

INPUT: Spiegeldruck3
-0 %

INPUT: Laserleistung_tatsaechlich
0 %

INPUT: y_Position
1 %

INPUT: Abweichung_vom_Grunddruck_Spiegel1
3 %

INPUT: Linsenbrennweite
4 %

INPUT: Taillenlage_des_Lasers
4 %

INPUT: k_Zahl_des_Lasers
5 %

INPUT: x_Position
6 %

INPUT: Abweichung_vom_Grunddruck_Spiegel2
7 %

INPUT: Strahlendurchmesser_in_der_Taille_des_Lasers
57 %

adjusted CoI [%] of OUTPUT: Fokusdurchmesser_am_Werkstueck_mm
Results with active compensation (mirror 3)
Summary

- First steps towards the field of CAE based robust design
- Sensitivity analysis are already helpful
- For simple models only a minor improvements can be achieved
- Knowing the technology and the simulation model is a huge benefit