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Numerical simulation of power control in laser-assisted metal-polymer joining

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Abstract

Laser-assisted joining enables a direct connection between polymers and metals without using additional elements (e.g. screws, rivets) or adhesives. The process is well known in terms of surface pretreatment, achievable mechanical properties and materials. However, the quality of the joint is affected by varying manufacturing conditions, e.g. heat accumulation at edges, heating of the clamping device or different material batches. The article is dedicated to power control in laser-based joining of polymers with metals for this reason. A PID controller was integrated to control the beam power of a diode laser as a function of temperature based on a transient thermal model. The investigations were carried out on polypropylene in combination with high-alloy steel AISI 304. A comparison of surface/interface temperatures, controlled/uncontrolled processes and the introduction of disturbances allow conclusions on process control and on implementation in real production processes.

Keywords: Joining; System Technology and Process Control; Fundamentals and Process Simulation; Metal-Polymer Joining; Metal-Plastic joining

1. Introduction and state of the art

Laser-assisted joining enables a direct connection between polymers and metals without using additional elements (e.g. screws, rivets) or adhesives. The process is well known in terms of surface pretreatment and achievable mechanical properties (Al-Sayyad et al., 2021) and different materials, e.g. Polyamide 6.6 and aluminum (Hirchenhahn et al., 2020), Polyimide and Titanium (Georgiev et al., 2004) or PMMA and steel (Hussein et al., 2013). However, the quality of the joint is affected by varying manufacturing conditions, e.g.

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heat accumulation at edges, heating of the clamping device or different material batches. The resulting temperature distribution and the temperature-time profile affects the bonded area (Lambiase et al., 2018) as well as its properties, e.g. the ductility of the joint (Schricker et al., 2020). The temperature distribution in the materials can be determined via numerical simulations, which was topic of various investigations carried out for this purpose, including for spot welds (Lambiase and Genna, 2020) and line joints (Lambiase et al., 2018). The determination of temperatures by thermocouples (Schricker et al., 2020) and temperature fields by infrared images (Lambiase and Genna, 2017) were carried out experimentally. The observation of the maximum temperature is of great importance, e.g. to prevent bubble formation (Schricker et al., 2018). Especially non-contact measurement set ups allow the recording of temperatures in an industrial environment especially for surface temperatures. Due to the fact that the measurement of surface temperatures in industrial environments and the effect of temperatures in the joining process are well known, both issues can be combined for realizing closed-loop process control.

The article is dedicated to a closed-loop power control in laser-based joining of polymers with metals. The investigations were carried out by means of numerical simulation, among other things to be able to make an initial estimate of the control parameters. A PID controller was integrated in a transient thermal model to control the laser beam power of a diode laser as a function of surface temperature. The investigations were carried out on polypropylene in combination with high-alloy steel. A comparison of surface/interface temperatures, controlled/uncontrolled processes and the introduction of disturbances allow conclusions on process control and on implementation in real production processes.

2. Materials and methods

2.1. Numerical simulation and evaluation quantities

A transient, 2D rotationally symmetrical thermal model was set up in Comsol Multiphysics 5.6 and used to calculate the temperature distribution in both joining partners. The simulation is based on a verified and validated model published in Schricker and Bergmann, 2018. The simulation reproduces an experimental setup with a diode laser (Laserline LDM 1000) for heat conduction joining of spot joints (overlap configuration with metal as upper and polymer as lower joining partner). In this paper, the maximum joining time was set to 2 seconds. The model concept and boundary conditions are shown in Fig. 1. Due to a high distance of the clamping jaws in reality, heat accumulation due to the clamping device can be avoided. That allows a simplification as a rotationally symmetrical model. The material properties specific heat capacity, density and thermal conductivity were considered temperature dependent. AISI 304 steel (X5CrNi18-10/1.4301) with a thickness of 1 mm was chosen as metal sheet. Polypropylene (PP) with a thickness of 5 mm was chosen as thermoplastic joining partner. The heat input by the laser beam was simplified as top-hat function over focal diameter which reflects reality well. The absorption coefficient was kept constant. The laser properties are listed in Table 1.

Table 1. Laser properties

Parameter	Value
Maximum laser beam power u_{max}	1000 W
Wavelength	980 nm
Focal diameter d_f	5.3 mm
Intensity over focal diameter	const. / top-hat

The simulation is evaluated using the punctual temperatures (see Fig. 1) at the surface (domain probe 1) and the interface (domain probe 2). This also showed whether process control based on surface temperatures were applicable and allowed a comparison to the deviation of temperatures in the interface, which were critical for the thermoplastic material in terms of thermal degradation. A temperature T_{em} above 178 °C was to be achieved in the interface to ensure the penetration of PP into the surface structures (see also Schricker and Bergmann, 2019). Furthermore, an additionally added disturbance term P_{dist} (1) can be activated at the surface in the region of 0 ≤ r 5 mm and worked as disturbance value in the subsequent control loop. It was activated in certain experiments in the period from 1 to 1.5 s and introduced a periodic disturbance on the surface. It should be noted that the value of -300 W and the periodic function were defined to obtain further information about controller response and its behavior against non-constant disturbances.

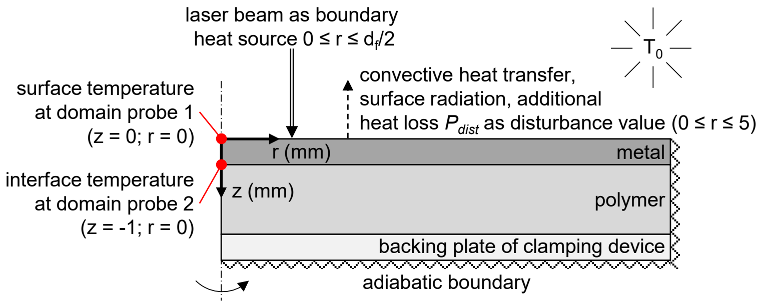

Fig. 1. Model concept, boundary conditions and evaluation quantities

$$P_{dist}(t)=-300W\cdot \cos\left(50\frac{1}{s}t\right) \text{ for } 1.0\text{ s} \leq t \leq 1.5\text{ s} \quad (1)$$

2.2. Closed-loop control

The simulation was extended by a PID controller. The PID controller equation of the output value u is given in (1) and based on Comsol Multiphysics 5.6, 2021, where reference value c_{set}, measured value c and controller parameters k_p, k_i and k_d are considered. u represented the nominal output power of the laser beam source. The maximum value u_{max} was set to 1000 W, the minimum value to u_{min} to 0. It should be noted that setting u_{min} to 0 was a simplification. The output power of real diode laser beam sources cannot be operated continuously between 0 and 100 % due to the threshold value. Furthermore, the operating time of the laser diodes, which is typically 50 µs, was neglected due to the long joining times of 2 s. The reference value c_{set} was set to 350 °C at the metal surface in order to prevent bubble formation due to thermal degradation of PP, occurring from 390 °C onwards (see also Schricker et al., 2018). The measured value c was recorded at the surface (domain probe 1, see Fig. 1). The controller parameters k_p (3), k_i (4) and k_d (5) were determined empirically by several simulation runs without final optimization at different scenarios. Additionally, anti-windup with time constant T_t of 1 s and lowpass filtering of derivative with time constant T_f of 1 s was applied.

$$u(t)=k_p[c_{set}-c(t)]+k_i\int_0^t[c_{set}-c(\tau)]d\tau-k_d\frac{d}{dt}c(t) \quad (2)$$

$$k_p=3\frac{W}{K} \quad (3) \qquad k_i=0.25\frac{W}{Ks} \quad (4) \qquad k_d=0.4\frac{Ws}{K} \quad (5)$$

3. Results and discussion

3.1. Uncontrolled reference process

Fig. 2 shows the uncontrolled reference process. The beam power *u(t)* was kept constant over time and the laser beam was switched off after a joining time of 2 s. The surface temperature is increasing immediately after process start at t = 0 s, the interface temperature follows slightly delayed due to the thermal conductivity of the high-alloy steel. With higher thermal conductivities of the metal joining partner, for example with aluminum, delay and temperature difference between surface and interface would be reduced. The temperature difference between surface and interface is approx. 25 K and was relatively constant during the joining process. The joining temperature T_{em} was reached after 0.56 s, when PP would start to penetrate the surface structures on the metal joining partner to form a joint. With the start of cooling after 2 s, the temperatures quickly equalized, since the heat loss due to convection and thermal radiation acted on the surface, but no more energy was supplied by the laser beam. From approx. 1.75 seconds onwards, the degradation temperature of the polymer was exceeded at the interface, i.e. irreversible damage and bubble formation would occur.

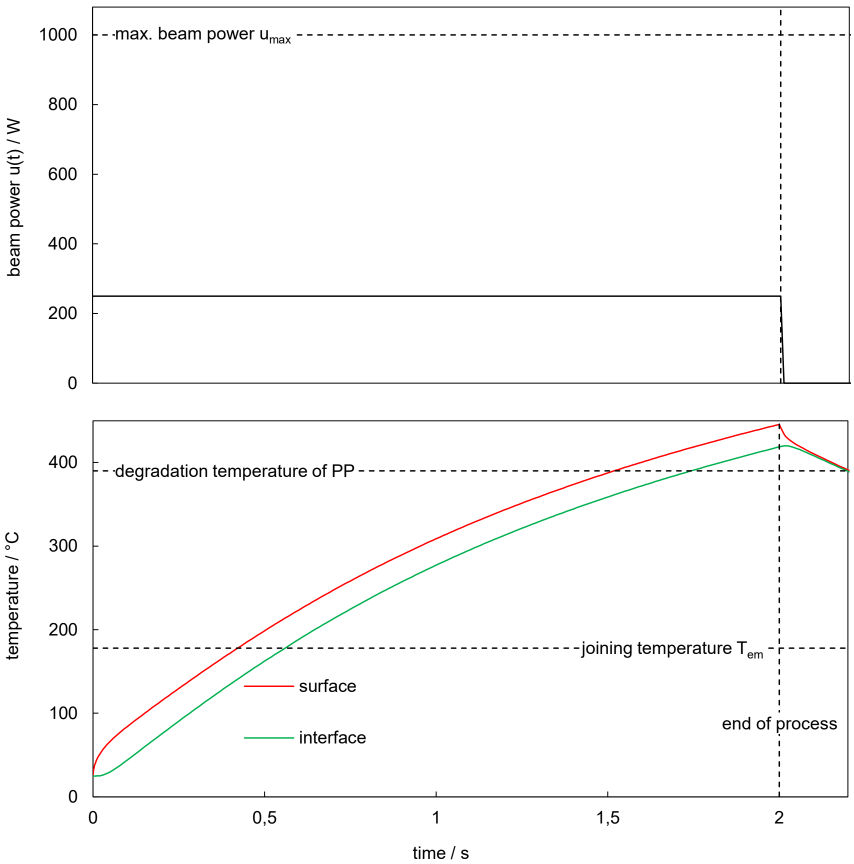

Fig. 2. Uncontrolled process without disturbance

In the following, the uncontrolled process is shown under the influence of an artificially introduced disturbance (Fig. 3). At time t = 1.5s, the disturbance term P_{dist} was activated, which followed a periodic course. This was also reflected in the temperature at domain probe 1 (surface) and domain probe 2 (interface). It is apparent that the resulting change in surface temperature had a delayed effect on the interfacial temperature due to heat conduction. Additionally, the amplitude of the fluctuating temperature was significantly lowered.

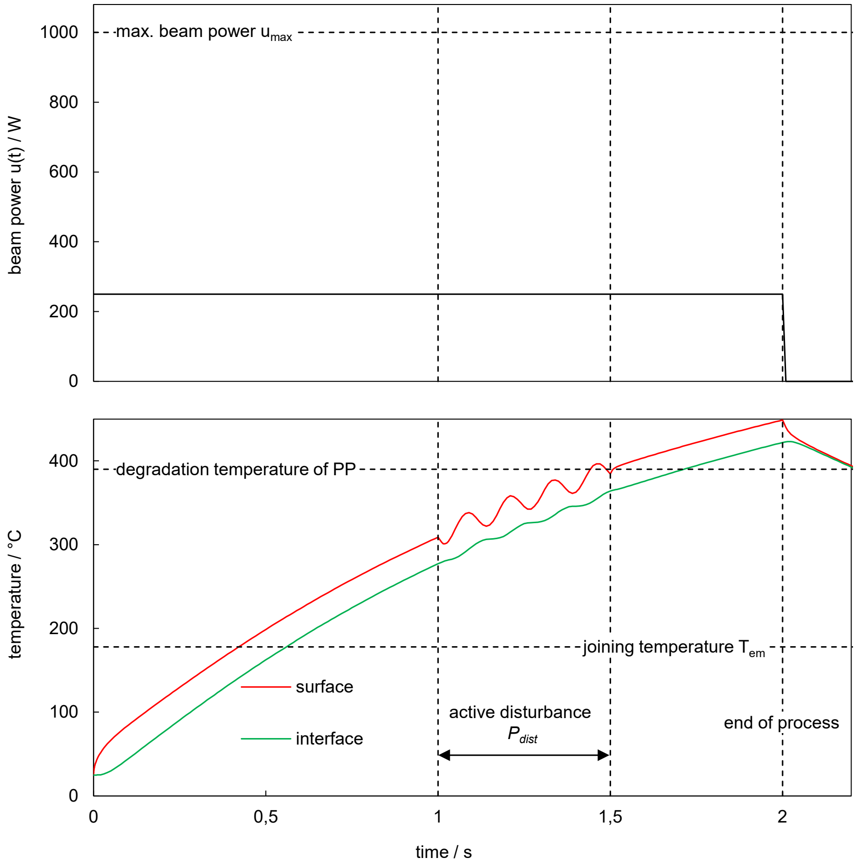

Fig. 3. Uncontrolled process with disturbance

3.2. Controlled process

For the following investigations, the power control was integrated into the model. In a first step, investigations were made without disturbance (Fig. 4). Compared to the uncontrolled process, a maximum laser beam power of 1000 W was applied at the process start and was reduced to approx. 120 W within 1 s. Therefore, the power control resulted in a much faster increased temperature at the surface and the interface. The joining temperature T_{em} was reached after 0.23 s, i.e. more than twice as fast as for the uncontrolled process. The reference value of 350 °C was reproduced very well and remained below by approx. 15 K. Compared to the uncontrolled process, it was thus possible to avoid decomposition of the polymer. Furthermore, it can be seen how a state of equilibrium was nearly reached with increasing joining time. The heat conduction losses within the joining partners were balanced by a laser beam power of approx. 120 W, because the temperatures at surface an interface remained almost constant.

The control also showed that shorter joining times were achieved by the controlled power output. It should be noted that the controller parameters k_p, k_i and k_d are decisive for this behavior.

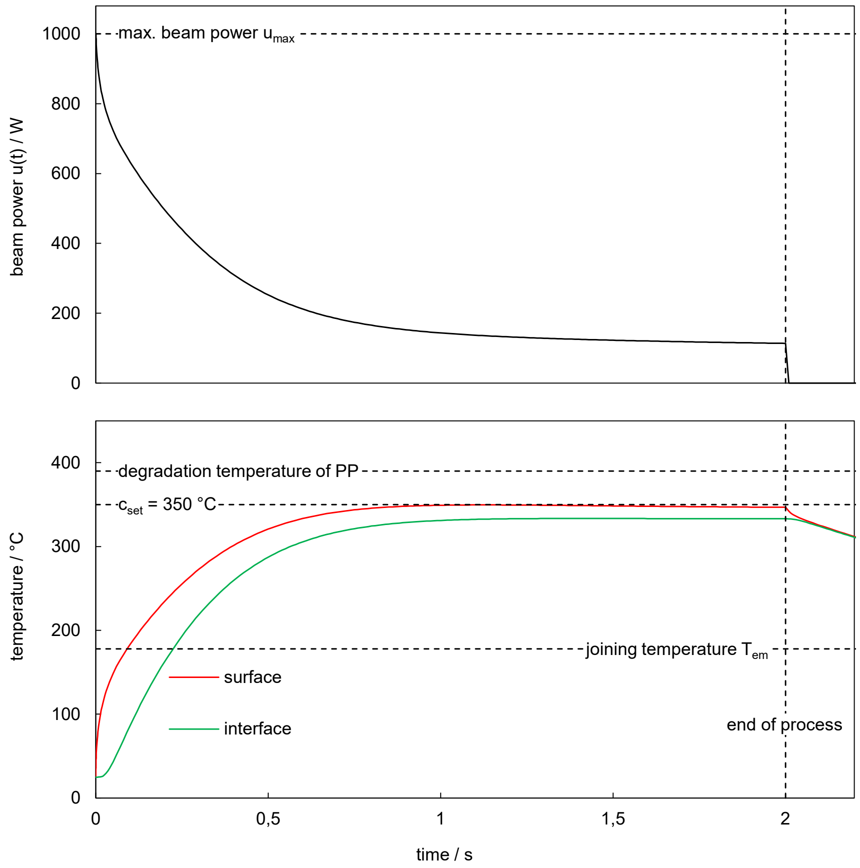

Fig. 4. Controlled process without disturbance

Considering a disturbance, the result is shown in Fig. 4. The process start was comparable, i.e., the changes occur with introducing the artificial disturbance P_{dist} after 1 s. It can be seen that the laser power was adapted to the changed surface temperature in short times. The adjusted power followed the periodic change of P_{dist}. This also resulted in the set temperature sometimes being exceeded by up to 10 K. However, by selecting a set temperature below the decomposition temperature, damage to the polymer could be avoided. In contrast, the changes at the interface temperature were delayed and significantly weakened due to heat conduction.

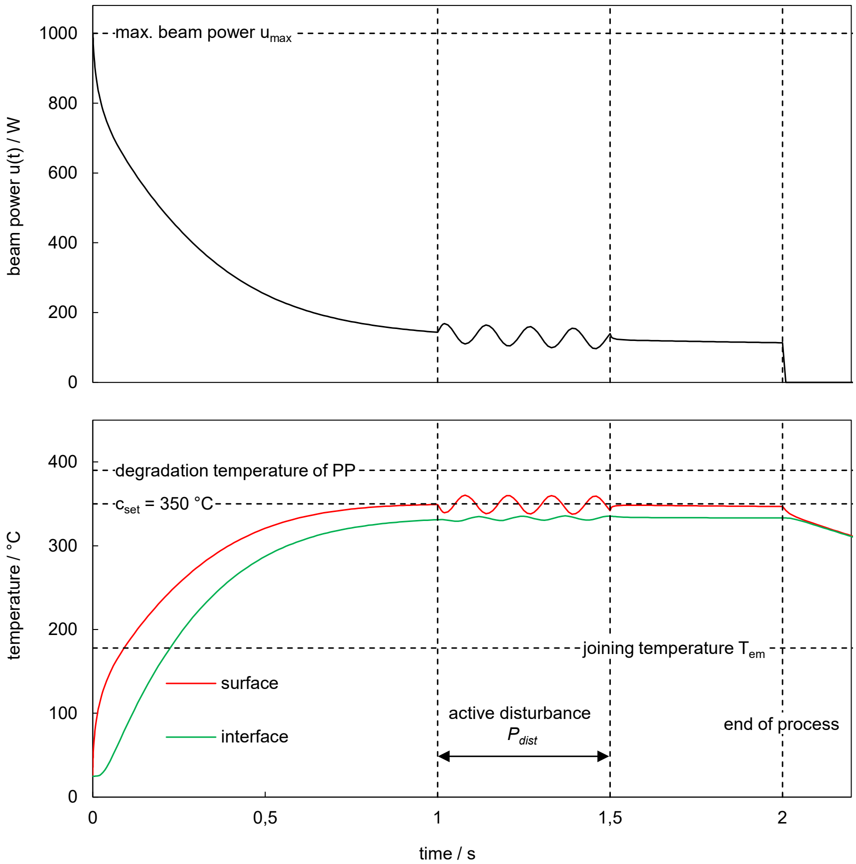

Fig. 5. Controlled process with disturbance

4. Summary and outlook

In this paper, the integration of a power control system for laser-based joining of metals with polymers was implemented based on a model for numerical simulations. The surface temperature was used as control variable to run the process above the processing temperature T_{em} and below the degradation temperature of PP. The comparison of surface to interface temperature showed that a sufficiently accurate representation was possible for the thickness considered and that the measurement of surface temperature is suitable for process control. In addition to avoiding decomposition and exceeding the joining temperature more quickly, it was shown that it is also possible to react promptly to disturbances. The simulation also provides a simple way to test and adjust k_p, k_i and k_d controller parameters. Based on the investigations carried out, the implementation of the control in the real process can be addressed and implemented in terms of system technology.

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