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Thermal welding of polymeric biomaterials: Development of a novel device for temperature controlled local application

Abstract: We present a thermal processing device, equipped for local heating and welding of biomaterials, e.g. electrospun nonwovens or polymer films. Depending on the application and choice of materials, we aim to determine appropriate processing parameters for permanent and non-permanent welds. Due to the modular device structure, application-specific heating tools can be used. Process temperature up to 250 °C is feasible.

In this concept study, a welding tool with interchangeable small-size heating tips of different geometric shapes were investigated regarding their suitability for welding of polycarbonate urethane based silicone elastomer nonwovens. Generated welds were examined by imaging techniques and tensile testing. Regardless of the tip shape, welds were generated withstanding forces up to 3.0 N and 4.3 N for tensile and shear loading, respectively.

Keywords: weld, biomaterial, nonwoven, polymer, implant

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1 Introduction

Welding techniques play an important role for implant manufacturing. The durability of implant designs highly depends on the quality and reliability of the required welds. To investigate and improve welding techniques, we developed a thermal processing device, enabling local heating of biomaterials, e.g. electrospun nonwovens or polymer films. The welding device is a modular stand-alone instrument consist-

ing of the control unit HC1 electrically connected to an application specific heating or welding tool, as shown in **Figure 1** and **Figure 2B**. For heating operation, display, switching and control elements are implemented. At temperatures from ambient up to 250 °C, integrated safety functions contribute to safe operation.

Three different geometries (triangle, square and circle) of small-size heating tips in **Figure 2A** were investigated regarding their suitability for welding of polycarbonate urethane based silicone elastomer (TSPCU) nonwovens. For comparison purposes, the heated surface areas were equal in size (9 mm²). Additionally, the circular tip with doubled area was compared. Materials, temperature, thermal exposure time and contact pressure were not varied. A micro-structured base plate was used to combine welding with micro-embossing of the welding spot, expecting an increase in tensile strength due to an increase of the effective surface area. Generated welds were examined by light as well as scanning electron microscopy (SEM) before and afterwards tensile testing.

2 Material and methods

2.1 Heating control HC1

The heating control unit HC1 was designed for active heating and passive cooling, limiting the range of application to user selectable temperatures above ambient. A split screen displays set point and process temperature, type of heating tool, the elapsed thermal exposure time, as well as error messages.

The HC1 operating system is controlled by an Arduino Uno Rev3 microprocessor (Arduino LLC, USA), implemented on our standardized development platform mounted in a small-size metal case. The thermal control system consists of the temperature measurement, a software based PID algorithm, a solid-state relay (SSR), and a heating element, as illustrated in **Figure 1**. The output of the PID controller is a pulse width signal (PWM) that modulates the

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power supply to yield precise temperature up to 250 °C, supporting full compatibility to 24 V heating elements up to 100 W.

Heating tools were equipped with a PT100 platinum resistance temperature detector (RTD). For high stability and total temperature accuracy better than ± 2 °C the PT100 is 3-wire electrically connected to a RTD-to-digital converter MAX31865 (Maxim Integrated Products, Inc., USA). The temperature sampling period is 200 ms. According to the manufacturer's specifications, the total accuracy over all operating conditions is better than 2 °C based on ± 0.5 °C [1] and ± 0.65 °C of RTD converter and PT100 (class A) accuracies, respectively. Gain and offset calibration were established in the HC1 firmware to compensate thermal error values for connected heating tools, individually.

Figure 1: Simplified block diagram of the thermal heating device. Heating tool (left) connected to control unit HC1 (right). Temperatures: SV = set point value (desired PV). PV = process value.

2.2 Heating tool

Various heating tools were designed as plates and tips for application-specific surface or local material heating. Thus, heating control parameters range widely for the variety of tools due to different thermal conductivities, heat capacities and convection effects. To achieve optimal performance, PID heating parameters were individually determined by manual loop tuning. Automatic tool identification ensures correct parameter setting while operating. Safety functions were also implemented to provide safe operation conditions, e.g. switching off heating due to a non-use timeout or a missing heating tool.

The exemplary described welding experiments on TSPCU nonwovens were performed with a heating tool equipped with interchangeable aluminum heating tips, shown in **Figure 2A**. The heating tool was mounted on a self-built lever stand (**Figure 2B**) for manual pressing the welding tip on the materials to be welded. The heating element is a small-size 35 W heater cartridge (3d Solex, USA).

Figure 2: Thermal welding device

A: Illustration of heating area (red colored) and photo of the interchangeable aluminum heating tips (shape: equilateral triangle, square, circle). The circular tip (circle I, third from left) is exemplary equipped with the PTFE mounting cover. **B:** Heating tool (left) connected to the heating control unit HC1 (right). Close-up view of the heating tip (blue framed).

2.3 Thermal welding

2.3.1 Differential scanning calorimetry

The differential scanning calorimetry (DSC) was used to determine thermal material properties, for estimating suitable heating temperatures. Thermal DSC analyses were performed by using a DSC 1 instrument (Mettler Toledo, USA). The DSC 1 was equipped with a MultiSTAR DSC ceramic sensor FRS5 (Mettler Toledo).

2.3.2 Sample preparation

Defined tensile specimens with standard specimen geometry 1BA (**Figure 3A** and **Figure 5**) according to DIN EN ISO 527 made of TSPCU nonwovens were provided by means of laser cutting [2]. Two specimens were required for one welding sample. The thickness of the nonwovens was between 80 and 140 μm . The 1BA specimen width of reduced section was 5 mm, matching dimensions of the heating tips in **Figure 2A**.

2.3.3 Welding process

Ten samples were produced for each of the four heating tip shapes in **Figure 2A**. After visual quality check, all 40 welded samples were used for tensile testing. A sample consisted of two tensile specimens welded together, congruently positioned to each other, as illustrated in **Figure 3A** and **Figure 5**. The welding spot was placed centered in the reduced section of the specimens, as shown in

Figure 5B. Based on DSC results, we chose a heating temperature of 90 °C, which is in between the melting points of the silicone and polycarbonate urethane blocks of the TSPCU. Thus, a weld can be created, while the polycarbonate urethane backbone remains intact. In preliminary tests, good results were achieved using a short heating exposure time of 2 - 3 s.

The micro-structured base plate (material: polyetheretherketone PEEK) was not heated. The circular groove structure with a profile depth of 30 µm, measured with an OLS5000 3D laser microscope (Olympus, Japan), was used to combine welding with micro-embossing. Embossing is effected by pressing the material between heated tip and the structured base plate, resulting in visible grooves similar to fingerprints, as shown in **Figure 4B**.

3 Results

3.1 Heat transfer

Welding is based on a suitable heat transfer into the material. To characterize the dynamic thermal process small-size PFA-insulated thermocouples (5TC-TT-KI-36-1M, Omega Engineering Inc., USA, Type K) with a diameter less than 0.4 mm were used. Thermocouple T1 was mounted at the end of the heating tip to monitor process temperature, as illustrated in **Figure 3A**. Thermocouples T2 - T4 measured the temperature profile above, inside and below the TSPCU nonwoven sample, respectively. Thermocouple T5 monitored the ambient temperature. The used thermocouples meet the EN 60584-2 tolerance class 1 resulting in a tolerance value of ± 1.5 °C within the required process temperature range. Thermocouple measurements were performed by using the 8ch data acquisition module OM-USB-TC (Omega Engineering Inc., USA, accuracy: ± 0.35 °C) and software TracerDAQ (Omega) for data logging, viewing, and analysis.

Figure 3: Heat transfer during thermal welding

A: Schematic illustration of test setup for measuring the temperature profile with thermocouples at the heating tip (temperature T1), in the individual layers (T2-T4) of the TSPCU nonwovens sample and at ambient air (T5). **B:** Time-temperature diagram for welding measured with thermocouples T1-T5. Desired process

temperature at heating tip 90 °C (T1). Heating tip: circle I (9 mm²). The heat transfer curves (**Figure 3B**), according to the measuring setup in **Figure 3A**, show a sharp increase of temperature during the welding process above, inside and below the TSPCU nonwoven sample, respectively. In the exposure time the desired process temperature of 90 °C was only achieved above the material sample due to the heat sink effect of the unheated base plate. Ambient as well as heating tip temperatures remained stable.

3.2 Imaging techniques

Generated welds were examined by light microscopy and SEM before and afterwards tensile testing, see **Figure 4**.

Micro-embossing effected grooves are visible in **Figure 4B** on the bottom side of the sample, due to the micro-structured base plate. **Figures 4C** and **Figure 4D** show the transition line between unaffected and welded area on both sides of the sample. Fibers in direct contact with the heating tip were melted together and no longer recognizable as individual fibers, as shown in **Figure 4C**. In contrast, individual fibers are still visible in the welding spot of the bottom side, due to the lower temperature in this layer, as determined in **Figure 3**.

Figure 4: Thermal welding (90 °C) of TSPCU nonwovens Exemplary welding results by using a square heating tip (9 mm²). **A, C:** Top side. **B, D:** Bottom side. Mirrored image. **A, B left:** Light microscopic view. Area of close-up view in **C, D** was marked with blue and orange frames, respectively. **A, B right:** Superimposed SEM view. **C, D:** Close-up SEM view of the transition line (unaffected to welded).

3.3 Tensile testing

Uniaxial tensile testing was performed with a Zwick material testing machine BZ2.5/TN1S (Zwick, Germany), as shown in **Figure 5**. Tests were conducted with a 10 N load cell and a crosshead speed of 25 mm/min at room temperature. The tensile force as a function of elongation was measured, while the force at break was compared. Regardless of the tip shape, welds were generated withstanding forces up to 3.0 N and 4.3 N for tension and shear loading (**Table 1**), respectively.

The observed failure cases were different. The welded joint detached in only 15 % of all tests. In 70 % of the tests under tension load, the entire welding spot tore out. On the other hand, under shear load, the material ruptured distant of the welding spot in 85 %.

Figure 5: Tensile testing of welded TSPCU nonwovens. Schematic illustration and photo of sample fixation for tension (**A**) and shear (**B**) loading. Welding spot marked in orange. F = tensile force.

Table 1: Tensile testing results on welded samples (n = 5) from four different heating tip shapes.

tip shape	area	max. tension load	max. shear load
triangle	9 mm ²	2.1 - 3.0 N	2.1 - 4.1 N
square	9 mm ²	1.6 - 2.6 N	3.0 - 4.3 N
circle I	9 mm ²	1.6 - 2.3 N	2.8 - 4.3 N
circle II	18 mm ²	2.5 - 4.3 N	3.1 - 5.0 N

4 Conclusion

Depending on application and choice of materials, we aim to determine appropriate processing parameters and heating tools for permanent and non-permanent welds. Tensile tests

have shown that the thermal processing device is suitable for creating firm welds just by heated contact. However, welding results highly depend on user skills, due to the simple manual pressing tool principle, as illustrated in **Figure 3A**. To increase reproducibility, the influence of the user must be minimized by improved contact pressure techniques. All presented welding results are based on heating processing using a combination of welding and micro-embossing. Created welding spots without embossing were not considered, as preliminary tests already showed the inferior effect on tensile strength. Based on the comparable results for all tip shapes in **Table 1**, round shape (circle I and circle II) is preferred because of the considerably simpler manufacturing. Doubling the welding spot area of circle I nearly doubled the force required to tear, expecting positive effects regarding material fatigue and the reliability of required welds for implant designs.

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