

# Microwave welding of polymers

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**Abstract.** The growing demand for fast, efficient and environmentally friendly polymer joining techniques has intensified research on microwave welding methods. However, there remains a knowledge gap regarding the influence of susceptor composition, welded material properties, field strength and welding duration on joint strength, which limits the optimization of this technology for industrial applications. In this study, we investigate the effects of several susceptor types – polypropylene (PP) supplemented with 75% graphite admixtures, polylactic acid (PLA) with 20% of carbon, polyethylene terephthalate glycol (PET-G) with tungsten, PLA with 45% of iron and PET-G with magnetite, and such thermoplastics as PET-G, PLA and PP on the mechanical strength of welded joints. The microwave welding process is conducted using dielectric heating at the frequency of 2.45 GHz. The results demonstrate that the interaction effects between susceptor type and welded material are found to be significant, highlighting the necessity of multivariate optimization rather than single-factor tuning. This work provides practical insights into the development of reliable, energy-efficient, and scalable polymer joining processes. The presented findings contribute to advancing microwave welding techniques and can serve as a foundation for further industrial applications.

## 1 Introduction

The shift toward lightweight, corrosion-resistant, and easily manufacturable heat exchangers has made polymeric materials an attractive alternative to metals in low- to medium-temperature energy systems. Among the most promising designs are hollow fiber-based polymeric heat exchangers, which can offer exceptionally high surface-to-volume ratios and structural flexibility. However, the practical implementation of such devices remains severely constrained by the challenge of joining thin-walled polymer microstructures in a reliable and scalable way [1].

Conventional welding techniques such as hot plate welding, ultrasonic welding, or resistance heating have significant drawbacks when applied to these geometries. Issues like uncontrolled thermal spread, mechanical stress, and poor energy penetration make them unsuitable for producing uniform, hermetically sealed joints across multiple fiber layers [2]. This bottleneck has prevented the broader adoption of polymer heat exchangers in commercial and industrial applications.

One way to overcome these limitations is microwave welding which uses suitable susceptors to join the desired parts of the polymer heat exchanger. Microwave welding allows not only local weld formation but also welding within the material without the need for direct contact with an external heating

element [3-4]. The heat required to form the joint is generated directly in the material by the conversion of absorbed electromagnetic energy.

In order to determine a suitable material for welding, it is necessary to know its dielectric properties [5-7], in particular its complex permittivity  $\epsilon^*$  (eq. 1) and permeability  $\mu^*$  (eq. 2)

$$\epsilon^* = \epsilon' - j\epsilon'', \quad (1)$$

$$\mu^* = \mu' - j\mu''. \quad (2)$$

where  $\epsilon'$  and  $\mu'$  represent the real components of permittivity and permeability, which express the ability of the material to accumulate electromagnetic energy. On the other hand,  $\epsilon''$  and  $\mu''$ , their lossy components, which indicate the rate of this energy conversion to heat. The electric polarization is associated with permittivity, while the magnetic polarization is associated with permeability.

Our ongoing study focuses on two key areas: the selection and characterization of commercially available polymer materials suitable for welding, and the selection of materials for the susceptor that will enable a high quality and reliable joint between the parts to be welded.

This paper presents the conceptual motivation, experimental procedure and preliminary results of the proposed welding approach. It highlights the interdisciplinary nature of the solution, which combines materials engineering, microwave engineering and

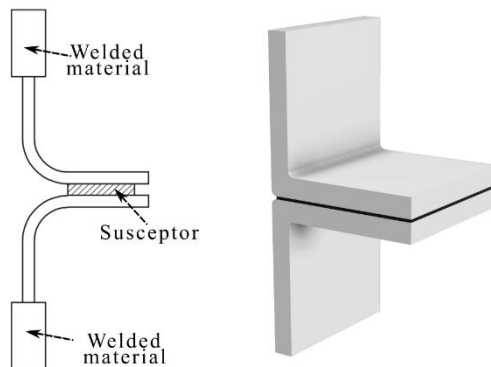
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thermofluid dynamics to create a functional technology for a new generation of polymer heat exchangers.

## 2 Principle of welding

From the perspective of microwave interaction, materials can be classified into three main categories according to their response to electromagnetic fields. The first category comprises transparent materials with low dielectric losses, which allow microwaves to propagate through them with minimal attenuation. The second category includes reflective materials, typically electrical conductors, which reflect most of the incident microwave energy and prevent field penetration. The third category consists of absorbing materials with high dielectric loss, capable of converting microwave energy into heat to varying degrees depending on their dielectric loss factor [8].

The basic concept of microwave polymer welding is that most thermoplastic polymers are microwave-transparent due to their low dielectric losses. As a result, they do not directly absorb microwave energy and therefore remain unaffected by the electromagnetic field [9-10]. As shown in Figure 1, the microwave absorbing material - susceptor (black layer) is positioned between two polymer components (gray blocks). When microwaves interact with this assembly, the susceptor becomes the only region of significant energy absorption.



**Fig. 1.** Schematic representation of localized microwave heating in a polymer-susceptor-polymer assembly [11].

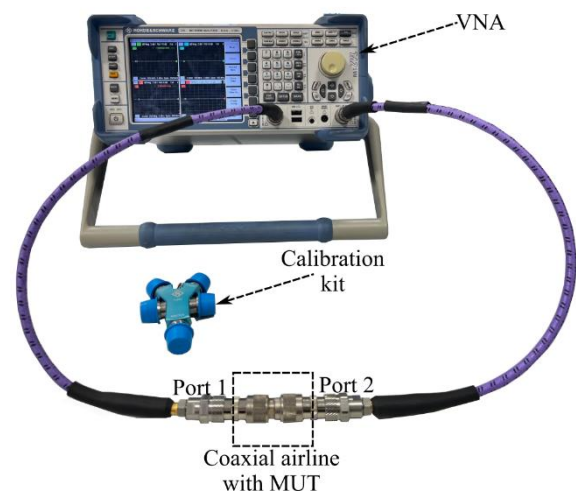
The localized heat causes the polymer surfaces in direct contact with the susceptor to melt. Once the desired fusion temperature is reached, the molten polymer chains from both sides interdiffuse across the interface, forming a strong molecular bond upon cooling.

## 3 Experiments and results

This chapter focuses on the selection of materials suitable for welding and on the susceptor, which is a key element for the proper creation of a joint in microwave equipment. The principle of testing will conclude with verification of the strength of the resulting joint.

### 3.1 Materials and Susceptors Validation

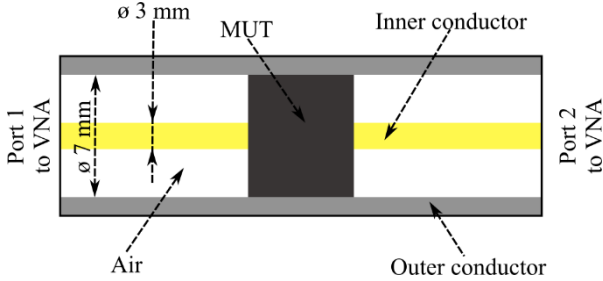
The materials intended for welding are commercially available thermoplastic polymers: polyethylene terephthalate glycol, polylactic acid and polypropylene. It is necessary to determine the absorption properties of these materials, with the aim of verifying that their dielectric losses are close to zero. To determine dielectric losses, measurements were taken in a coaxial airline on a vector network analyzer (VNA) ZVL, from which S-parameters were obtained for frequencies ranging from 2.35GHz to 2.55 GHz. The most important S-parameters are at the frequency of 2.45 GHz, because the magnetron operates at this frequency. The frequency step on the VNA was set to 400 kHz and IF bandwidth was set to 100 Hz to ensure sufficient dynamic range of our measuring equipment. To eliminate systematic errors, a two-port calibration [12] of the measuring assembly was performed. The measurement set-up is shown at Fig. 2.



**Fig. 2.** Measuring set with calibration kit and coaxial airline containing material under test (MUT).

Based on these S-parameters, the complex values of permittivity and permeability were determined using the Nicholson-Ross-Weir (NRW) method [13]. The imaginary parts of these parameters express losses in the material. When using this method, it is necessary to avoid errors that could distort the results. These are most often errors caused by the placement of the measured sample in the coaxial airline and the lack of tightness throughout the entire volume on the outer and inner conductors of the coaxial airline. The measured samples or material under test (MUT) are cylindrical-shaped with an outer diameter of 7 mm and an inner diameter

of 3 mm. The MUTs consisting of PET-G or PLA were printed on a 3D printer with 100% fill. The MUT formed by PP was molded by injection molding method and then the desired cylinder was cut out. The principle of NRW and the positioning of the measured sample is shown in Fig. 3.



**Fig. 3.** Principle of NRW and positioning of the sample in the coaxial airline.

The measurement results for individual types of materials (transparent versus pigmented) are shown in Table 1. Since these materials do not contain magnetic additives, it can be assumed that their relative permeability is equal to one. At the same time, it can be stated that pigmented materials exhibit slightly higher losses than transparent materials.

**Table 1.** Permittivity and permeability of samples.

Type	Colour	$\epsilon^*$		$\mu^*$		Manufacturer
		$\epsilon'$	$\epsilon''$	$\mu'$	$\mu''$	
PLA	Crystal clear	2.45	0.059	$\mu^* = 1$		Fillamentum
PLA	Grey	2.46	0.09	$\mu^* = 1$		DevilDesign
PP	Clear	2.21	0.51	$\mu^* = 1$		-
PP	Beige	2.24	0.031	$\mu^* = 1$		-
PET-G	Transp	2.58	0.11	$\mu^* = 1$		Prusa Research
PET-G	Black	2.78	0.12	$\mu^* = 1$		DevilDesign

On the contrary, a susceptor should have good absorption properties and convert absorbed microwave energy into thermal energy, i.e., it exhibits higher dielectric losses. Commercially available composite materials were selected for the production of susceptors. The same measurement principle and VNA setting as described in the previous section were used to estimate their dielectric properties.

The selected materials for susceptors, together with their basic properties, are listed in Table 2. Susceptors with carbon admixtures appear to be the most suitable candidates.

**Table 2.** Permittivity and permeability of susceptors.

Type	Filling	$\epsilon^*$		$\mu^*$		Manufacturer
		$\epsilon'$	$\epsilon''$	$\mu'$	$\mu''$	
PLA conduct	Carbon 20%	14.3	12.4	$\mu^* = 1$		Protospasta
PLA iron	45%	3.66	0.13	1.03	0.2	Protospasta
PP graphite foil	75%	55.5	13.6	$\mu^* = 1$		-
PP graphite foil	50%	29.8	5.86	$\mu^* = 1$		-
PET-G tungsten	75%	4.99	0.2	$\mu^* = 1$		Prusa Research
PET-G magnetite	40%	4.06	0.16	0.08	1.2	Prusa Research

The following appear to be suitable candidates for welding: for PET-G and PP susceptors – PP graphite foil 75% and for PLA susceptor – PLA conductive. The following section describes the experimental setup for welding, presents the results of welded materials, and measures the strength of the resulting welds.

### 3.2 Experimental Setup and Validation of Welds

Welding tests were performed using a standard household microwave oven, shown in Fig. 4, with a total power consumption of 1050 W, of which the microwave power is 700 W. The magnetron of this device operates at the frequency of 2.45 GHz.



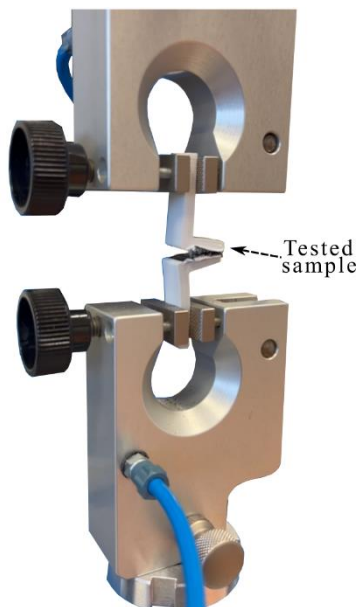
**Fig. 4.** Chamber of household microwave.

The test samples were placed in a specially designed spring-loaded pressing device made from ABS polymer (Fig. 5), which ensured uniform pressure across the entire surface of the joint. The entire assembly was placed in the center of a microwave chamber. The samples were then exposed to microwave radiation, which created a joint at a predetermined location.



**Fig. 5.** Photo of spring-loaded pressing device.

After the samples cooled, they were tested for tensile strength using a calibrated force gauge. Figure 6. shows the device used for tensile strength testing together with the test sample.



**Fig. 6.** Tensile strength testing machine with a sample.

Table 3. shows the results of the tensile strength tests performed. The results appear to be acceptable, especially for PLA polymer, which showed excellent bond strength. The tests confirm that microwave heating has great potential for microwave welding of polymer parts, except that PET-G susceptors with metallic admixtures require a longer exposure time to the microwave field to heat up sufficiently. During this time, however, the welding material itself starts to heat up, leading to premature degradation. For this reason, these selected types of susceptors appear to be unsuitable for application.

**Table 3.** Resulting force loads of tested

samples. Material	Susceptor	Resulting force [N·cm <sup>-1</sup> ]
PET-G	PP graphite foil	129.8
PP	PP graphite foil	186.5
PP	Conductive PLA foil	Not welded
PLA	Conductive PLA foil	545.315

## 4 Conclusion

The results demonstrate that the effectiveness of microwave welding strongly depends on both the type of susceptor and the polymer matrix used. In all tested configurations, localized heating occurred exclusively at the polymer–susceptor interface, confirming that the energy absorption was governed primarily by the dielectric losses of the susceptor material rather than the bulk polymer.

A significant observation was the interaction between susceptor type and polymer substrate. Among the tested susceptors, the conductive PLA film exhibited the most controlled and reproducible heating behavior. Its composite structure enabled uniform heat generation and effective thermal coupling with PLA substrates, producing consistent welds with satisfactory mechanical strength.

The graphite-filled polypropylene (75 wt%) film demonstrated unstable behavior and unreproducible results, offering sufficient absorption but limited heat transfer.

For polypropylene, the desired welded joint was not achieved with any of the tested graphite-filled films. Instead of gradual heating, degradation and charring of the material surface occurred. This suggests that the graphite additive content of the susceptors used is too high. At these filling ratios, the foil did not perform well as a susceptor.

Overall, the results highlight the importance of balancing susceptor efficiency and polymer thermal stability. Excessive energy absorption may lead to rapid local overheating and degradation, while insufficient absorption results in incomplete fusion. Therefore, future optimization should focus on fine-tuning susceptor composition, and microwave power output, as well as implementing active temperature monitoring or feedback control to prevent runaway heating and combustion.

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