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Microwave Welding: A Comparative Analysis with Contemporary Methods of Welding Thermoplastic Based on Prioritization Matrix

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Abstract— Thermoplastics are groups of materials characterized by large molecules that built up by the joining of smaller molecules. They do not have a specific melting temperature. Hence welding of thermoplastics has become a difficult problem. A number of methods right from utilization of conventional heat sources to radiant energy heat sources has developed for welding of thermoplastics. However not a single method can be used in all the cases. The aim of the present paper is to study, analyze and discuss the characteristics of the existing processes in order to establish suitability of the process. In addition, the paper tries to search out the characteristics, needs and the suitability of the future process microwave welding.

Keywords— Conventional, contemporary method, microwave, prioritization matrix,radiant energy, thermoplastic ,welding.

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1 INTRODUCTION

THERMOPLASTIC assemblies are being done either by mechanical fastening, adhesive bonding, or by welding. Each of these methods has its own advantages and disadvantages. Mechanical fastening can join two components quickly by metallic or polymeric screws, or by integrating design elements that moulded into the parts such as snap-fit or press-fit joints. However, these joints have certain disadvantages like it do not provide leak proof joint. In addition, the localized stress may cause them to pull free of the polymeric material. In adhesive joining, adhesive applied between the adjacent parts to join them. By this method fully sound and good quality joints can be made, however joint preparation, joint strength and surface cleanliness need to be given due importance. Welding is use to produce bonded joints with mechanical properties approaching to that of parent materials. Heat is use to melt or soften the material at the interface, which allows intermolecular diffusion across the interface followed by chain entanglement resulting in higher joint strength. The limitation of welding of plastics is that the process is confine to thermoplastics only, as thermosetting polymers are difficult to weld without the addition of thermoplastic layers. Two types of heating methods are employed in the welding of plastics, they are external and internal heating.

Internal heating can further be subdivided into two categories- internal mechanical heating, and internal electromagnetic heating. Internal mechanical heating, depends on the conversion of mechanical energy into heat through surface friction and intermolecular friction. The process that employed internal heating includes- ultrasonic welding, vibration and spin welding. Whereas, internal electromagnetic heating methods rely on the absorption and conversion of electromagnetic radiation into heat and the method includes- infrared, laser, radiofrequency and microwave welding.

External heating methods rely on convection and/or conduction to heat the weld surface. The process includes- heated tool, hot gas, extrusion, induction and resistance welding.

The present work makes a comparative analysis of microwave welding of thermoplastic with contemporary methods using prioritization matrix.

2 FUNDAMENTALS OF THERMOPLASTIC WELDING

Thermoplastics' welding is fusion process. It consists of five steps: surface penetration, heating, pressing, intermolecular diffusion & cooling.

In case of thermoplastic welding of similar materials, when interfaces are brought to molten state they conform to each other with time followed by diffusion of molecules and chain entanglement. Many parameters like- material properties, interface pressure, temperature, etc. influence the quality of weld thus produce. According to DeGennes, P.G. [3] and Wool, R. [4], the reptilian motion can approximate the motion of the polymer molecules. These investigators considered some fundamental assumptions, as the interfaces are in full intimate contact and at a relatively constant temperature. However, investigators Grewell, D. et al. [1] found that these assumptions are not true in most of the applications. They found, even with surfaces that are

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relatively smooth, the asperity peaks prevent full intimate contact and welding occurs only after the squeeze flow of theses asperity peaks. During the process of welding, these peaks get soften and they flow to fill the interstitial spaces.

3 THERMOPLASTIC WELDING METHODS

In industries, thermoplastics are welded by using methods like Ultrasonic welding; Vibration welding; Radiofrequency welding; Hot plate welding and Laser welding.

3.1 Ultrasonic Welding-

This is a technique of fusion bonding of thermoplastics. The method uses mechanical vibration to form joints. The parts to be assembled are held together under pressure between the oscillating horn and an immobile anvil. This assembly is then subjected to low amplitude (1to250µm) and high frequency (10 to70KHz) ultrasonic vibrations at right angles to the contact area. Alternating high frequency stress results in cyclic deformation of the parts at the faying surfaces and surface asperities. This cyclical energy is converted into heat through intermolecular friction within the thermoplastic. The heat which is highest at the surface (because asperities are straining more than the bulk) is sufficient to melt the thermoplastic and to fuse the parts. (Fig.1A.) Sometimes man made asperity (artificial asperity) in the form of a triangular protrusion is moulded into one of the parts to improve the consistency of heating and welding (Fig.1B) [11] .

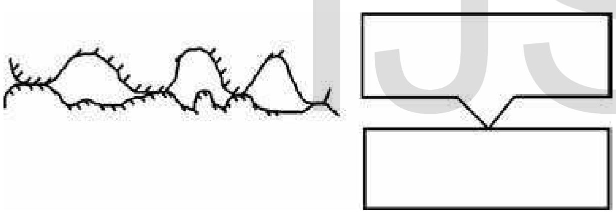

Fig. 1: Ultrasonic heating through cyclic deformation of (A) Surface asperities; (B) Man made energy director. (Ref- 11)

This protrusion, which is also known as an energy director or concentrator, experiences the highest levels of cyclic strain, producing the greatest level of heating. Hence the energy director melts and flows to join the parts.

The tools and equipment's of Ultrasonic welding are quite expensive but the welding time is quite short (<1 Sec), therefore they are used for mass manufacturing. Also it is a flexible technique therefore it is also used for small lot size production. The process is applicable to both amorphous and semi crystalline thermoplastics. It can also be used to bond dissimilar materials [12]. Due to these advantages, ultrasonic welding is one of the most common methods used in industry to join plastics.

However, ultrasonic welding is limited to small components with weld length not exceeding few centimetres as the weld size depends on horn size. In addition to these limitations, the process and tools must be adapted to the material to be welded. Amorphous materials tend to less attenuate the electronic energy as compared to crystalline materials, thus they are typically easier to weld. This type of welding is usually divided into two major groups: near field and far field welding. In industries, which are based on the most extensively used 20 KHz welding systems, considers applications where the distance between the horn or part interface and the weld interface is less than 6mm as near field welding. Far fielding ultrasonic welding is used to describe applications where the distance is greater than 6mm.Some of the process parameters of ultrasonic welding is shown in Fig. (2):

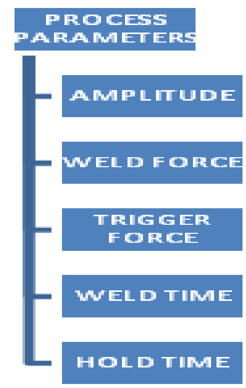

Fig. 2: Process parameter of Ultrasonic Welding

3.2 Vibration Welding-

In case of vibration welding, due to rubbing of two parts, under pressure along their common interface, heat is generated. The generated heat is sufficient to melt the interfacing material and weld [8],[9.] . Most industrial machines available operate at fixed weld frequencies of 120Hz & 240Hz. The amplitude of vibration is normally less than 5mm, and the weld time varies between 1 to 10seconds. The rubbing vibratory motion is normally produced by exciting a tuned spring mass system. At higher frequency welds can be achieved at amplitudes as low as 0.32mm, which can be important when a part has to be welded into a recessed cavity, where sufficient clearances may not be available for large amplitude vibration.

During vibration welding, the externally imposed interfacial weld pressure causes the molten interface film to flow laterally outward, thereby resulting the two parts coming closer. The decrease in distance between two parts caused by this lateral outflow, known as weld penetration, is useful for understanding the phenomenon of vibration welding. The complete welding process consists of four phases: solid friction, transient flow, steady state flow, and re-solidification.

In the first phase, heat is generated by solid interfacial frictional heating up to the melting temperature. The second phase is the transition phase, in which the energy supply is converted into heat by means of shearing and where solid frictional heating is replaced by viscous heating. During this phase the thickness of the melt layer increases until the third phase, known as steady state phase is reached. In this phase the thermal state of equilibrium between the supply of heat by shearing and supply of heat by the outflow of the melt is maintained. The final phase is the re-solidification phase where the melt is allowed to solidify under welding pressure. [8],[9.] , [21].

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The speed of operation (typically less than 10sec. cycle time), ability to weld internal walls and ability to weld relative large components are some of the advantages of the process. Limitations often associated with vibration welding processes, particularly for large systems, are- capital investment for equipment and tooling. In addition some materials such as polycarbonate (PC) can generate dust like particulates that can create problems in some applications.

Vibration welding finds its application in welding thermoplastics intake manifolds for the automotive industry. It is also used for larger (V-8) engine manufacturing. Other applications are ranging from household goods (washing machine parts, base plates of tumble driers, door reinforcement) to the automotive industry (spoilers , instrument panels, glove boxes, motor covers, servo oil reservoirs, filters , suction pipes). Some of the key parameters of vibration welding are shown in Fig. (3).

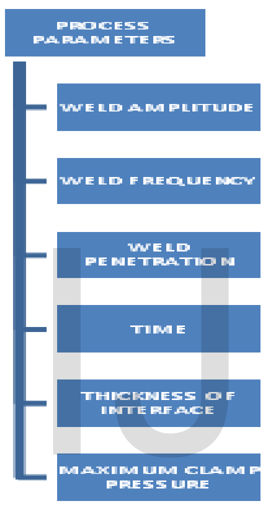

Fig. 3: Process parameters of Vibration Welding.

3.3 Radiofrequency Welding-

This is a very mature technology of welding thermoplastics that has been developed around 1940s. "Dielectric Welding" is the other name of it, as the process depends on internal heat generation by dielectric hysteresis losses in thermoplastics with polar side groups. It is used for fusing together polar plastics like PVC and PU. When the electric field changes rapidly these polar groups try to orient themselves in the field which results in intermolecular friction and heat generation. This is a very fast and consistent method of welding. It also does not require any especial joint designs and produces welds that are relatively cosmetically appealing. [1]

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The limitation of the process is the technique of weld generation which requires strong electric field. This strong field can be generated only when the welding electrodes are brought together in close proximity of 0.03-1.27mm. Another limitation of the process is the materials being joined must have good electrical properties. Apart from this it is required that the material must have relatively high dielectric loss as power dissipation within the plastic material increases as the frequency of the applied field increases. Therefore most of the RF machines today in practice are standardized at a frequency of 27.12MHz, to minimize electromagnetic interference.

RF welding is most exclusively used for welding thin sheets or films. It is used to weld PVC bladders, such as intravenous drip bags in the medical industry. It is also used for welding of books and binding covers. Common applications include making of blister packs for packaging and medical appliances. Some of the process variables are shown in Fig. (4):

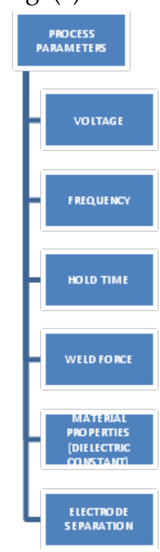

Figure 4: Process parameters of Radio Frequency Welding.

3.4 Hot Plate Welding-

This is one of the most common and highly reliable welding methods in the world of thermoplastic industries. Complex interfaces can be joined by this type of welding. In this welding process, the faying surfaces to be joined are brought together in contact with the hot plate. Initially in the matching phase with the application of pressure, there is a squeeze flow of well-defined faying surfaces and irregularities of all parts are removed. This pressure is removed, by pressure regulators when sufficient matching displacement is achieved, so that a thick melt layer is developed. The heating time is pre-selected and the parts are retracted and taken away from the tool. The parts are then brought together so that the two molten interfaces weld to each other. During the cooling phase, the amount of displacement may be limited to prevent the excess material to squeeze out, leaving a cold weld.

There are two types of hot plate welding; high temperature contact hot plate welding and non-contact hot plate welding. Applications of this type of welding are associated with gas line installations, pipe welding for a drainage system, for saddle Tee joints. Batteries are often assembled by this type of welding and it is also applicable in fuel tank assemblies for automotive industries. The major limitation to hot plate welding is the longest cycle time. [6]. Some of the key parameters of this type of welding are shown in Fig. (5):

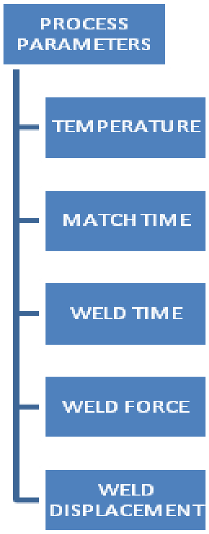

Figure 5: Process parameters of Hot Plate Welding.

3.5 Laser Welding-

Application of laser lights for welding of plastics has been reported far back in 70's but it was not popular as the technique was extremely expensive at that time. The current laser units are considerably cheaper; hence this process is in use for cutting a wide range of materials and welding of metals. Laser welding is a versatile process, suitable for both small and mass production. Moreover it can be used for micro components as well as large products.

There are two different process variants for laser welding of plastics[1.]

- Laser butt welding process
- Laser transmission welding

In case of laser butt welding process, the surfaces of the components to be joined are heated by a system of mirrors and then pressed together in the molten state, usually for 2 to 10 seconds. Once the surface is fully melted, the tool is withdrawn, the parts are forged together and the melt is allowed to solidify. An array of laser diodes can also be used to heat each of the joining surfaces.

The laser transmission welding is based on the concept of passing the laser radiations through one of the components which is transparent to the wavelength of laser light, and second component which has high absorption.

This absorption helps to convert laser energy to heat, when the joining surfaces are irradiated by a beam passing through the transparent part. This helps in heating and melting of the interfaces and allows the parts to be welded. The advantages of this process include speed and flexibility while one of the limitations is material suitability. [11]

A common feature of laser transmission welding is that the heat affected zone is relatively small, and the heat can get into the joining zone in a contact free manner. It is possible to perform welds at points that are difficult to access. For electronic and micromechanical parts that would be difficult to be welded by ultrasonic or vibration welding, are possible to be welded by this method. Contour welding process one of the variants of laser transmission welding, can be used to achieve dense welds without any flash, by selecting the appropriate weld geometry. Simultaneous or quasi-simultaneous welding processes which are the other variants of this process can be used if the moulded parts have to overcome fairly high tolerances. [10]

Advantages of laser welding are: Excellent visual appearance wide applicability, minimal influence on the product, welding of 3D shaped contours, process flexibility. Some of the process variables of laser welding are shown in Fig. (6):

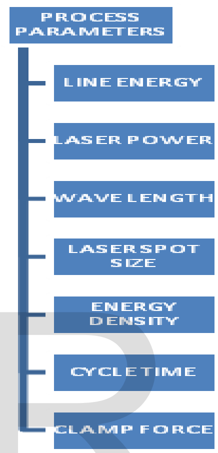

Fig. 6: Process parameters of Laser Welding.

3.6 Microwave Welding Process- an emerging technology-

This welding has a number of advantages over conventional welding due to its ability to heat specimens directly through specific interactions of electromagnetic radiations with the materials. Thus it is possible to consider highly localized rapid melting of thermoplastics using microwave radiation as a means of welding. [14],[19]. Microwave energy may be delivered to a material via several designs of applicator such as single mode, multimode probes, antennae and lenses. Microwave welding of plastics has been developed as a versatile assembly technique suitable for exploitation in mass production industries such as automotive. Microwave energy can weld thermoplastic components of any shape, provided that the thermoplastic is, to a first order approximation transparent to the microwave radiation in a multimode cavity, the only part to be welded will be a pre-positioned weld implant at the joint line. [18]

Heating in a microwave field essentially takes place by the following physical processes:

- Polarization heating (polar materials)
- Electrical resistance heating (electrically conductive materials)
- Heating through the Maxwell-Wagner effect (multi-

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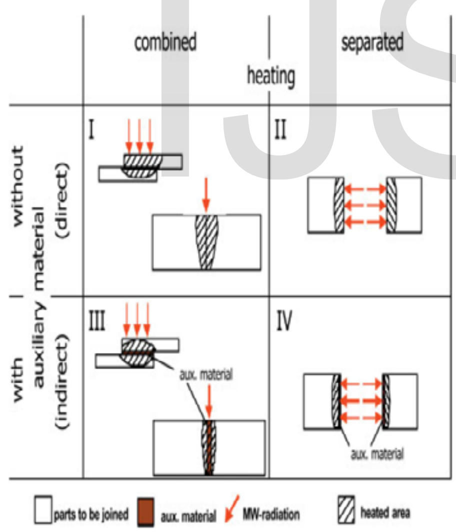
phase materials)
- Ion-polarization (electrolytes, ceramics at high temperature)
- Electron polarization.

In case of Microwave heating, an electromagnetic interaction takes place between the incident microwave radiation and the target material. The type of interaction is governed largely by the material dielectric properties. [24]

Welding with microwave radiation can essentially be divided into two variants i.e. welding with and without auxiliary materials.

Welding without auxiliary materials (direct heating) is only possible to join parts made of materials that will heat up in a microwave field. Welding with auxiliary materials (indirect heating) is feasible for all thermoplastics but it is suitable for microwave inactive plastics that cannot be heated directly. In this process, a material is inserted between the parts to be joined which heats up under microwave radiations and passes this heat on to the parts being joined through thermal conduction. After the heating phase most of these auxiliary materials are displaced into the weld bead. One of the special advantages of this second process is too selective weld zones which are inside when the parts are put together. A weld of this type can be detached by melting this ancillary material through microwave heating. Fig.(7)[10]



Advantages of microwave welding are:
- Non-contact heating i.e. suitable for filled, high melting plastics with a low viscosity in the molten state.
- A high efficiency in the generation and conduction of microwave radiation.
- Microwave radiation is only generated during the heating phase i.e. the energy is only used when necessary.
- Cold heating equipment, such as a higher level of occupational safety than for systems that operate with heated elements.

Process parameters of Microwave welding are shown in Fig. (8):

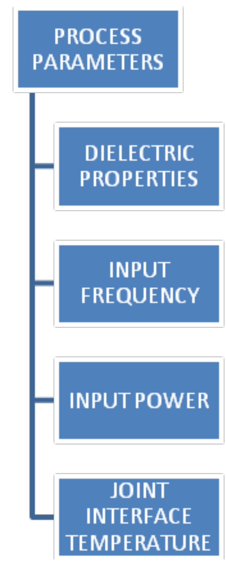


Fig. 8: Process parameters of Microwave Welding.

4 COMPARATIVE ANALYSIS BASED ON PRIORITIZATION MATRIX

Microwave welding is an emerging technology in the field of thermoplastic welding. In order to understand its applicability in thermoplastic welding a comparative analysis is made with respect to the present methods. Table (1) summarizes the process capability of different methods of welding of thermoplastic with respect to the type of heating, energy transferred, time, process variable, and applications.

Welding methods taken for the analysis are:

A. Radio frequency welding
B. Laser welding
C. Microwave welding
D. Vibration welding
E. Ultrasonic welding
F. Hot plate welding

Table 1: Comparative analysis microwave welding with contemporary welding processes

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Sr. no.	Welding Method	Type of Heating	Energy Transferred	Time	Process variable	Applications
1	A	Internal Electromagnetic Heating (Linear Heating)	Electromagnetic Energy	01-05sec cycle time	Voltage, Frequency, Dielectric constant.	Blister Packs for Packaging, Medical applications: water bed mattresses
2	B	Internal Electromagnetic Heating (Linear Heating)	Electromagnetic Energy	01-05sec cycle time	Wavelength, Melting Speed	Automobile Lamps, Medical Components
3	C	Internal Electromagnetic Heating (Volumetric Heating)	Electromagnetic Energy	Minimum Time	Frequency, Power, Dielectric constant	Films & Sheets, moulded parts and semi-finished products.
4	D	Internal Mechanical Heating (Linear Heating)	Mechanical Energy	10sec cycle time	Velocity, Weld Time, Weld Force	Thermoplastic intake manifolds for automobile industry
5	E	Internal Mechanical Heating (Linear Heating)	Mechanical Energy	Less than 1sec cycle time	Amplitude, Energy, Peak power	Food Packaging, Computer Components, Consumer Package
6	F	External Heating (Linear Heating)	Mechanical Energy	30-90sec Cycle time	Temperature, Weld time, Weld force	Fuel tank assemblies, PE pipelines

From table (1) it is quite understandable that the microwave heating is a volumetric heating which make the welding of material very fast but in order to determine the effectiveness of microwave welding further quantitative analysis is required. Table (2) summarizes the comparison of different types of thermoplastic welding methods with respect to different product requirements or voice of customers.

The voices of customer identified in the analysis are:

I. Welding of thin sheets (< 2mm)
II. Welding of thick sheets (>2mm)
III. Weld time (minimum)
IV. Weld strength (high)
V. Weld pressure (low)
VI. No edge preparation
VII. Volumetric heating is possible
VIII. Weld of dissimilar material
IX. Heat affected zone
X. Filler material can be used
XI. Difficult to weld parts
XII. Thermoplastics

Table 2: Comparative Analysis between different thermoplastic welding processes

Welding methods → / Voices of customers ↓	A	B	C	D	E	F
Thin Sheet (< 2mm)	X	x	x	_	_	_
Thick Sheet (> 2mm)	X	x	x	x	x	x
Welding time (minimum)	X	x	x	_	x	_
Weld strength (high)	X	x	x	_	x	x
Weld pressure (low)	X	x	x	_	_	_
No edge preparation	X	x	x	_	x	_
Volumetric heating	_	_	x	_	_	_
Dissimilar material welds	_	_	_	_	x	_
Heat affected zone	X	x	x	_	x	_
Filler material	X	x	x	_	_	_
Difficult to weld parts	_	x	x	_	_	_
Thermoplastic (crystalline /amorphous polymer)	X	x	x	x	x	x

From table (2) it is found that for different type of applications most prominent welding of thermoplastic are Microwave welding, Laser welding and Ultrasound welding. To strengthen the outcome, it is being decided to make a prioritization matrix between the voices of customers and technical parameters of welding methods. For making the quantitative analysis weight has been given based on the scale of 0.1 to 10.

1.0 =The criteria being considered is equally important or equally preferred.

5.0 = the criteria being considered is significantly more important or more preferred.

10.0 =the criteria is extremely more important or more preferred.

0.2 =It is significantly less important or preferred.

0.1 =It is extremely less important or preferred.

Table 3: Prioritization Matrix

Welding methods → / Voices of customers ↓	A	B	C	D	E	F
Thin Sheet (< 2mm)	1.0	0.1	1.0	0.1	0.1	0.1
Thick Sheet (> 2mm)	1.0	1.0	1.0	1.0	1.0	1.0
Welding time (minimum)	5.0	5.0	10.0	0.2	10.0	0.1
Weld strength (high)	5.0	10.0	10.0	0.1	10.0	5.0
Weld pressure (low)	1.0	1.0	1.0	0.1	0.1	0.1
No edge preparation	10	10.0	10.0	0.2	5.0	0.2
Volumetric heating	0.1	0.1	5.0	0.1	0.1	0.1
Dissimilar material welds	0.1	0.1	0.1	0.1	10.0	0.1
Heat affected zone	5.0	0.2	5.0	0.1	0.2	0.1
Filler material	1.0	1.0	1.0	0.2	0.2	0.2
Difficult to weld parts	0.2	5.0	5.0	0.2	0.2	0.2
Thermoplas-plastic(crystalline/amorphous polymer)	1.0	1.0	1.0	1.0	1.0	1.0
Column total	**30.4**	**34.5**	**50.1**	**3.4**	**37.9**	**8.2**

(Source: Grewell, D.,et al[7]; Stokes, V.K.[9]; Potente, H.,et al[10])

5 CONCLUSION

All the six different processes of welding thermoplastics are reviewed in this paper considering the different process parameters. These parameters are analysed using prioritization matrices. From the above Table 1, Table 2 & Table 3, it can be concluded that Microwave welding has an edge over other contemporary welding methods. Microwave welding and ultrasonic welding occupy higher positions among all the welding methods. Though ultrasonic welding finds wide application in industries due to its shorter welding time (less than 1sec.) , ability to weld dissimilar materials but its limitation relating to horn size has made the researchers worldwide to identify alternate methods and Microwave has the potential to fill that gap. Other advantages of Microwave welding are which improve its candidature for thermoplastic welding are : cost savings (time and energy, reduced floor space); rapid heating ; precise and controlled heating; selective heating; volumetric and uniform heating; short processing times; improved quality and properties; synthesis of new materials; processing not possible with conventional means; reduction of hazardous emission; increased product yields; environmental friendly; self- limiting heating in some materials; remote power supply; and clean.

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