EFFECT OF MICROWAVE HEAT TREATMENT ON STEEL COMPONENTS

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Abstract

Microwave energy is being used as a process heat source for over five decades with numerous advantages including rapid and uniform bulk heating, reaction acceleration and specificity, yield improvement, absence of side reactions and minimization of impurities. To the best of our knowledge, microwave application to processes involving metallic parts and components have not been attempted and reported as yet. Bulk metals are reflectors of microwaves under ambient conditions. This is the technical barrier in microwave use for heat treatment of bulk metallic parts and components. With the expertise and experience of technology behind the heat treatment of materials in general, the authors have attempted the heat treatment of bulk metallic parts including surface treatment by microwaves under controlled conditions. This was done for normalizing and hardening-tempering of selected steel components being manufactured at Pradeep Metals Ltd. Properties of microwave treated components were compared with traditionally processed components. The authors have successfully reproduced the heat treatment effects on these metallic components using short duration microwave irradiation. This novel attempt of microwave based heat treatment of metallic parts and micro-structural similarity of the products will be discussed.

Key Words : Steel Heat Treatment, Normalization, Surface Hardening, Microwave Processing, Bulk Metal Treatment

Introduction

Heat treatment is the controlled heating and cooling of metals to certain specific temperatures is a well recognized process step to achieve desired material properties in forged or moulded metal components. Heat treatment is often associated with increasing the strength of material, but can also be used to improve machinability, formability or to restore ductility after cold working operations on the components. Few commonly used heat treatments are softening, hardening, annealing, normalizing, tempering. Such heat treatment controls the phase composition, and refines microstructure including grain size and grain-boundary chemistry and other properties such as hardness, ductility, toughness and remove residual stress. Conventionally, heat treatment of metals before and after forging or moulding is done either in electrical or oil-fired furnaces at temperatures in the range of 600°C to 1350°C depending on the desired application and properties of the finished products. The total heating and sintering time is usually in the range of 3 to 10 hours whereas temperature, complexity of the shape and type of material being important parameters. Typically such long duration of heating in the furnace results in scale formation due to the oxidation. To avoid oxidation of metals, one needs to maintain controlled atmosphere that is expensive and cumbersome. This paper reports the benefits of rapid bulk or volumetric heating of steel using microwave techniques to minimize these disadvantages of conventional heat treatment process.

Microwave heating is fundamentally different from conventional heating. During conventional heating using traditional heat source, thermal energy is transferred to the object via convection and radiation to the surface of the object and then via conduction to the inside of the object. On the other hand, during heating with microwaves, its electromagnetic energy is converted into thermal energy within the body of the object as its atoms or molecules interact with the microwave photons. This interaction results in volumetric heating, which is highly efficient and instantaneous throughout the entire volume of the object simultaneously. This is in contrast to conventional heating wherein heat passes into the body of the object from the surface by conduction rendering the surface too hot and the interior not so hot until thermal equilibrium is achieved.

Microwaves correspond to frequencies between 300 MHz and 300 GHz of electromagnetic spectrum. However, most research and industrial activities are carried out at 2.45 GHz frequency. Based on the interaction of microwaves with the materials, they are classified into following categories:

- Metals are ‘opaque’ to microwaves and good reflectors as these contain free electrons and are electrical conductors too.

- Insulators which are electrically non-conducting, such as some ceramics viz. Al_2O_3, MgO, SiO_2, glasses are ‘transparent’ to microwaves at ambient temperatures. When some of these materials are heated above a critical temperature (T_{crit}), they begin to absorb and interact with microwaves and heat up.

- Dielectrics which posses the properties ranging from conductors to insulators, for example, many ceramic materials (Co_2O_3, MnO_2, NiO, CuO, Fe_2O_3) are good ‘absorber’ of microwaves at room temperature, hence these absorb and interact with microwaves efficiently and heat up rapidly.

- Other materials such as composite materials in which the absorption of microwaves can be enhanced by adding conducting or magnetic materials into a transparent material. These additives absorb microwaves more rapidly than the matrix and hence material will be heated more rapidly and selectively compared to that without such additives.

Various advantages of microwave processing have been reported in literature. Sutton[1] reported the benefits of microwave processing such as cost saving due to lesser time and energy consumption, as well as precise, controlled and selective heating of the objects. Clark[2] listed benefits such as instantaneous heating, better product uniformity, faster production throughput, less floor place, reduction wasteful heating of surroundings etc. Agrawal[3] indicated that the process is cheaper and greener.[*] These advantages attracted worldwide attention from academia and industries to exploit these advantages for varied applications. Likewise many such advantages have been published from time to time by various authors.[4]

Microwave techniques can be applied effectively and efficiently to heat and sinter the ceramic materials; however, processing of ceramic materials using microwaves is a relatively recent phenomenon. Some instances of commercialization of microwave based ceramic processing have been also reported.[reference needed]

Sintering of metal powders have also drawn attention of engineers active in microwave processing. This is a surprising application in view of the fact that usually the bulk metals reflect microwaves at ambient temperatures. Powder metal usually absorbs microwaves at room temperature and gets effectively heated very rapidly. This technique can be used to sinter various powder metal components to produce useful products ranging from small cylinders, rods, gears and automotive components in a very short span of time, e.g., 30 to 90 minutes.

Usually solid metals reflect microwave radiation. Particularly, nonporous metals at ambient temperature almost always reflect microwaves and do not absorb its energy significantly. Levinson[5] mentions that metals can be heated in microwave but the formation of an arc depends on the size and shape of the metal pieces, the relationship of such metals with each other, distance of metallic objects from the walls and the loss-characteristics of the load in the microwave cavity. It was found that bulk metals could absorb microwaves at relatively high temperatures.[5]

In a preliminary attempt we explored the possibility of heat treatment of some forged components based on the information mentioned above. Steel components of A105 and EN19 grades were selected and were either “only normalized” or “normalized and tempered” as per standard practices. This paper presents the results obtained by heat treatment of these materials using microwave technique and compares with conventionally processed samples.

Experimental

The samples selected for heat treatment were valve gland forged from A 105 type carbon steel weighing about 310 g and valve equalizer forged from EN19 type steel weighing about 200 g each. Conventionally A 105 type steel components are normalized in a oil fired furnace of about 7’ deep and 4’ wide furnace in which oil is fired through two nozzles and oil consumption is about 10 -15 l/h. During production trials about 1 T material is loaded in the furnace and soaking time is decided based on the highest dimension of the component. As a thumb rule after reaching normalization temperature , soaking time is set about 1”/h i.e. if the component one dimension is

[*] So-called “Green” processes are characterized by much lower emission of greenhouse substances in environment compared to those conventional processes that are not “Green”.

about 3”, soaking time is 180 min. Both samples used for study had highest dimension about 2”, hence the soaking time set was 120 min. Identical samples, in parallel, were heat treated in a microwave furnace. Microwave furnace sued was model L 0316V manufactured by M/s Synothern Corporation, China. Technical specifications of this microwave furnace are as follows:

Operating frequency : 2450 MHz
Magnetron power : 3 kW (variable from 0.3-3.0 kW)
Maximum operating temperature : 1600°C
Woke zone : 8” diameter X 8” height (around 2-3 kg/batch)
Temperature measuring system : RayTek Marathon series IR Pyrometer (350-2000 ^{0}C)
Vacuum : Max. 10^{-2} Torr,
Atmosphere control : Possible through gas control valves and gas mix tank

Conventional heat treatment: A105 carbon steel samples were normalized in an oil fired furnace between 900-920°C for a soaking time of 120 min. and EN19 samples were normalized at 900°C for a soaking time of 120 min. After normalization, EN19 samples were tempered at 650°C for a soaking time of 120 min. whereas A105 samples are *not* tempered.

In the present study, normalization and tempering of the samples were performed at the temperatures usually maintained in the conventional process; i.e., A105 samples were normalized at 920°C and EN19 samples at 900°C. This was followed by tempering of EN19 samples at 650°C.

Microwave heat treatment: During microwave trials, the samples were placed in a microwave cavity, well insulated and surrounded with susceptors made of SiC. During this heat treatment, the microwave power was gradually increased from 0.5-0.8 kW to 2.7 kW to avoid arcing in the chamber. As temperature increased, the microwave input power gradually increased. The time and temperature profile was monitored for all samples. The desired temperature 900 or 920^{0}C, was reached in about 30 to 40 minutes. The samples were soaked for different durations from 10 min. to 60 min. In case of EN19 samples, tempering was done at 650°C in a separate run.

Environment control: No special environment was maintained around the samples during the microwave system and were carried out under ambient conditions.

Characterization: After heat treatment, the samples were characterized under optical microscope model TCM 400, Labomed equipped with the transferring photograph to computer. Using this system the sample for grain morphology and size was analyzed. For Microstructure examinations, etchant used was 2% Nital. The hardness of the sample was determined using Brinell Hardness Number (BHN) analyzer.

Results & Discussions

Typical composition of the steel used is listed below in Table 1:

Table 1: Typical chemical composition of the steel used for this study

Component	Bonnet	Equalizer
Type of steel	A 105	EN19
Typical composition (%)		
C	0.19	0.39
Mn	0.86	0.76
Cr	0.24	0.95
Ni	0.10	0.13
Si	0.19	0.21
S	0.028	0.015
P	0.029	0.018
Mo	0.008	0.24

(A) Heat treatment of EN19

EN 19 is a special grade steel used in special engineering applications where high tensile strength and toughness is expected. Typical heating profiles for conventional and microwave based heat treatment processes are compared below in Figure 1 for EN19:

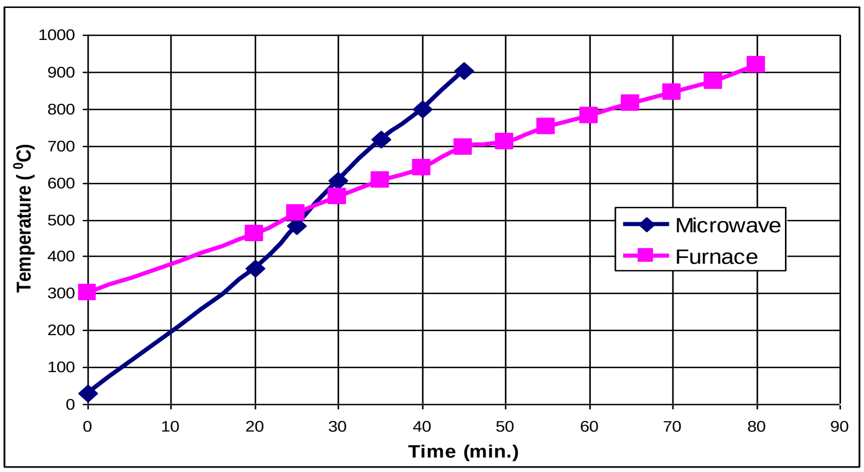


Figure 1: Comparison of heating profile of EN19 component in microwave furnace.

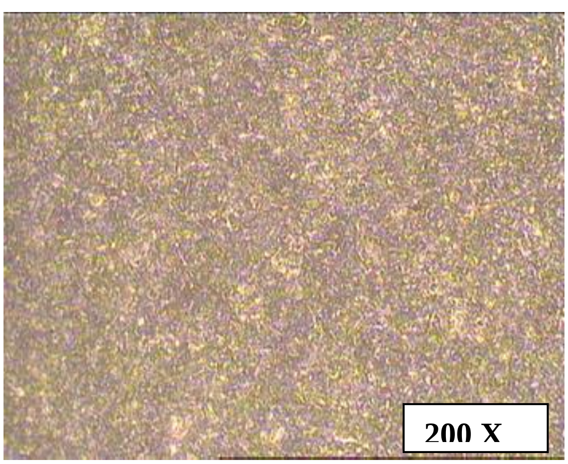
Brinell Hardness Number (BHN) results of conventional and microwave heat treated samples are compared below in Table 2. BHN of conventionally normalized and tempered samples was about 215, while microwave treated samples indicated BHN values varying from 197 to 225 depending on the treatment duration. However these values were will within the specifications (180-220) of the desired objects being manufactured.

Considering the experimental errors (standard deviations) of the observed BHN values and the specifications of the object, it appears that the variations in BHN numbers in Table 2 are well within the tolerance limits of acceptance.

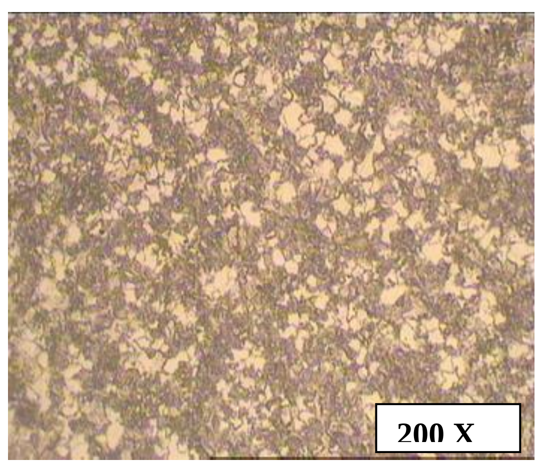
Table 2: Brinell Hardness Numbers of conventional and microwave heat treated EN19 samples

Properties	Conventional Normalized at 900 ^{0}C for 2 h & tempered at 650 ^{0}C for 3h	MW Normalized (900 ^{0}C – 10 min.)	MW Normalized (900 ^{0}C – 20 min.)	MW Normalized (900 ^{0}C C -30 min.)	MW Normalized (900 ^{0}C - 40 min.)	MW Normalized (900 ^{0}C – 60 min.)
		Tempering at 650^{0}C for 30 min.				
Brinell Hardness Number (BHN)	215	197	225	217	207	197

The grain morphology of 30 min. microwave normalized followed by 30 min. microwave tempered sample was different than conventionally normalized (2h) and tempered (3h) sample. Although the grain structure as determined by optical microscope of both samples indicated fine pearlite & ferrite with carbides grains, a distinct difference in grain size is observed with conventional and microwave heat treated samples. Microwave treated samples indicated bigger grains size than the conventional samples (fig. 2). The microstructure of 10 min. microwave normalized followed by 30 min. microwave tempered sample indicated pearlite & ferrite at austenite grain boundaries.



Conventionally. Normalized & tempered



MW Normalized & tempered (30/30 min.)

Fig. 2 : Photomicrographs of conventionally and microwave normalized & tempered EN19 samples

(B) Heat treatment of A 105

As forged shapes of A105 steel were heated in the microwave system up to 920 ^{0}C. The temperature was reached in around 35 min. and soaking time was maintained at 10, 15, and 20 min. Power consumption during each trial was around 2.5 units (i.e. kW/h). Typical heating profiles for conventional and microwave based heat treatment processes are compared below in Figure 3:

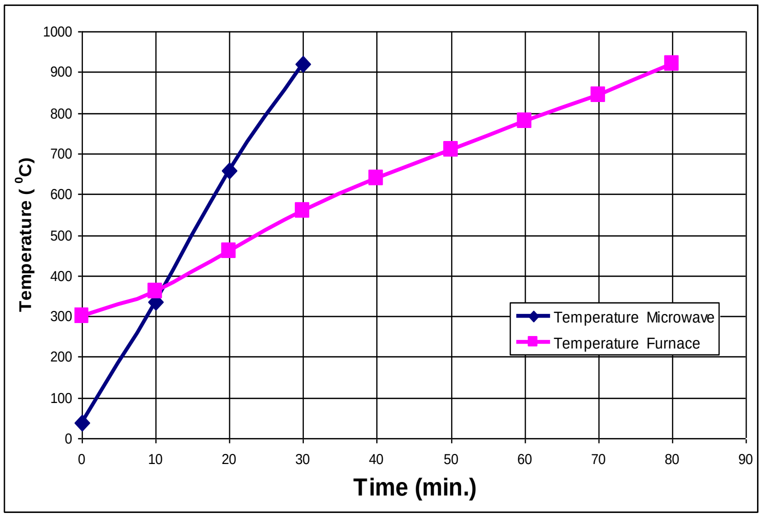


Figure 3: Comparison of heating profile of A 105 carbon steel based component in microwave furnace.

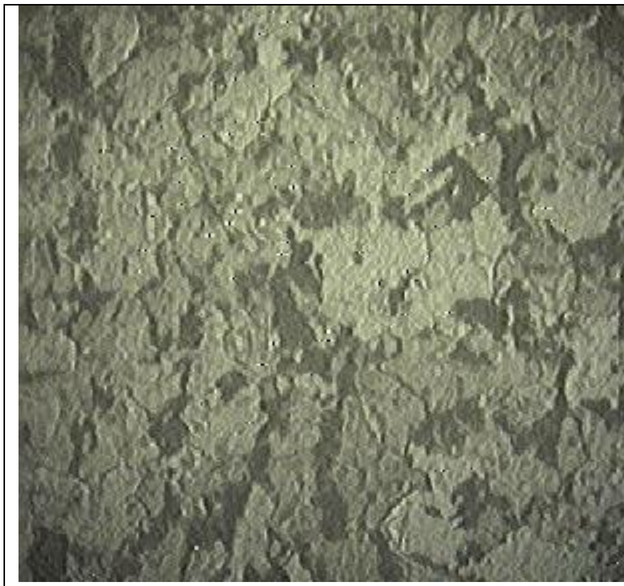
Samples were subjected to hardness and microstructural evaluations. Results are tabulated in table 3 below:

Table 3: Hardness and microstructure of conventional and microwave heat treated A105

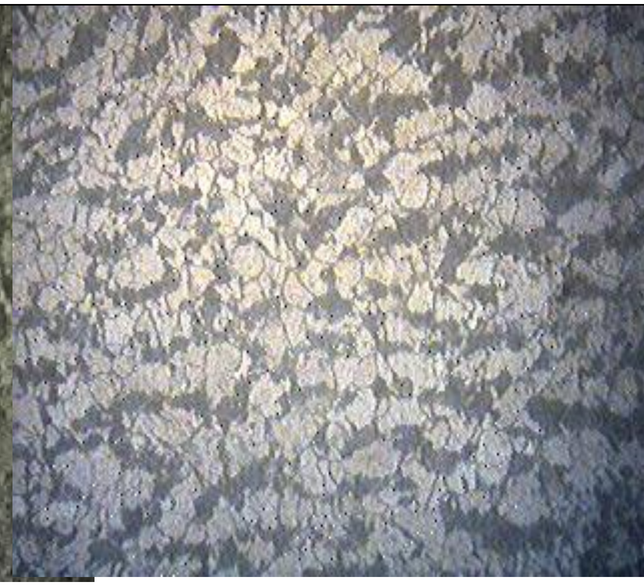
Properties	Conventionally Normalized	MW Normalized (920 ^{0}C -10 min.)	MW Normalized (920 ^{0}C -15 min.)	MW Normalized (920 ^{0}C -20 min.)
Brinell Hardness	144/145/143	141/142 / 140	144/145 / 143	149/150 / 148

Number (BHN)				
Grain size (ASTM NO.)	8 and Finer	8 & finer	8 & finer	8 & finer

Microstructure of conventionally normalized and microwave normalized samples are depicted below in fig. 2. Conventionally normalized sample indicated non-uniform distribution of pearlite & ferrite grains with dispersed carbide particles, while microwave normalized samples after 15 min. indicated uniform pearlite & ferrite grains. Hardness of microwave normalized samples were within the specifications.



Conventionally. Normalized (920- 3h)



MW Normalized 920 -20 min.

Fig. 3 : Photomicrographs of conventionally and microwave normalized A105 samples

Conclusions:

The results of above described comparison of conventional and microwave heat treatment given to A105 and EN19 samples indicate that normalization and tempering of such steel components can be done rapidly using microwave technique. Our study also concludes that long soaking time of several hours is usually not required during microwave based normalization and tempering of the steel components for achieving the desired grain morphology, hardness and other material properties; typically up to 30 min soaking time is sufficient.

[1] Willard H. Sutton, “Microwave processing of ceramics – an overview”, Materials Research. Symposium Proceedings (vol. 269,1992, pp 3-20)

[2] David E. Clark (1996): “Microwave processing of materials”, Annual Review of Material Science, vol. 26,pp. 299-331

[3] Dinesh Agrawal “Micro-processing of ceramics”, Current opinion in solid state & material science (1998, pp 480-485);

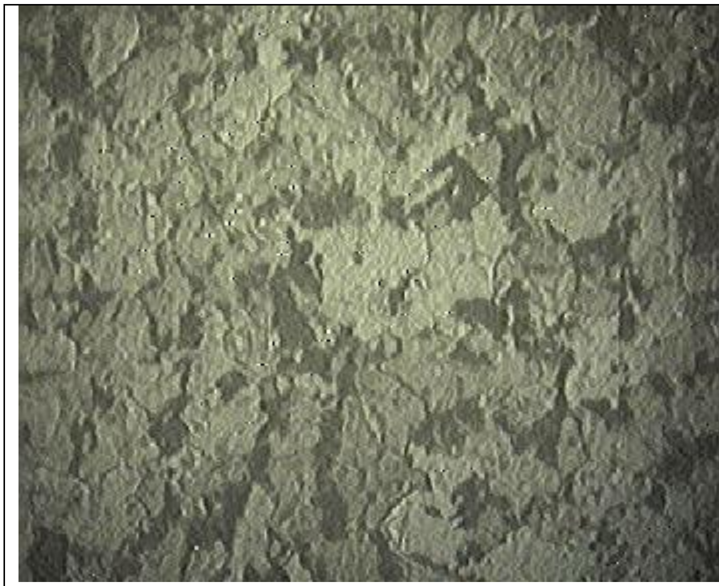
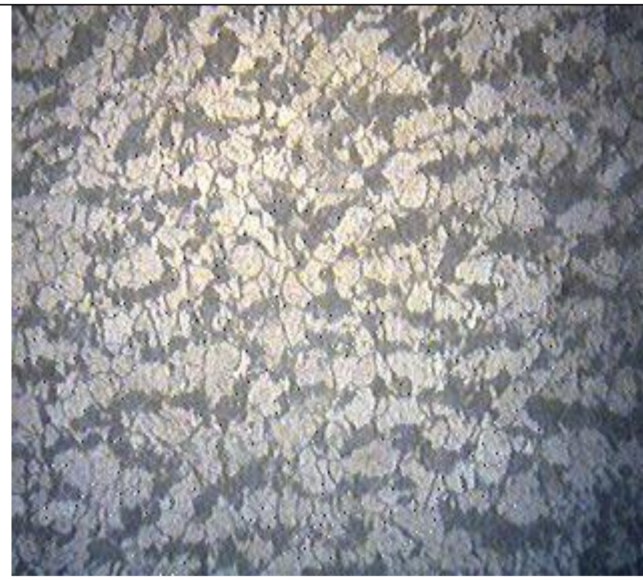
[4] Robert F. Schiffmann, with title “Commercializing microwave systems : path to success or failure”, Microwave theory and application in materials processing III, Ceramic transactions (vol 59, The American Ceramic Socociety,1995, pp 7-16); Bernard Krieger with title “Commercialization - steps to successful applications and scale-up”, Microwave theory and application in materials processing III, Ceramic transactions (vol 59, The American Ceramic Society,1995, pp17-21); K.J. Rao, “Use of microwaves for the synthesis and processing of materials”, Bulletin of Material Science (vol. 18, 1994, pp 447-465)

[5] Melvin L.Levinson,the article was captured on site: http://home.att.net:80/~mrmicrowave/index.html as on 12th September 2009

Properties	& tempered at		MW Normalized (900 ^{0}C – 20 min.)	MW Normalized (900 ^{0}C C -30 min.)	MW Normalized (900 ^{0}C - 40 min.)	MW Normalized (900 ^{0}C – 60 min.)	
Brinell Hardness Number (BHN)		197	225	217	207	197	

Tempering at 650^{0}C for 30 min.

Normalization conditions	Conventional 900 ^{0}C for 2 h	MW 900 ^{0}C – 10 min.	MW 900 ^{0}C – 20 min.	MW 900 ^{0}C – 30 min.	MW 900 ^{0}C – 45 min.	MW 900 ^{0}C – 60 min.
Tempering conditions	650 ^{0}C for 2h	650^{0}C for 30 min.	650^{0}C for 30 min.	650^{0}C for 30 min.	650^{0}C for 30 min.	650^{0}C for 30 min.
Brinell Hardness Number (BHN) Specs 200-250	215	197	217	229	207	197

 Conventionally. Normalized (920- 3h)	 MW Normalized 920 -20 min.