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Monitoring of Cure State through the Use of Microwaves

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(54) **MONITORING OF CURE STATE THROUGH THE USE OF MICROWAVES**

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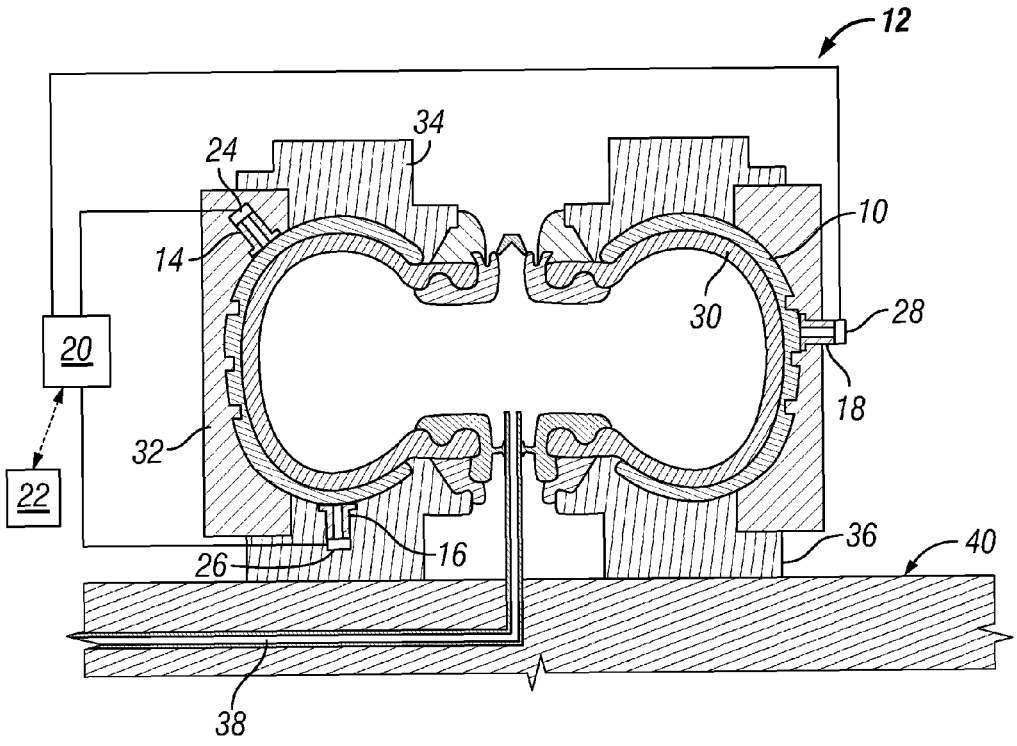
(57) **ABSTRACT**

A method of manufacturing a tire is provided that includes curing the tire (**10**) in a curing press (**12**) and applying microwave energy at a given frequency band into the tire. The interaction between the microwave energy and the tire is monitored to obtain a complex reflection coefficient. A root-mean-squared error is calculated using the measured complex reflection coefficient and a reference reflection coefficient. The reference reflection coefficient is from a fully cured tire made from the same material as the tire. Continuous monitoring of the interaction takes place to obtain the complex reflection coefficient along with continuous calculation of the root-mean-squared error at different times during the curing of the tire in the curing press. The calculated root-mean-squared errors are used to determine whether to stop the curing of the tire in the curing press.



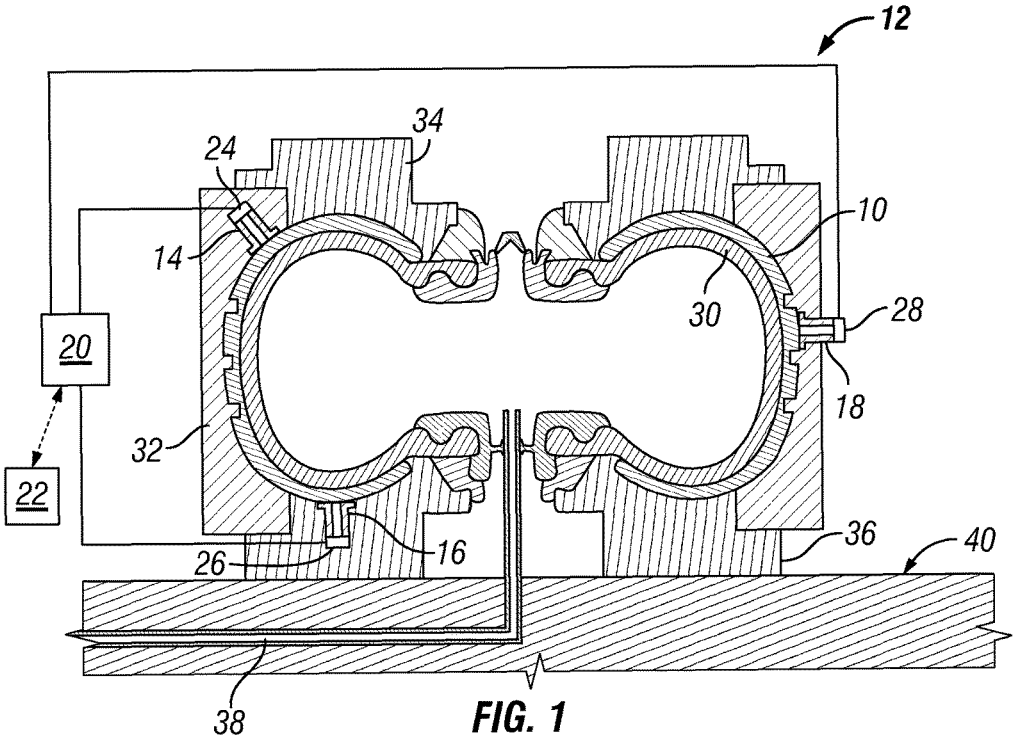

12
34
24
14
10
30
28
20
18
32
22
36
40
26
16
38

FIG. 1

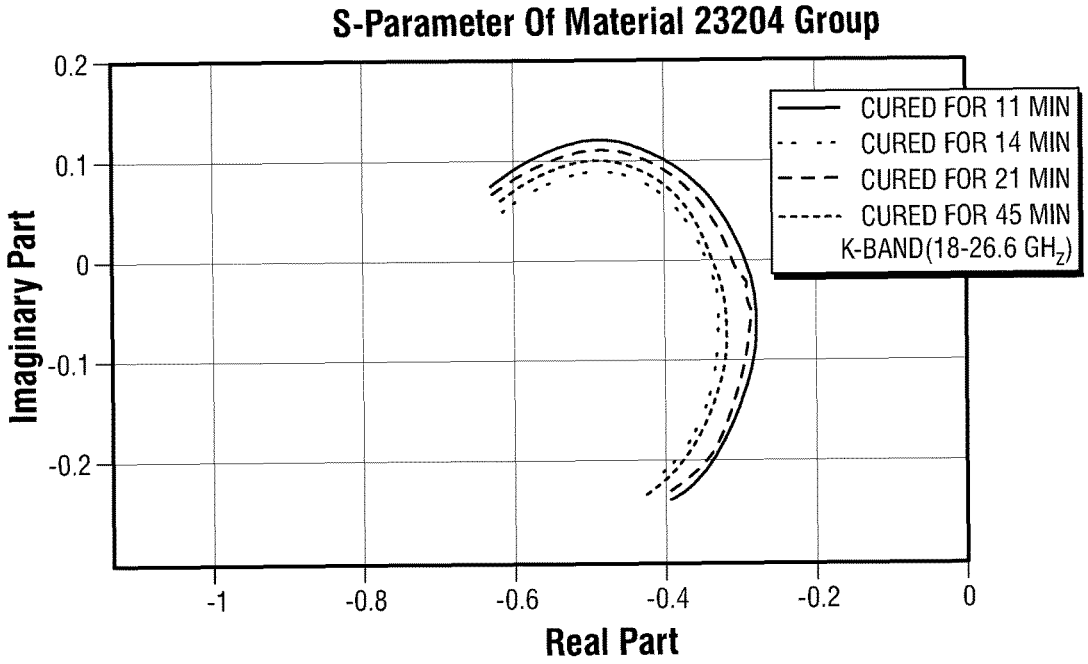

S-Parameter Of Material 23204 Group
Imaginary Part
Real Part
0.2
0.1
0
-0.1
-0.2
-1
-0.8
-0.6
-0.4
-0.2
0
CURED FOR 11 MIN
CURED FOR 14 MIN
CURED FOR 21 MIN
CURED FOR 45 MIN
K-BAND(18-26.6 GHz)

FIG. 2

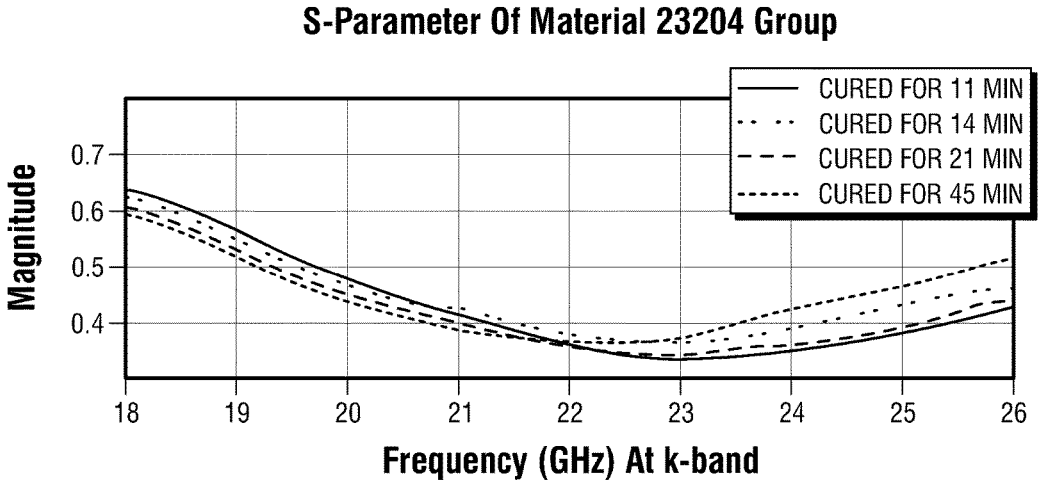

S-Parameter Of Material 23204 Group
CURED FOR 11 MIN
CURED FOR 14 MIN
CURED FOR 21 MIN
CURED FOR 45 MIN
Magnitude
0.7
0.6
0.5
0.4
18
19
20
21
22
23
24
25
26
Frequency (GHz) At k-band

FIG. 3

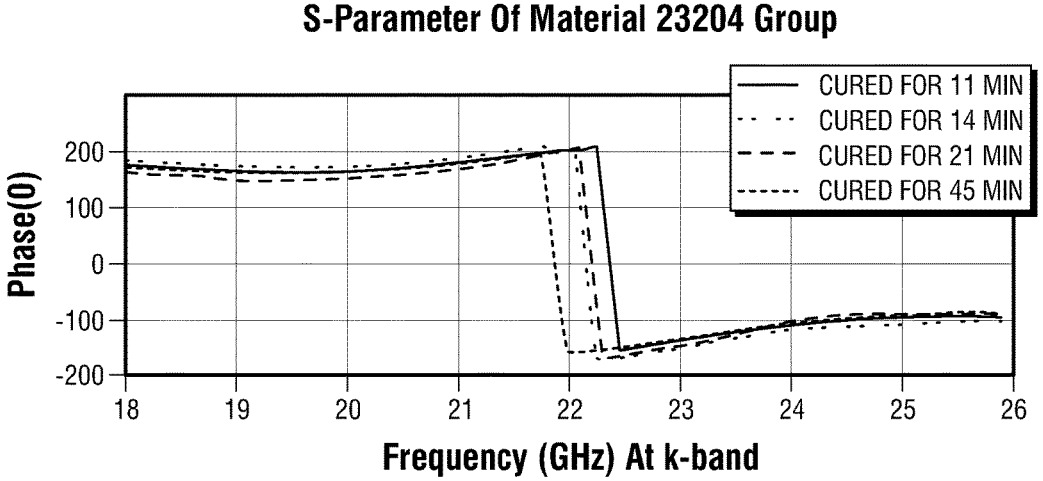

S-Parameter Of Material 23204 Group
CURED FOR 11 MIN
CURED FOR 14 MIN
CURED FOR 21 MIN
CURED FOR 45 MIN
Phase(0)
200
100
0
-100
-200
18
19
20
21
22
23
24
25
26
Frequency (GHz) At k-band

FIG. 4

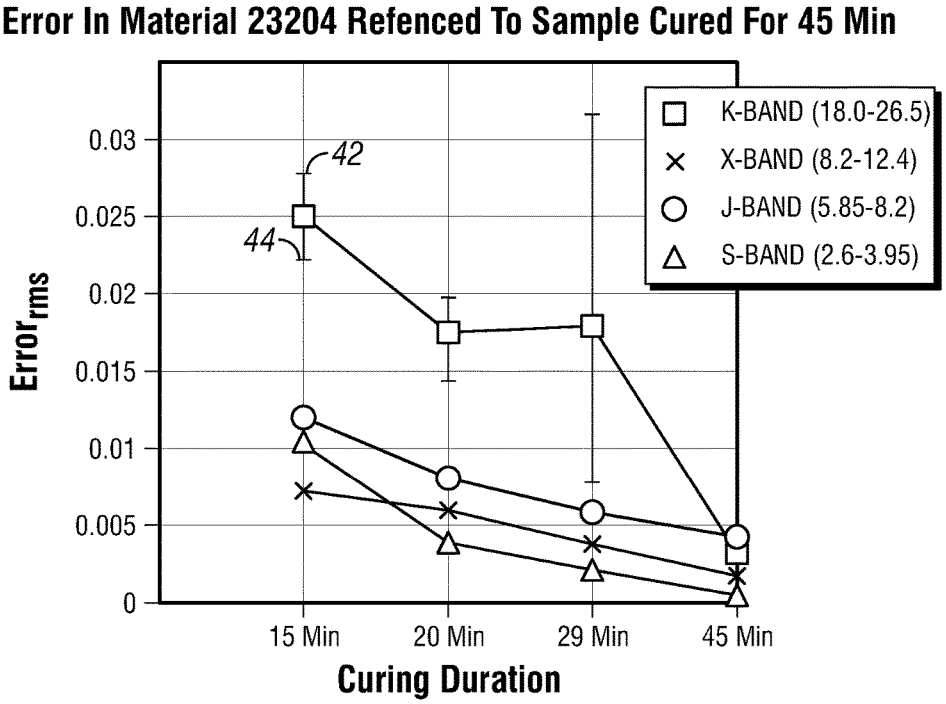

Error In Material 23204 Refenced To Sample Cured For 45 Min
K-BAND (18.0-26.5)
X-BAND (8.2-12.4)
J-BAND (5.85-8.2)
S-BAND (2.6-3.95)
42
44
0.03
0.025
0.02
0.015
0.01
0.005
0
Error rms
15 Min
20 Min
29 Min
45 Min
Curing Duration

FIG. 5

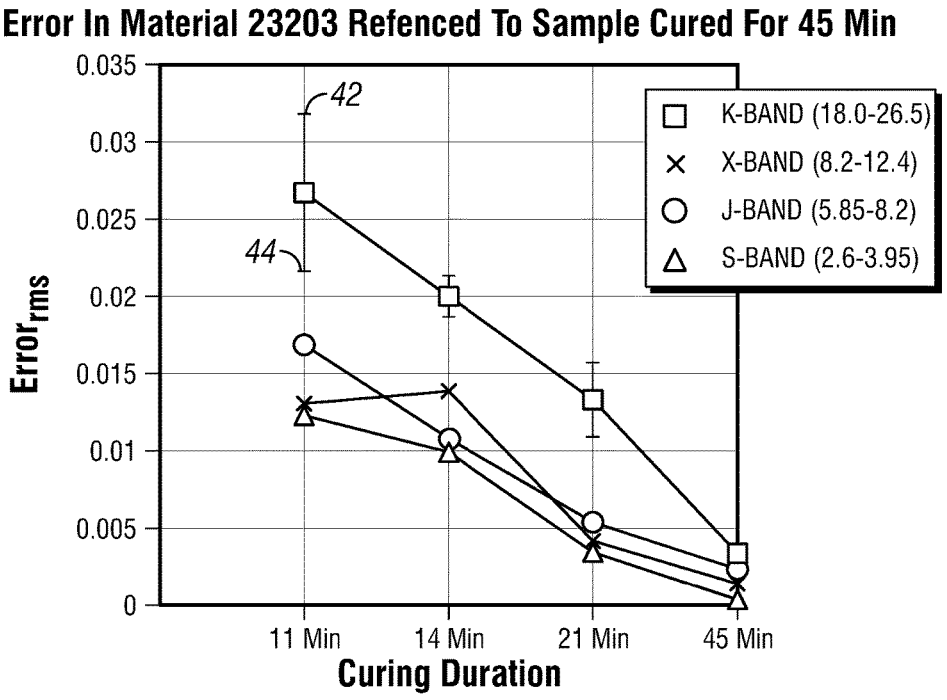

Error In Material 23203 Refenced To Sample Cured For 45 Min
K-BAND (18.0-26.5)
X-BAND (8.2-12.4)
J-BAND (5.85-8.2)
S-BAND (2.6-3.95)
42
44
0.035
0.03
0.025
0.02
0.015
0.01
0.005
0
Error rms
11 Min
14 Min
21 Min
45 Min
Curing Duration

FIG. 6

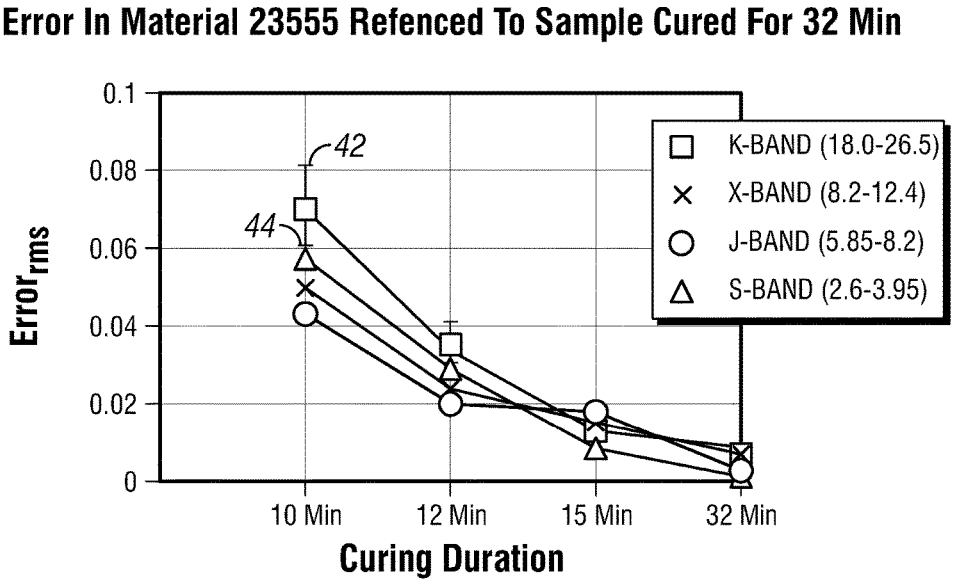

Error In Material 23555 Refenced To Sample Cured For 32 Min
0.1
0.08
0.06
0.04
0.02
0
Error rms
42
44
K-BAND (18.0-26.5)
X-BAND (8.2-12.4)
J-BAND (5.85-8.2)
S-BAND (2.6-3.95)
10 Min
12 Min
15 Min
32 Min
Curing Duration

FIG. 7

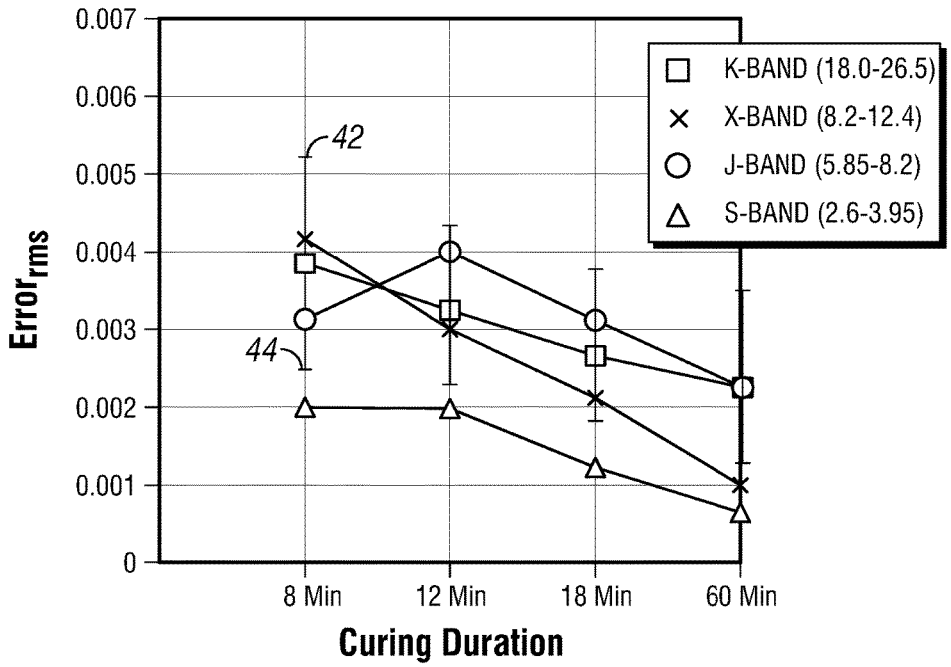

Error In Material 25610 Refenced To Sample Cured For 60 Min
0.007
0.006
0.005
0.004
0.003
0.002
0.001
0
Error rms
42
44
K-BAND (18.0-26.5)
X-BAND (8.2-12.4)
J-BAND (5.85-8.2)
S-BAND (2.6-3.95)
8 Min
12 Min
18 Min
60 Min
Curing Duration

FIG. 8

MONITORING OF CURE STATE THROUGH THE USE OF MICROWAVES

FIELD OF THE INVENTION

[0001] The subject matter of the present invention relates to the monitoring of cure state through the use of microwaves. More particularly, the present application involves monitoring the curing of a tire by the application of microwave energy to the tire during curing and study of the interaction between the microwave energy and the tire.

BACKGROUND OF THE INVENTION

[0002] The production of tires involves the step of placing a green/uncured tire into a curing press and applying heat and pressure for a sufficient amount of time in order to achieve cure. If the tire is under cured in the press, air bubbles or other non-uniformities may develop in the tire and result in a final product with weakened areas and undesired construction. Knowledge of exactly how much time is needed to completely cure a tire may not be able to be achieved because of variations in tire materials and in the tire building process. These variations cause tires to require different amounts of cure time. In order to ensure the tires are properly cured, a safety factor is introduced into the curing stage of the tire. In this regard, extra time is added to the amount of time all tires are cured so that any variation in the tire necessitating a different amount of cure time is taken into account. The downside of adding additional cure time into the process is that this cure time may not be necessary and thus unnecessary time is wasted by keeping the tire at the curing stage. As the curing stage is typically a bottleneck in the tire production process, any wasted time at this stage of manufacture is undesirable. As such, a way of monitoring the tire to determine whether it has achieved cure would help in achieving better through put at the curing stage.

BRIEF DESCRIPTION OF THE DRAWINGS

[0003] A full and enabling disclosure of the present invention, including the best mode thereof, directed to one of ordinary skill in the art, is set forth in the specification, which makes reference to the appended figures, in which:

[0004] FIG. **1** is a cross-sectional view of a tire in a mold with waveguide probes positioned in the mold and in communication with a vector network analyzer and microprocessor.

[0005] FIG. **2** is a plot of a measured complex reflection coefficient from a material 23204 group sample.

[0006] FIG. **3** is a plot of the magnitude of the measured complex reflection coefficient of the measured sample from FIG. **2**.

[0007] FIG. **4** is a plot of the phase of the measured complex reflection coefficient of the measured sample from FIG. **2**.

[0008] FIG. **5** is a plot of the root mean squared error measured in four different microwave bands for material 23204.

[0009] FIG. **6** is a plot of the root mean squared error measured in four different microwave bands for material 23203.

[0010] FIG. **7** is a plot of the root mean squared error measured in four different microwave bands for material 23555.

[0011] FIG. **8** is a plot of the root mean squared error measured in four different microwave bands for material 25610.

[0012] The use of identical or similar reference numerals in different figures denotes identical or similar features.

DETAILED DESCRIPTION OF THE INVENTION

[0013] Reference will now be made in detail to embodiments of the invention, one or more examples of which are illustrated in the drawings. Each example is provided by way of explanation of the invention, and not meant as a limitation of the invention. For example, features illustrated or described as part of one embodiment can be used with another embodiment to yield still a third embodiment. It is intended that the present invention include these and other modifications and variations.

[0014] A method of determining whether a tire **10** is cured is provided that involves the application of microwave energy into the tire **10** along with associated monitoring of the interaction between the tire **10** and this applied microwave energy. A complex reflection coefficient is obtained via the microwave/tire **10** monitoring, and a root-mean-squared error value is calculated. The calculation of the root-mean-squared error includes the complex reflection coefficient, and includes a reference reflection coefficient that is from a fully cured tire **10** of the same material. The root-mean-squared error is monitored during the curing of the tire **10** in the curing press **12**, and it is used to determine whether the tire **10** has been appropriately cured. In this manner, variations in the tire **10** building process can be accounted for in tracking the cure state of the tire **10** because the curing of the tire **10** is monitored on an individual level. The throughput of the curing press **12** can be optimized and the overall cure time reduced for tires **10** running through the curing press **12**.

[0015] FIG. **1** illustrates a curing press **12** that is used to apply heat and pressure to a tire **10** over a certain amount of time in order to cure the tire **10**. Once cured, the tire **10** is removed from the curing press **12** and moved downstream to the next stage of production. After removal, the tire **10** may still be warm and portions of the material making up the tire **10** may still cure for some amount of time even though pressure is no longer being applied to the tire **10**. As such, the tire **10** may not be said to be fully cured upon exiting the curing press **12** because some curing still takes place afterwards. However, as used herein it is to be understood that the term curing refers to the curing of the tire **10** while located in the curing press **12**, and such curing may be fully cured so that the tire **10** undergoes no further curing upon removal from the curing press **12**, or such curing may be partial curing such that the tire **10** does undergo some further curing upon leaving the curing press **12**.

[0016] The curing press **12** includes a sidewall segment **36** located on the ground **40**, and oppositely disposed sidewall segments **34** located farther form the ground **40**. A series of tread segments **32** are located circumferentially around the tire **10**. The segments **32** and **34** may move in relation to the ground **40** and segment **36** to provide a space to allow the tire **10** to be placed inside of the curing press **12** and subsequently removed from the curing press **12**. The curing press **12** also includes a bladder **30** that can be inflated, and possibly deflated, via an inflation line **38** in communication with a pressure source (not shown). During tire **10** curing,

the bladder **30** is deflated and the tire **10** is placed onto the sidewall segment **36**. The treat and sidewall segments **32** and **34** may be closed towards one another, and the bladder **30** can be inflated into its inflated orientation as shown in FIG. **1**. Pressure from the segments **32**, **34**, and **36** applied to the outside of the tire **10** will be counteracted by pressure from the bladder **30** on the inside of the tire **10** to cause the tire **10** to have pressure applied to it during the curing process. Heat can be transferred through the segments **32**, **34** and **36** via temperature probes in these segments **32**, **34** and **36** or through the material making up the segments **32**, **34** and **36** themselves.

[0017] A waveguide probe **14** is shown being located within the tread segment **32** so that it engages the outer surface of the tire **10** at a shoulder portion of the tire **10**. Another waveguide probe **16** is located in sidewall segment **36** and engages the tire **10** at a bead portion of the tire **10**. A further waveguide probe **18** is located in the tread segment **32** and engages the outer surface of the tread of the tire **10**. The waveguide probes **14**, **16** and **18** may engage the tire **10** as shown, or may be spaced from the tire **10** but directly face the tire **10** so that nothing is between them and the tire **10** in various embodiments. Further, although shown as being three in number, one, two, from 4-8, or up to 16 waveguide probes may be employed in various exemplary embodiments. Still further, other areas of the tire **10** may be associated with the waveguide probes instead of or in addition to those shown. Also, the waveguide probes **14**, **16** and **18** could be located in any of the segments **32**, **34** or **36** or even at locations of the curing press **12** that are not the segments **32**, **34** or **36**.

[0018] Microwave energy may be transferred through the various waveguide probes **14**, **16** and **18** and into the tire **10**. The microwave energy upon contacting the tire **10** will have a portion that is reflected back into the waveguide probes **14**, **16** and **18** and a portion that permeates through the tire **10**. Energy through the waveguide probes **14**, **16** and **18** can be transferred back to a vector network analyzer **20** that is in communication with the waveguide probes **14**, **16** and **18** to obtain their readings. The waveguide probe **14** may have an adapter **24** that functions to convert the received microwave energy into a signal capable of being used by the vector network analyzer **20** to determine a complex reflection coefficient. The waveguide probe **16** may have its own adapter **26**, and waveguide probe **18** may have its own adapter **28** as well to convert received signals for input into the vector network analyzer **20**.

[0019] The vector network analyzer **20** is in communication with the waveguide probes **14**, **16** and **18** and may send data to and receive information from the waveguide probes **14**, **16** and **18**. The vector network analyzer **20** (VNA) is capable of measuring the complex reflection coefficient (magnitude and phase) of the tire **10** upon receiving the signal from the waveguide probes **14**, **16** and **18**. A processor **22** can be in communication with the vector network analyzer **20** and may function to perform calculations associated with the disclosed method. Alternatively, the vector network analyzer **20** itself may perform calculations on the computed complex reflection coefficients to determine the cure state of the tire **10**.

[0020] Curing of the material making up the tire **10** causes the dielectric constant of the material to change as the material becomes more and more cured. The dielectric constant may sometimes be referred to as relative permittivity and may be the absolute permittivity of the material expressed as a ratio relative to the permittivity of vacuum. The dielectric constant is an intrinsic property of the material. A change in the dielectric constant of a material causes a change in the complex reflection coefficient of the material. The complex reflection coefficient may be measured by the method and this value can be manipulated through calculation to ascertain the cure state of the tire **10**. When the microwave hits the tire **10**, a portion of the microwave is reflected back off of the tire **10**, and a portion of the microwave passes through the tire **10**. The complex reflection coefficient may be thought of as a ratio of the reflected wave amplitude to the incident wave amplitude. The complex reflection coefficient can be expressed as a complex number. Additionally or alternatively, the complex reflection coefficient can be expressed as having magnitude and phase components.

[0021] During the curing process the waveguide probe **14** measures the microwave energy at its location at the tire **10** and transmits this information to the vector network analyzer **20** that establishes a measured complex reflection coefficient. The vector network analyzer **20** may obtain the measured complex reflection coefficient from the data supplied by the waveguide probe **14** in a variety of manners. In some instances, a forward-iterative optimization algorithm using an nlayer model is used to arrive at the complex reflection coefficient. With the complex reflection coefficient, a root-mean-squared error (RMSE) may next be calculated to ascertain the cure state of the material. To do this, a reference reflection coefficient must first be obtained. The reference reflection coefficient is the complex reflection coefficient obtained from a fully cured sample. With respect to the waveguide probe **14**, a reference tire **10** that is fully cured may be measured at the same location as the location of the waveguide probe **14** on the tire **10**. The reference tire **10** and the measured tire **10** are made of the same material so that they yield the same measured reflection coefficients depending upon their state of cure. The reference reflection coefficient can be an average of measurements from multiple reference tires **10** at the location in question.

[0022] The measured reflection coefficient S_{11} and the reference reflection coefficient S_{11ref} are used in the following equation to calculate the root-mean-squared error (RMSE) or $Error_{rms}$:

$$Error_{rms} = \sqrt{\frac{1}{nf}\sum_{f}|S_{11} - S_{11ref}|^2}$$

[0023] As the tire **10** cures, the root-mean-squared error can be calculated at various points in time. The time intervals can be evenly spaced or unevenly spaced. As the tire **10** cures, the root-mean-squared error will decrease at a generally constant rate. This rate of change may be linear or close to linear. Once the tire **10** reaches a fully cured state, the root-mean-squared error will level off in that it will change its slope or will no longer decrease but instead be a line moving forward in time. The plotted line of the root-mean-squared error of the tire **10** will thus exhibit a stabilization of the rate of change of the microwave energy when the tire **10** reaches a point of cure in the curing press **12**. The method may recognize the tire **10** as being fully cured and then stop the curing of the tire **10** in the curing press **12** and

remove the tire **10** for subsequent downstream processing. In some embodiments, once the fully cured state has been realized by monitoring of the root-mean-squared error, the method may continue to cure the tire **10** in the curing press **12** to ensure that the fully cured state is reached. This additional curing time may be referred to as a safety factor in the tire **10** curing. Once the fully cured state is realized, the method may then decide to stop the curing of the tire **10** in the curing press **12** by executing the additional curing to achieve the safety factor and then stopping the curing in the curing press **12**. Additionally or alternatively, the method may denote the fully cured state in the curing press **12** by denoting a low error value of the root-mean-squared error. If the root-mean-squared error drops below a threshold value, the method will interpret this as the tire **10** being fully cured.

[0024] If the curing press **12** is outfitted with the additional waveguide probes **16** and **18**, complex reflection coefficients from these locations can be obtained by the vector network analyzer **20** at different times during the tire **10** cure. Root-mean-squared errors may also be calculated at these locations associated with the additional waveguide probes **16** and **18**. The fully cured state can be realized once all of the root-mean-squared errors from the various locations on the tire **10** stabilize and/or fall below a certain threshold value. In still other embodiments of the method, the various root-mean-squared errors that are obtained at a point in time from the various waveguide probes **14**, **16** and **18** can be averaged to obtain an average root-mean-squared error that is then analyzed to determine whether its plot has stabilized over time and/or has fallen below a threshold value to determine the fully cured state.

[0025] Experiments have been conducted in carrying out the disclosed method. In this regard, two samples each of various rubber materials at different curing levels were provided as illustrated in Table #1.

TABLE #1

	Sample Detail		
Material Label #	t#	Curing Temperature	Curing Time (min)
23203	t70	150 degrees C.	11
23203	t80	150 degrees C.	14
23203	t90	150 degrees C.	21
23203	t100	150 degrees C.	45
23204	t70	150 degrees C.	15
23204	t80	150 degrees C.	20
23204	t90	150 degrees C.	29
23204	t100	150 degrees C.	45
23555	t70	150 degrees C.	10
23555	t80	150 degrees C.	12
23555	t90	150 degrees C.	15
23555	t100	150 degrees C.	32
25610	t70	150 degrees C.	8
25610	t80	150 degrees C.	12
25610	t90	150 degrees C.	18
25610	t100	150 degrees C.	60

[0026] The material label numbers are different types of rubber that are made up of different components. The times such as # t70 mean that this particular sample was cured for 70 percent of its fully cured state in the curing press **12**. The #t100 means that the particular sample was in fact fully cured. The curing times show the amount of time each of the samples was cured in the curing press **12**. As may be seen, different types of rubber denoted by the material label numbers show that different curing times are needed in order to fully cure the sample. It is thus the case that the curing time needed is dependent upon the material making up the particular sample/tire **10**. The material samples tested were square samples all having generally the same size.

[0027] The microwave energy imparted onto the tire **10** can be at various frequency bands, and it may be the case that one type of microwave energy would work better for a particular material than a different type of microwave energy. In this regard, the method may be optimized so that the best type of microwave energy imparted onto the material making up the tire **10** is used so that the best root-mean-squared results are obtained to determine the cure state of the tire **10**. For experimental purposes, multiple types of microwave energy was imparted onto the various samples to study how the material reacts to the different types. The microwave energy imparted was K-band (18-26.5 gigahertz), X-band (8.2-12.4 gigahertz), J-band (5.85-8.2 gigahertz), and S-band (2.6-3.95 gigahertz). The use of different bands of microwave energy for measurement may require different sized waveguide proves **14** and adapters **24**, and if these components are different sized then it may be the case that the same number of measurements at different locations on the samples cannot be obtained for all of the microwave bands. This is because an edge effect that distorts the received microwave energy can occur and the different sized equipment is thus sensitive to this edge effect.

[0028] FIG. **2** shows the complex reflection coefficient obtained from material sample 23204 using K-band microwave energy. The real and imaginary portions of the complex number making up the reflection coefficient is graphed for the four cured times given on the four different samples at a corresponding location on each of the four samples at different curing rates. The change at the different levels of cure is small, but it can be measured. The complex reflection coefficient can also be expressed as having a magnitude and phase, and this illustration of the complex reflection coefficient at the four different cured times of the four samples of the 23204 material at a corresponding location is shown with reference to FIGS. **3** and **4**.

[0029] The size of the waveguide prove **14** and adapter **24** with the K-band allowed for seven locations on the sample to be measured. As such, seven different complex reflection coefficients can be obtained at each one of the cure states provided. In addition, two samples from table **1** were provided for each one of the rows, and the second sample of the 23204 material provided at each one of the four cure times were additionally measured to result in 14 different complex reflection coefficients obtained for each cure state.

[0030] Each one of the complex reflection coefficients S_{11} are used in conjunction with the reference reflection coefficient S_{11ref} to obtain the root-mean-squared error (RMSE) or $Error_{rms}$ at each point in time t70, t80, t90 or t100. As fourteen points are obtained at each point in time, fourteen root-mean-squared errors are calculated. From this, the mean of the fourteen root-mean-squared errors is calculated by adding up the fourteen values and then dividing this result by fourteen, which is the number of values added. In some embodiments, the standard deviation of the fourteen root-mean-squared error numbers can be calculated. The standard deviation can be obtained from the following formula:

$$\sigma = \sqrt{\frac{1}{N}\sum_{i=1}^{N}(x_i - \mu)^2}$$

[0031] With reference to FIG. **5**, the K-band measurements for material 23204 is shown at t70 which is at 15 minutes of cure time. The mean is from the fourteen measurements of the root-mean-squared error value and is at 0.025. The standard deviation was also calculated at the K-band and is represented at the 15 minute mark by the standard deviation high 42 mark, located at approximately 0.032 root-mean-squared, and the standard deviation low **44** reference mark, located at approximately 0.022 root-mean-squared error.

[0032] The root-mean-squared error can be calculated at the 20 minutes mark for the t80 samples that again generate fourteen complex reflection coefficients. The root-mean-squared calculation for time t80 will use the same reference reflection coefficient S_{11ref} as that at the t70 time. In fact, all calculations of the root-mean-squared error will use the same reference reflection coefficient S_{11ref} at all times. However, different reference reflection coefficient S_{11ref} values may be found across different points of the sample as this value may be different at different points on the sample/tire **10**. The mean of the fourteen calculated root-mean-squared error values will be found and is 0.017, and the standard deviation of these fourteen values can be again calculated and are shown in FIG. **5** as the horizontal lines above and below the mean. This process may be repeated for the t90 values at the 29 minute cured samples, and the mean and standard deviations are again shown in FIG. **5**. Study of the K-band calculations of the root-mean-squared error values in FIG. **5** shows that they decrease from t70 to t80, but remain essentially the same between t80 to t90. The root-mean-squared error does drop from t90 at 29 minutes to t100 at the 45 minute cured sample. There is a general downward trend of the root-mean-squared error value as the cure times increase, and this downward trend can be used to recognize a fully cured state.

[0033] The same process can be repeated with the same 23204 samples although using different microwave bands as shown in FIG. **5**. The X-band and its associated waveguide probe **14** and adapter **24** are capable of measuring five different locations on the 23204 samples due to the difference in size from the K-band equipment and the desire to reduce or eliminate edge effect. Since two samples are present, ten complex reflection coefficients can be obtained at each time provided. The means of the root-mean-squared errors may be calculated in the same manner as previously described with respect to the K-band numbers, although with the X-band ten instead of fourteen values are employed. The resulting means are plotted on the graph of FIG. **5**, and the standard deviations are not shown for sake of clarity on the graph but could be included if desired in other plots. The same calculations can be done for the J-band although with the J-band only three locations on the 23204 are measured due to the size difference in equipment, resulting in six measurements taken at each point from which the mean of the root-mean-squared error values are derived. The S-band can also be done although it is too large to measure different locations on the 23204 sample. Instead, three measurements at the center can be executed to again result in six total complex reflection coefficient measurements taken at each time. The root-mean-squared error values are plotted on the graph for the S-band.

[0034] As shown in FIG. **5**, the general trend of the root-mean-squared error values is downward as the 23204 samples approach the fully cured state. To determine the fully cured state, a threshold value can be set, for example at 0.005. Once the root-mean-squared error value drops below 0.005 the sample/tire **10** is designated as being fully cured. Additionally or alternatively, a flattening out or changing of the rate of change of the plot of root-mean-squared error values can designate the fully cured condition. The flattening out could be when the root-mean-squared error value does not change from one point in time to the next to next several subsequent points in time. This is not seen in FIG. **5** due to the fact that data in only four different points in time were plotted. However, a greater number of data points found at points closer in time may reveal a flattened root-mean-square error value and thus a designation of the fully cured state.

[0035] A slope or rate of change of the root-mean-squared error values can be found at points before the fully cured state. If this slope or rate of change of the plot changes, then the fully cured state can be established. The J-band results show a change in the rate of change of the plot from the 29-45 minute mark that is different than the rate of change or slope from the 20-29 minute mark. The fully cured state may be identified by this rate of change. In other manners, additional data points at additional time points can be found in the plot to better capture or see a change in the slope or rate of change of the root-mean-squared error values. It may be the case that some of the microwave bands do not work well for the material in that particular sample. As shown, the K-band appears not to show a downward slope of the root-mean-squared error value between the 20-29 minute marks so the K-band may not be an optimum microwave energy band to use with the 23204 sample. As some bands are better than others depending upon the material analyzed, an optimal microwave band for each sample/tire **10** type can be selected from the reactions shown of all the variously used bands.

[0036] The other samples of the material/tire **10** were analyzed in the same manner. FIG. **6** shows the plot of all four microwave bands for the 23203 material. The means of the root-mean-squared error values are calculated in the same manner as previously discussed with respect to the 23204 material. The K-band is shown as yielding a good indication with respect to slope or rate of change to discover the fully cured state. The slope of the root-mean-squared value is consistent from t70 at 11 minutes to t90 at 21 minutes. However, the slope and rate of change changes between the t90 and t100 times from 21 to 45 minutes so that this slope and rate of change is different at this time interval than from the 11 minutes to 21 minute interval. This slope or rate of change shows the fully cured condition is indicated. Additionally or alternatively, the K-band shows a threshold of 0.005 below which the fully cured state is realized and this threshold may be used to likewise identify the fully cured state. The X, J and S-bands are not very strong indicators of the threshold as they are likewise below or just above the threshold at the t90 time. The 23555 material sample is shown in FIG. **7** again at the four microwave bands with the root-mean-squared errors calculated in the same manner previously discussed. The slope

can be seen as leveling off for the K-band as it approached the fully cured state. In this regard, the slop from the 15-32 minute mark is different and flatter than the slop from the 10-15 minute marks to show a rate of change adjustment. The thresholds, if used, may be at a 0.01 root-mean-squared error value below which all four bands tend to show a fully cured state.

[0037] FIG. **8** shows the root-mean-squared plot versus time for the 25610 samples again over the four microwave bands. The K-band shows a leveling off from 18-60 minutes as opposed to the different slope or rate of change from the 8-18 minute mark. This microwave band may be the optimal band to use for detection of the fully cured state if using a slope or rate of change difference. The threshold values can be used to identify the fully cured state as well. For example, if using the S-band, a threshold of below 0.001 can be used, and if using the X-band a threshold of below 0.002 can be used. Different threshold can be used for the K and J-bands as the K-band may have a threshold of below 0.0025, while the J-band can have a threshold of below 0.003 to identify the fully cured condition. If a leveling off is desired to be used to identify the fully cured condition, the plot can be evaluated to determine when the root-mean-squared error does not change from one point in time to another and at this state the fully cured condition can be determined.

[0038] While the present subject matter has been described in detail with respect to specific embodiments and methods thereof, it will be appreciated that those skilled in the art, upon attaining an understanding of the foregoing may readily produce alterations to, variations of, and equivalents to such embodiments. Accordingly, the scope of the present disclosure is by way of example rather than by way of limitation, and the subject disclosure does not preclude inclusion of such modifications, variations and/or additions to the present subject matter as would be readily apparent to one of ordinary skill in the art.

1. A method of manufacturing a tire, comprising:

curing the tire in a curing press;

applying microwave energy at a given frequency band into the tire during the curing of the tire;

monitoring the interaction between the microwave energy and the tire to obtain a complex reflection coefficient;

calculating a root-mean-squared error using the measured complex reflection coefficient and a reference reflection coefficient, wherein the reference reflection coefficient is from a fully cured tire made from the same material as the tire;

continuing to monitor the interaction to obtain the complex reflection coefficient and continuing to calculate the root-mean-squared error at different times during the curing of the tire in the curing press; and

using the calculated root-mean-squared errors to determine whether to stop the curing of the tire in the curing press.

2. The method of manufacturing as set forth in claim **1**, wherein the determination of whether to stop the curing of the tire in the curing press is made when one of the calculated root-mean-squared errors falls below a threshold value.

3. The method of manufacturing as set forth in claim **1**, wherein the calculated root-mean-squared errors decrease at a rate of change as the tire is cured in the curing press, wherein the determination of whether to stop the curing of the tire in the curing press is made when the rate of change of the calculated root-mean-squared errors levels off.

4. The method of manufacturing as set forth in claim **3**, wherein the leveling off occurs when the rate of change of the calculated root-mean-squared errors becomes zero.

5. The method of manufacturing as set forth in claim **1**, wherein the microwave energy is in the X-band ranging from 8.2-12.4 GHz.

6. The method of manufacturing as set forth in claim **1**, wherein the microwave energy is in the K-band ranging from 18-26.5 GHz.

7. The method of manufacturing as set forth in claim **1**, wherein the microwave energy is in the J-band ranging from 5.85-8.2 GHz.

8. The method of manufacturing as set forth in claim **1**, wherein the microwave energy is in the S-band ranging from 2.6-3.95 GHz.

9. The method of manufacturing as set forth in claim **1**, wherein the applying the microwave energy at the given frequency band into the tire during the curing of the tire is a first frequency band; further comprising:

applying microwave energy at a given second frequency band into the tire during the curing of the tire;

monitoring the interaction between the microwave energy at the second frequency band and the tire to obtain a second complex reflection coefficient;

calculating a second root-mean-squared error using the measured second complex reflection coefficient and a reference reflection coefficient, wherein the reference reflection coefficient is from a fully cured tire made from the same material as the tire from the microwave energy at the second frequency band;

continuing to monitor the interaction to obtain the second complex reflection coefficient and continuing to calculate the second root-mean-squared error at different times during the curing of the tire in the curing press; and

using the calculated second root-mean-squared errors to determine whether to stop the curing of the tire in the curing press.

10. The method of manufacturing as set forth claim **1**, wherein during the monitoring of the interaction between the microwave energy and the tire a waveguide probe collects reflected microwave energy from the tire and information from the waveguide probe is sent to a vector network analyzer to obtain the complex reflection coefficient.

11. The method of manufacturing as set forth in claim **1**, wherein the root-mean-squared error is calculated using the following formula:

$$Error_{rms} = \sqrt{\frac{1}{nf}\sum_{f}|S_{11} - S_{11ref}|^2}$$

wherein S_{11} is the complex reflection coefficient; and

wherein S_{11ref} is the reference reflection coefficient.

12. The method of manufacturing as set forth in claim **1**, wherein multiple complex reflection coefficients are obtained during the monitoring that are at multiple locations on the tire at one point in time;

wherein multiple root-mean-squared errors are obtained during the calculating using the multiple measured complex reflection coefficients and multiple reference

reflection coefficients, wherein the multiple reference reflection coefficients are from the fully cured tire made from the same material at the multiple locations on the tire;

wherein multiple complex reflection coefficients are obtained and multiple root-mean-squared errors are calculated during the continuing to monitor at different times during the curing of the tire in the curing press;

wherein the multiple calculated root-mean-squared errors at different times are used in the using step to determine whether to stop the curing of the tire in the curing press.

13. The method of manufacturing as set forth in claim **12**, further comprising calculating means of the multiple root-mean-squared errors at the various times, wherein the calculated means are used in the using step to determine whether to stop the curing of the tire in the curing press.

14. The method of manufacturing as set forth in claim **12**, further comprising calculating the standard deviation of the multiple root-mean-squared errors at the various times.

15. The method of manufacturing as set forth in claim **1**, further comprising stopping the curing of the tire in the curing press.

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