INTERNATIONAL JOURNAL OF APPLIED TECHNOLOGY RESEARCH
2020, VOL. 1, NO. 2, PP. 98-109
https://ijatr.polban.ac.id/ijatr/

Manufacturing Process beyond Conventional Plasticity Theory: Case Study in Manufacturing Low Spring Index Coil

[a]Yunan Prawoto*, [a]S. Manville, [b]T. Sakai, [c]M.Tanaka, and [d]T. Gnauple-Herold

[a]NHK International Co. 46855 Magellan Dr. Novi MI 48377 USA
[b]NASCO Spring USA, 3251 Nashville Road, Bowling Green, KY 42101 USA
[c]NIST Center for Neutron Research, 100 Bureau Dr. Gaithersburg, MD 20899 USA

Received 2 July 2020; accepted 12 September 2020

ABSTRACT
In the academic world, conventional plasticity theory limits the cold process due to energy inefficiency, material properties and residual stress that may inhibit the quality of a product, and therefore usually not recommended. However, industrial competition pushes that limits against the edge. Knowing the consequences in advance helps reducing the damage that may have been caused by such a violation. This paper shows an example in the form of a case study. A coil spring with a very low spring index that academically suggested to be made using hot process was attempted to be manufactured using cold coiling machine. The case study shows that although it is possible, extra careful and timely handling must be done to successfully manufacture it. A coil with excessive residual stress is shown in this paper. That residual stress alone was capable in damaging the coil during manufacturing. The defect takes place after coiling and before tempering process. A fracture mechanics was used to analyze the failure, which is the splitting due to excessive residual stress. The case study also shows that the problem can be solved by speedy and subsequent stress relieve annealing process.

KEYWORDS
Residual stress
Neutron diffraction
Cold forming
Stress intensity factor
J-integral

INTRODUCTION

The demand of weight reduction in automotive industry forces the suspension spring manufacturers to use higher strength steel in order to meet the demand from the customers. The traditional approach in forming such materials is based on the hot coiling of the wire at temperature higher than AC_3 line to increase material formability while the material is still in Austenite form. This method has been taught at almost every university worldwide. From the theory of plasticity, this is the only way in making a bending on a large object. Recent development however, is to manufacture the coil spring in cold forming at the martensitic form. Consequently, the coiling process becomes extremely critical because the formability of these high-strength martensitic steel is usually very low, compared to austenite in the case of hot coiling.

Conventional wisdom in spring making has been dependent on spring index. A spring index up to 3.9 cannot be manufactured, while spring index between 4 to 5 falls in the difficult to

*Corresponding Author: yunan.prawoto@nhkusa.com

manufacture category, too much stress on the tooling and higher possibility in cracking during manufacturing process which results in higher cost to manufacture. The spring index in the range of 6 to 12 is known to be the preferred choice for coil manufacturers. Above 12, the tolerance becomes an issue and coil manufacturers typically cannot meet the drawing provided by the design engineers[1].

Cold forming of the wire can be extremely difficult triggering manufacturing failure caused by the breakage of the spring and splitting. These types of problem for some manufacturers that used to hot coiling could be a troublesome. Similar problems in cold coiling are also reported in several other publications[2,3]. In their paper, Matejicek *et.al*[3] used neutron diffraction and found the residual stress mainly responsible for splitting.

In this study, a coil that was considered impossible to make (very low spring index) with cold coiling was intentionally made. The coil was than split by itself due to excessive residual stress. Speedy and subsequent stress relieve annealing was proven to cure the problem.

THEORY

To approach the problem, basic knowledge of fracture mechanics is needed. The residual stress is converted to stress intensity factor and subsequently used to analyze the splitting. In this case, Mode I and Mode II are used in the analysis simultaneously, instead of *J*-Integral concept that is more suitable for softer materials[4]. Since the material is very hard and brittle, as it is discussed in the metallography section, the approach to use the stress intensity factor is fully justified. Recall that the stress intensity factor, *K*, is used in fracture mechanics to predict the stress state near the tip of a crack caused by a remote load or residual stresses. It is a theoretical idea applied to a homogeneous, linear elastic material and is useful for providing a failure criterion for brittle materials and is a favorite technique in the discipline of damage tolerance. The value depends on sample geometry, the size and location of the crack, and the magnitude and the modal distribution of loads on the material. The stress state near the crack

$$\sigma_{ij}(r,\theta) = \frac{K}{\sqrt{2\pi r}} f_{ij}(\theta) \tag{1}$$

where

K – is the stress intensity factor

f_{ij} – is a dimensionless quantity that varies with load and geometry

In our case, the Mode I and Mode II respectively is

$$K_I = \lim_{r\to 0} \sqrt{2\pi r}\, \sigma_{yy}(r,0) \tag{2a}$$

$$K_{II} = \lim_{r\to 0} \sqrt{2\pi r}\, \tau_{xy}(r,0) \tag{2b}$$

The failure criterion in this case, is taken as

$$K_c \leq \sqrt{K_I^2 + K_{II}^2} \tag{3}$$

Where K_c is the material fracture toughness. This approach is believed to be much better and more suitable than the conventional failure criteria, such as Tresca or Von Mises failures[5,6].

EXPERIMENT AND SIMULATION

Figure 1 shows the representative appearance of coil made and splatted due to too much residual stress. Suspicion is due to excessive residual stress created during coiling. For the purpose of evaluation FEA simulations, neutron diffraction and X-ray residual stress measurement.

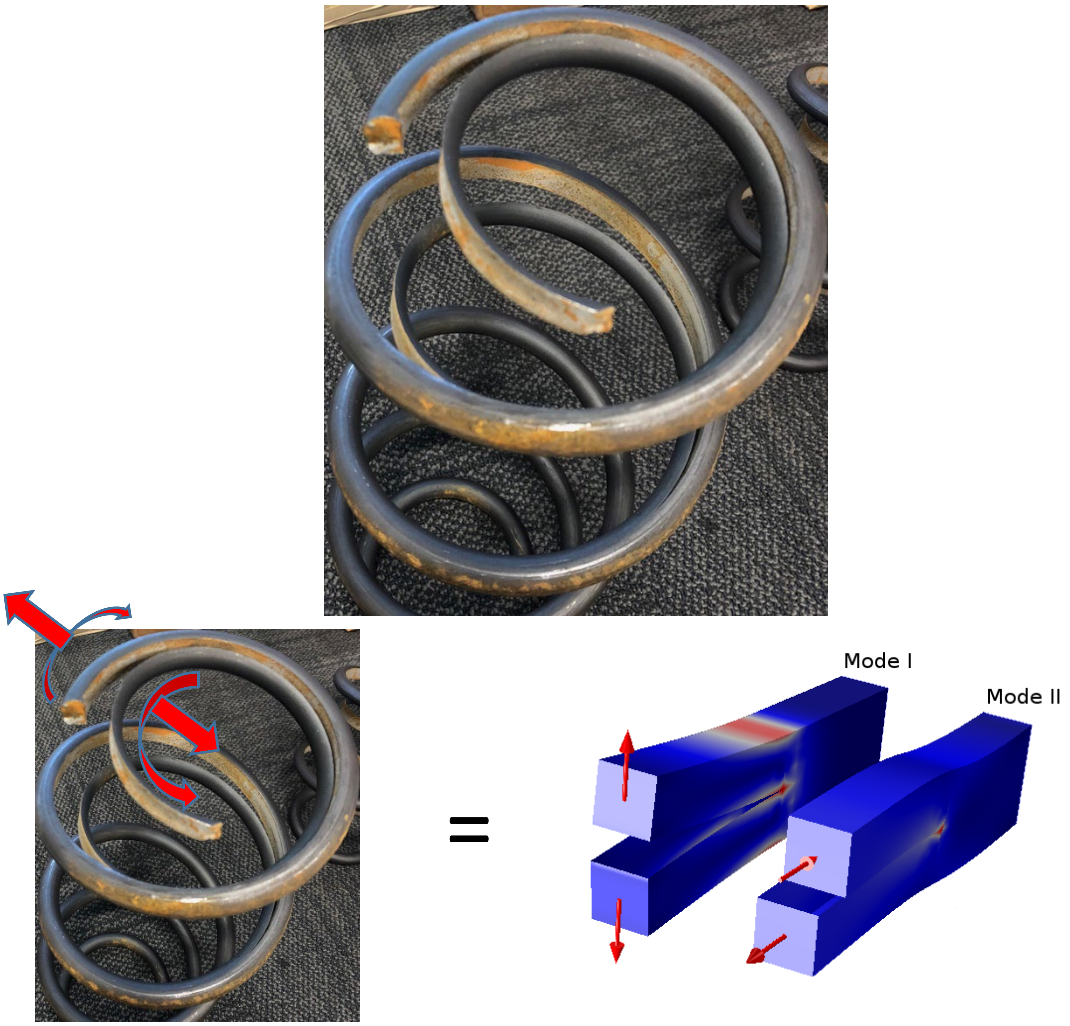

Figure 1. Appearance of the Splitting that takes place after coiling before stress relieve annealing. The picture also shows the concept for the usage of mixed mode

FEA Simulation

Figure 2 shows the initial set up of the model. The model mimics the real experiment, where the wire is fed into a wire-feeder and eventually shaped into coil using Roller 1 and Roller 2. Both rollers are constrained as rigid bodies having 0.1 friction coefficient relative to the wire. The rollers can spin with respect to its center axles with the friction coefficient of 0.3 relative to the axles. The friction coefficient between the wire and the wire-guide is also 0.3. This variation of the friction coefficient is able to produce similar situation with the experiment where the angular displacement at the surface of the roller is slower than wire displacement due to the wire being pushed.

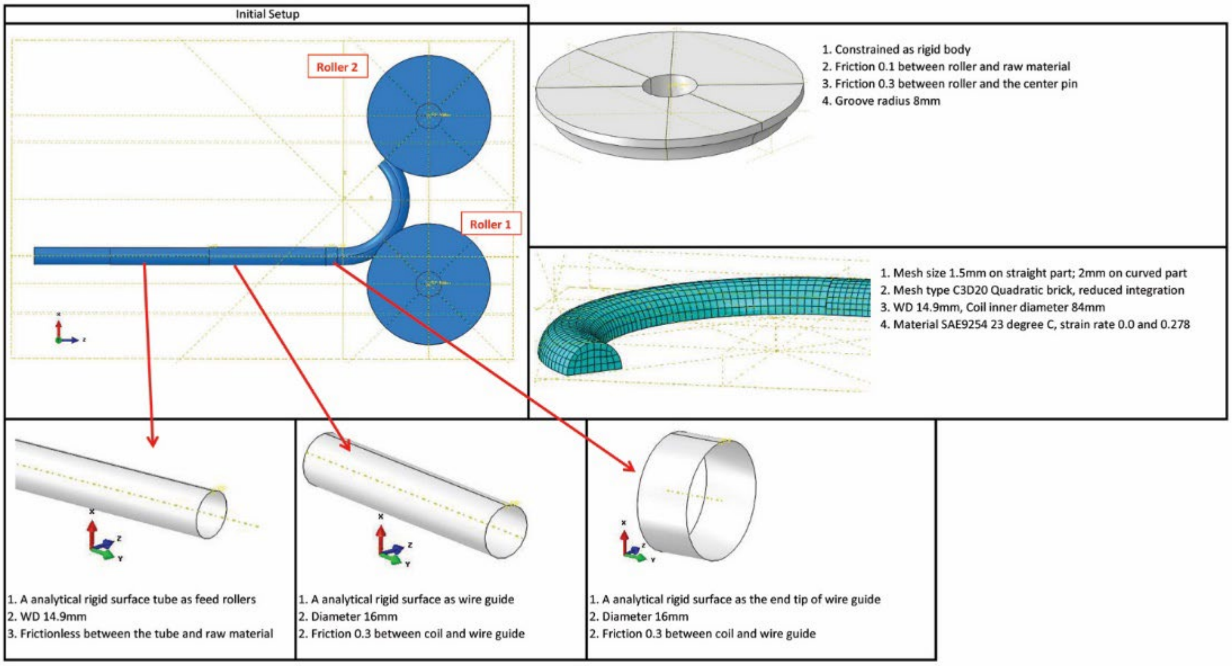

Figure 2. Initial set up of FEA model

In general the procedure consists of two steps. The first step is to feed the wire, until an additional of more than 180^{0} of new coil is formed. In this step, it simulates the coil manufacturing, where the energy supplied to the system is used to plastically bend the wire and the slipping between the wire and the roller, as well as the rotation of the rollers. The first step is ended by stopping the displacement of the left end of the wire. This first step left the system in an elastic equilibrium of the wire giving a compression to the roller. The second step is to move the rollers away from the wire leaving the wire in the coil shape. At this step, the spring back of the coil due to the removal of elastic compression experienced by the wire to the rollers takes place. Consequently, the coil shape is changed from the original shape obtained in step 1. The simulation is completed after the second step.

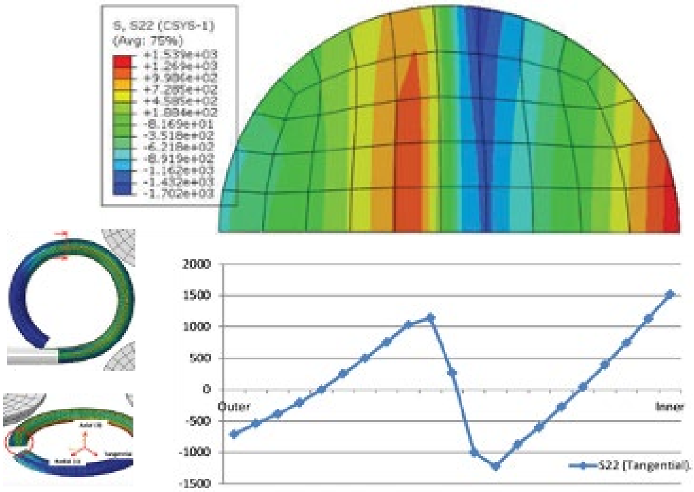

Figure 3. Tangential (wire direction) residual stress distribution

The change from the straight wire to coil basically takes place in a mixture of compression and tension inside the system. Furthermore, the degree of the plastic deformation also varies a lot. As a result, the system consists a variation of residual stress due to new equilibrium of the wire being in the shape of coil. The analysis result is retracted as stress residue in all elements. With some coordinate manipulations, the results are presented here. Figure 3 shows the result of the tangential residual stress, which is the residual stress in the wire direction. It is like what we expect the longitudinal stress distribution to be, as the stress in this direction is the residue of the applied bending moment in classical mechanics:

$$\sigma_T = \frac{My}{I} \tag{4}$$

where σ_T is the tangential/hoop stress, M is the applied moment, y is the distance from the neutral axis and I is the moment of inertia of circular cross section, $\pi r^4/4$. According to Equation (4), the applied stress due to the moment given during coiling would become tension at the outer diameter of the bending and compression. Figure 4 illustrates the estimate of tangential residual stress. This concept is to make the system to be in both force and moment balance, an imaginary negative moment is introduced. Similar concept can be used to comprehend the radial direction of stress, shown in Figure 4. In the case of stress in radial direction the problem becomes similar to that of thick walled cylinder problem where the stress in the radial direction is formulated by:

$$\sigma_r = \frac{E}{1-v^2}\left(\frac{du}{dr} + v\frac{u}{r}\right) \tag{5}$$

where σ_r is the radial stress. The term (du/dr) is actually the radial strain, ε_r. Equation (5) for our system cannot be solved easily since they form partial differential equations that involves two constants that require two boundary conditions that the difference is too small to be even considered. This direction of stress is usually neglected. However for this particular investigation, this stress is not neglected despite its small amount, maximum about 50 MPa. This is far from the tangential stress value, which is above 1000MPa. The radial direction of residual stress here is computed because it relates directly to Mode I falure discussed in Equation (2a) and eventually in Equation (3).

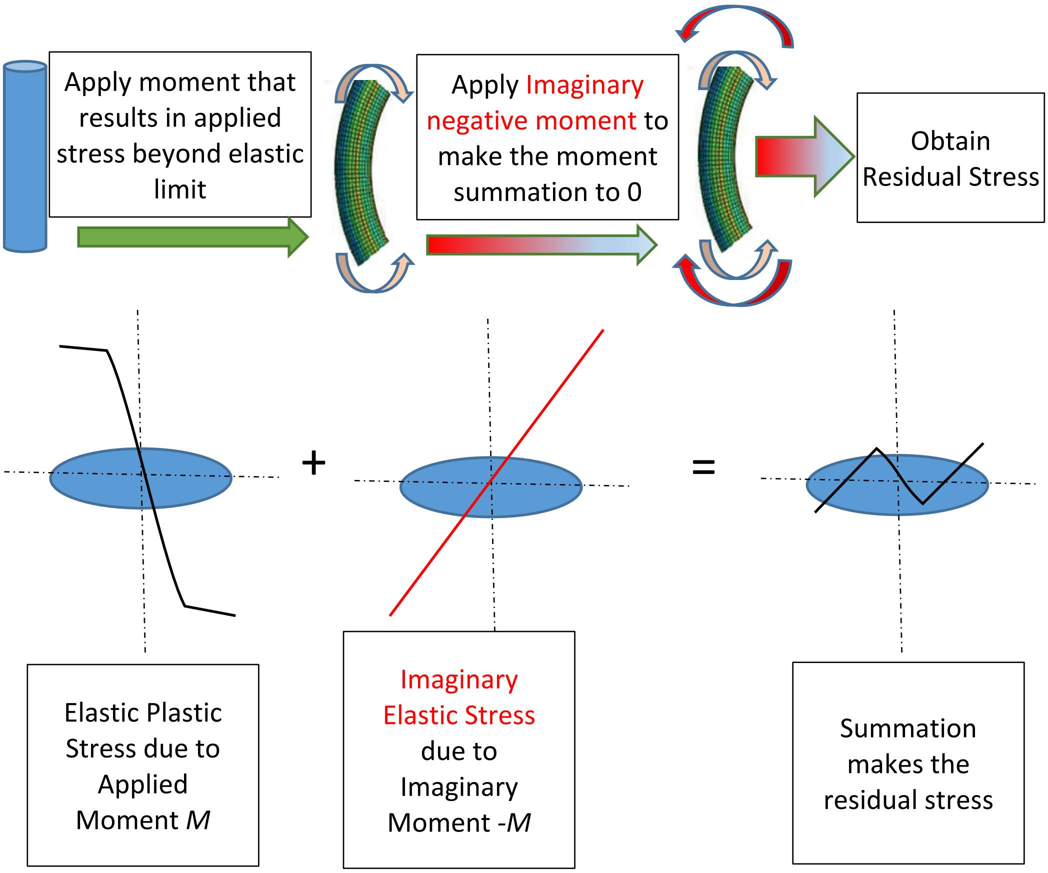

Figure 4. Illustration of tangential stresses at the wire, note that the imaginary moment only creates elastic stress

What more significant is the shear stress at the same location. The shear stress is related directly to Equation (2b), which is Mode II in fracture mechanics and eventually to Equation (3). Figure 5 shows the distribution of the residual shear stress. This is the most important aspect in this research since this Mode II is also the factor that contribute to the splitting along with Mode I as it is shown in Equation (3). Figure 6 can be understood by the concept of shear stress in beam in classical mechanics:

$$\tau_T = \frac{V}{I\,b}\int_{y0}^{c} y\,da \tag{6}$$

where τ_T is the shear stress, V is the applied shear load which in our case is $V = \frac{dM}{dx}$. Recall that M is the applied moment used in Equation (4) y is the distance from the neutral axis and I is the moment of inertia of circular cross section, $\pi r^4/4$, while b is the width. The integral part would be in the form of first moment, which is the area of wire cross section.

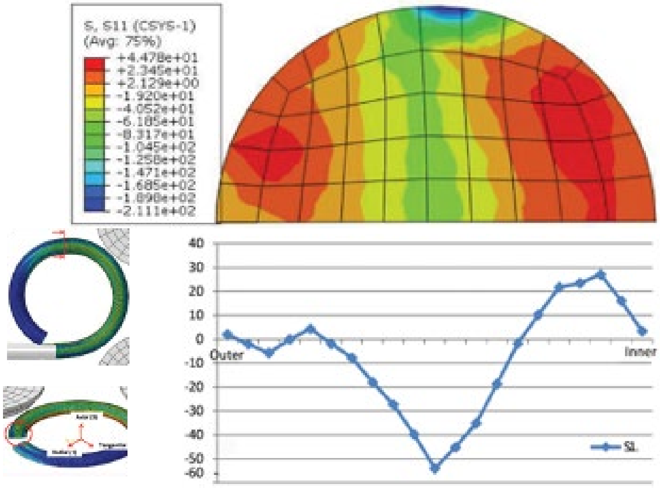

Figure 5. Radial (Coil radius direction) residual stress distribution. In here this stress is related directly to Mode I of fracture mechanics

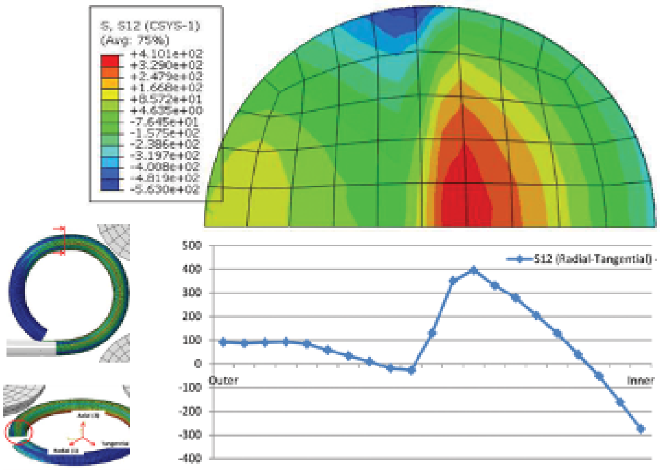

Figure 6. Shear (Radial-Plane;Tangential-direction) residual stress distribution. In here this stress is related directly to Mode II of fracture mechanics

Neutron and X-ray Diffraction Analyses

The measurement of residual stress with neutron diffraction is based on measurements of changes in crystal lattice spacing, which manifest themselves as shifts in angular position of respective diffraction peaks, according to Bragg's law:

$$n \cdot \lambda = 2d \sin\theta \quad (7)$$

where
n is the reflection order
λ the radiation wavelength
d the plane spacing, and

The strain can then be computed by:

$$\varepsilon = \left(\frac{d - d_0}{d_0}\right) \tag{8}$$

Where
ε is the strain in a particular direction
d the stressed, and d_o the unstressed interplanar spacing

The stress components can be calculated as:

$$\sigma_{11} = \frac{E}{(1+v)(1-2v)}[(1-v)\varepsilon_{11} + v(\varepsilon_{22} + \varepsilon_{33})] \tag{9a}$$

$$\sigma_{22} = \frac{E}{(1+v)(1-2v)}[(1-v)\varepsilon_{22} + v(\varepsilon_{11} + \varepsilon_{33})] \tag{9b}$$

$$\sigma_{33} = \frac{E}{(1+v)(1-2v)}[(1-v)\varepsilon_{33} + v(\varepsilon_{11} + \varepsilon_{22})] \tag{9c}$$

In our case, σ_{11} is the stress in tangential direction, while the σ_{22} is the stress in the radial direction, see Figure 7. The gage volume for this measurement was 1.5mm x 1.5mm x 1.5mm. Figure 8 shows the measurement results. The tendency of the residual stress measured by neutron diffraction is similar to that of the FEA computational results. However, the residual shear stress can only be calculated and not measured by neutron diffraction.

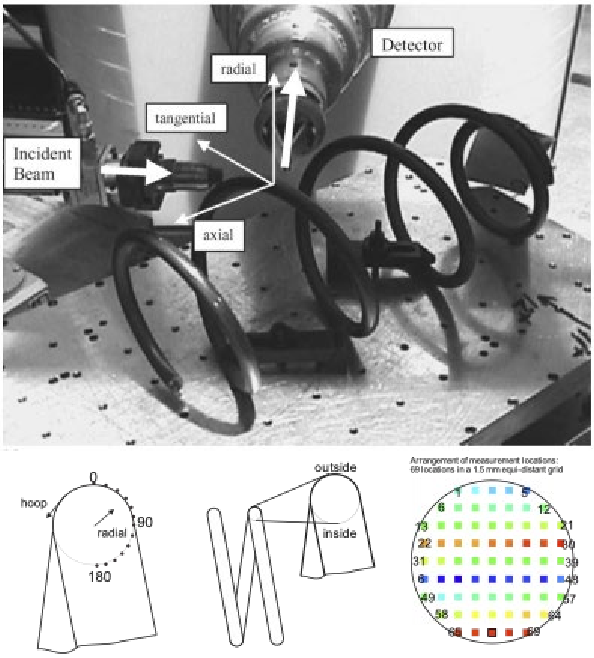

Figure 7. Measurement orientation is to mimic the measurement of Matejicek's[3]. The lower diagram shows the coordinate and points of measurements

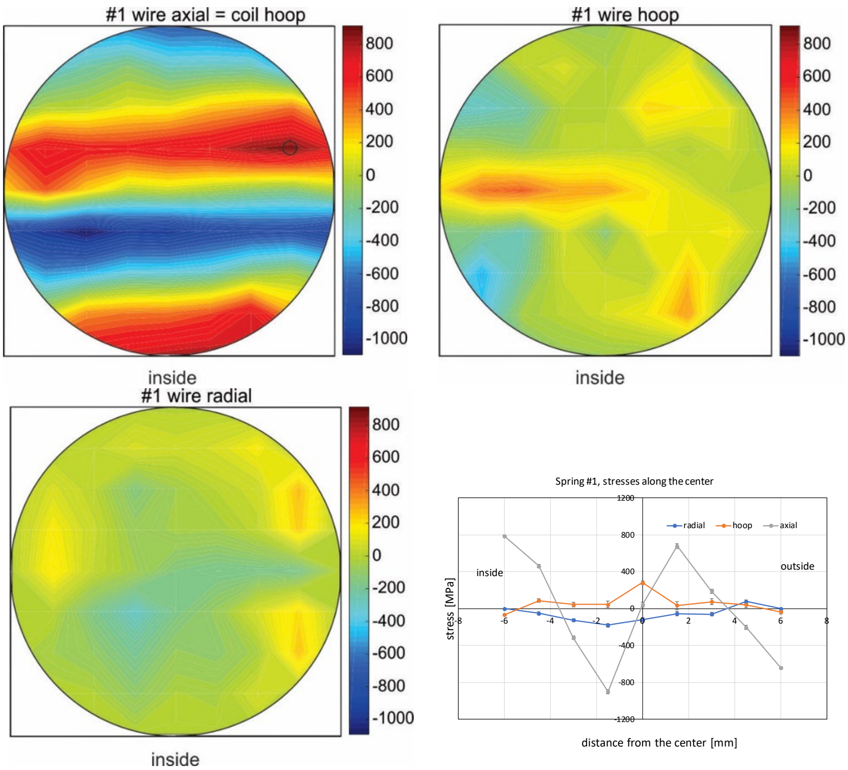

Figure 8. Neutron diffraction measurement results for spring

DISCUSSIONS

Qualitatively, one can get the idea that excessive residual stress caused the splitting to take place after the cold coiling process. However, to what extend does the residual stress can cause the splitting remains unexplainable, since the classical mechanics only states that if the Von Mises stress is lower than the UTS, no splitting can ever take place. If the generalized concept is used, the maximum average stress would never even crack the sample, given the fact that the residual stress value is not even 80% of the material's ultimate tensile strength.

In this research, the idea is to get explanation on why the splitting takes place only with residual stress. To do that, the stress intensity factor is brought in. Furthermore, the concept of weight function is also adopted in converting the residual stress to residual stress intensity factor.

$$K_I = \int_0^a \sigma^R(x) h_I(x,a) dx \tag{10}$$

and

$$K_{II} = \int_0^a \tau^R(x) h_{II}(x,a) dx \tag{10}$$

where $\sigma^R(x)$ and $\tau^R(x)$ are the normal residual stress and the shear residual stress along the crack prospective line, respectively. K_I and K_{II} are Mode I and Mode II stress intensity factors and $h_I(x,a)$ and $h_{II}(x,a)$ are the weight functions that depend solely on the geometry[8–10]. Generally the value of the weight function is computable through:

$$h(x,a) = \frac{H}{K(a)^{(1)}} \frac{\partial u^{(1)}(x,a)}{\partial a} \tag{11}$$

H is E for plane stress condition and $\frac{H}{1-v^2}$ for plane strain condition. $K(a)^{(1)}$ and $u^{(1)}(x,a)$ are respectively the known stress intensity factor and the crack face displacement. To find those, another help of FEA was utilized. A model to mimic this was created, subsequently the stress intensity factor, $K^{(1)}$ is calculated and the displacement function $u^{(1)}$ also obtained. For this purpose, the computation was via J-Integral and the following relation is used.

$$J = K^2 \frac{(1-v^2)}{E} \tag{12}$$

The correlation of the displacement behind the crack, the crack face displacement, $u^{(1)}(x,a\ )$ was obtained by FEA. At the same time, the corresponding $K(a)^{(1)}$ was also obtained. The analysis to simulate both Modes I and II were performed by giving a dummy displacements of unity. Subsequently the relation of the displacement vs. stress intensity factor can be obtained. Computation results in the value of K 85.2 $MPa\sqrt{m}$, which is above the critical value of the fracture toughness.

CONCLUSIONS

Spring manufacture with cold coiling process has possibility of splitting during manufacturing. The defect can be minimized by subsequent residual stress relieve annealing.

REFERENCES

Childs, P. R. N. *Springs. Mechanical Design Engineering Handbook* (2014). doi:10.1016/B978-0-08-097759-1.00015-0 .

Guido, B. & Manuel, M. Experimental and numerical analysis of the cold forming process of automotive suspension springs. 1–18 (2011).

Matejicek, J., Brand, P. C., Drews, A. R., Krause, A. & Lowe-Ma, C. Residual stresses in cold-coiled helical compression springs for automotive suspensions measured by neutron diffraction. *Mater. Sci. Eng. A* 367, 306–311 (2004).

Prawoto, Y. & Onn, I. H. Application of J-integral concept on blister coating problem. *Eng. Fract. Mech.* 92, 114–125 (2012).

Chao, Y. J. Ultimate Strength and Failure Mechanism of Resistance Spot Weld Subjected to Tensile, Shear, or Combined Tensile/Shear Loads. *J. Eng. Mater. Technol.* 125, 125 (2003).

Qu, R. T., Zhang, Z. J., Zhang, P., Liu, Z. Q. & Zhang, Z. F. Generalized energy failure criterion. *Sci. Rep.* 6, 1–8 (2016).

Vilela Costa, L., Gonçalves Carneiro, J. R., Pinto Coelho Catalão, R., Ribas, O. K. & Brito, P. Residual Stress Gradients in AISI 9254 Steel Springs Submitted to Shot Peening and Heat Treatment for Increased Fatigue Resistance. *Adv. Mater. Res.* 996, 749–754 (2014).

Fett, T., Tilscher, M. & Munz, D. Weight functions for cracks near the interface of a bimaterial joint and application to thermal stresses. *Eng. Fract. Mech.* 56, 87–100 (1997).

Fett, T. Stress intensity factors and weight function for a void with an annular crack. *Int. J. Fract.* 67, (1994).

Coules, H. E., Horne, G. C. M., Abburi Venkata, K. & Pirling, T. The effects of residual stress on elastic-plastic fracture propagation and stability. *Mater. Des.* 143, 131–140 (2018).