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Removal of Residual Stress of Zr Alloy Thin Sleeve Tube

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1. Introduction

The objective of this study is to find the influx of residual stress on Zr Alloy Thin Sleeve Tube during the manufacturing process and solution to residual stress. The residual stresses on thin sleeve tube are normally generated from pilgering process which reduces tube OD & wall size on the purpose of forming adequate mechanical property for nuclear fuel and they appear in the form of distortion in the process of slotting thin sleeve tube which obstructs the assembly in the nuclear fuel, causing larger outer diameter. The feasibility of the process application of the solution to residual stress on Zr Alloy Thin Sleeve Tube was verified through the relevant tests.

2. Methods and Results

The created stresses in the tube manufacturing processes did not reveal itself until after the slot was made. For more details, the stresses caused the tube to "spring out" after the slot was added to the sleeve. This distortion in thin sleeve is the reason the slotting process was unable to meet the ovality tolerance on the machined OD when cutting and installing these sleeves in the nuclear fuel assemblies. The bigger concern is that it is difficult to detect the residual stress on thin sleeve tubes in the manufacturing process ahead of slotting thin sleeve tube, which results in massive tube loss at the step of final products. Therefore, it is more important to solve the problem in the manufacturing process rather than applying solution after slotting thin sleeve tubes.
In order to find where this residual stress on sleeve comes from among manufacturing steps, the anticipated processes that affect residual stress were selected and narrowed down to two processes such as stress relief annealing and straightening process. The two processes were separately tested to observe any change in terms of residual stress before and after applying each process.

2.1 Relief of Residual Stress during Stress Relief Annealing

2.1.1 Soaking time at stress relief annealing

One of the objectives of tube annealing is to make tube stress relief after residual stresses on tubes are created from OD&wall reduction process.
It was previously found that 7 hours for stress relief annealing was effective time but it was not as effective as that of experimental annealing compared to heavy weight annealing.
The soak time at temperature for the stress relief annealing is comprised both the time for the tubes to get to the target temperature and the time at soak temperature in the case of heavy weight annealing whereas that for the experimental annealing is comprised of only the time at temperature. The difference comes from the different weight charge in the furnace between experimental annealing and heavy weight annealing circumstance. It was estimated from the previous study that all tubes would be at the target temperature after spending a few hours at the maximum weight charge of furnace during heat treatment of 7 hours under argon gas.
In addition, the difference is affected by the reason that the thin sleeve tubes need to be inserted into stainless tubes to avoid damage in the furnace. Sleeving will affect the load in the furnace which affects ductility and could eventually influence distortion.
As a result of the different conditions between the experimental annealing and heavy weight annealing, it was confirmed that annealing the sleeve in the furnace only for 7 hour sock is not long enough to receive an adequate degree of stress relief anneal to eliminate the residual stresses that were initially generated from pilgering process which reduces tube OD & wall size on the purpose of forming adequate mechanical property for nuclear fuel.

2.1.2 Re-annealing thin sleeve with residual stress

In an effort to determine if additional time for re annealing will be effective to remove residual stress on sleeve tubes, re-stress relief annealing test was performed at the same level of temperature. Through the test, it was found that re-annealing for 1.25 hour, relieves the residual stress, thereby at least considerably reducing residual stress on tube which results in less distortion that used to be observed after wire cutting first of two pairs of slits on one end of the sleeve cross section. These test results and study represent the feasibility that the extension of annealing time can be effective to reduce residual stress on thin sleeve tubes at the same annealing temperature considering the effectiveness of stress relief annealing can be accumulated in proportion to the total effective annealing time despite of discontinuance of annealing.
Fig.1 shows the change to OD size following slotting thin sleeve tubes before and after re-annealing for 1.25 hour and maximum OD sizes of thin sleeves are

reduced after re-annealing. Even though not all test samples meet OD acceptance criteria, most of them got closer to acceptance criteria, which means the less residual stresses on tubes remain after re-annealing.

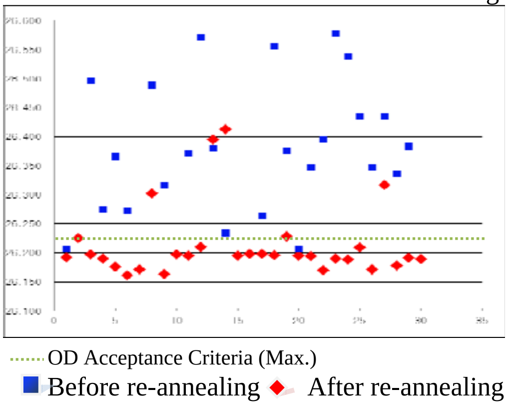


Fig.1.Chart about the change to maximum OD size of thin sleeve tubes before and after re-annealing

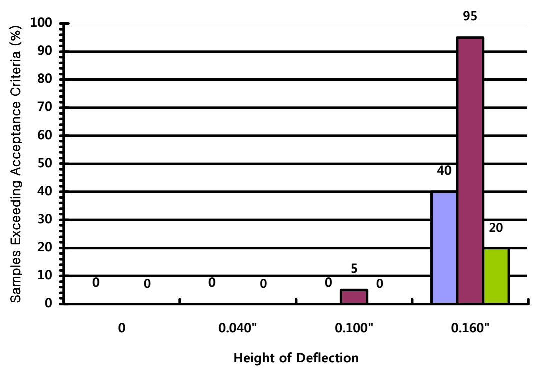
Apart from re-annealing test for 1.25 hour, another re-annealing trial for 7 hours was performed with new test tube samples with residual stresses to demonstrate all test samples can meet the acceptance criteria by the re-annealing at the same temperature as the target annealing temperature. After it was confirmed that all test samples met the acceptance criteria, it was expected that application of pre-heating for a few hours can be on behalf of 7 hours re-annealing as long as the effectiveness of stress relief annealing is accumulated in proportion to the total effective annealing time.

2.1.3 Implementation of adequate pre-heating before stress relief annealing

Based on the test results from the re-annealing, it was anticipated that application of pre-heating time prior to the stress relief annealing is an effective solution to avoid the consuming time to get to the target temperature in soak of 7 hours. As a result of adopting pre-heating time for a few hours, which is minimum time to have the adequate effectiveness of pre-heating for the stress relief annealing, all sample tubes were found acceptable to pass Max. OD acceptance criteria. Residual stresses on sleeve tubes were thereby reduced enough for the level of nuclear fuel assembly process.
On the other hands, the difference in final mechanical properties raised from the application of pre-heating for a few hours at the same temperature as the following annealing temperature would be small considering the stress relaxation characteristics of thin sleeve tube, and it was found that all related mechanical property such as corrosion, tensile and grain size met acceptance criteria, showing the values from each test were not remarkably different from previously performed process qualification results. The pre-heating time was thereby optimized to stabilize annealing condition.

2.2 Influx of Residual Stress from Tube Straightening Process

Apart from adopting pre-heating time at stress relief annealing, a test for checking residual stress per deflection of the straightener rolls was performed following tube straightening process. Review of results from the test indicated that the reason for the observed distortions in some tubes was due to the use of higher deflection of the straightener rolls by squeezing the tubes between the top and bottom rollers during machine straightening used for tube straightness. When the deflection is high, tubes tend to be squeezed which leads to residual stress in the material as Fig2. shows the higher deflection the straightener applies, the higher failure the samples present. Eventually, the residual stress appears as a form of distortion when cutting and installing these sleeves in the fuel assemblies. Therefore, it was found that application of lower deflection in the straightening process is the solution to avoid influx of residual stress.



Note]
-Violet : Percents of samples exceeding Max.OD (Spec limit)
-Purple : Percents of samples exceeding Max.OD (In-house limit)
-Green : Percents of samples exceeding Min. ID

Fig.2. Percents of samples exceeding Max. OD size or Min. ID per height of straightening deflection following slotting sleeve tubes

3. Conclusions

It was found that supplemental pre-heating at the target temperature prior to stress relief annealing is an effective way to reduce residual stress on sleeve tubes. Apart from the stress relief time, high deflection of straightening is the other reason that causes residual stress on thin sleeve tubes for nuclear fuel.
Following the implementation of adopting pre-heating and minimizing deflection to lower tube squeeze in the tube manufacturing process, it was found that the level of distortion was significantly reduced enough to apply these solutions to thin sleeve manufacturing process.