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# Estimation the Remaining Life for Reformer Unit Tubes Furnace Operated Beyond the Design Life

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## Abstract

The aim of this work is to study and model creep damage accumulation for remaining safe working life estimation of tube material used in petroleum industry plants operated at a high temperature for long time beyond the design life. Material constants and other data required for life estimation were extracted from the output results of real accelerated creep rupture tests conducted at three test temperatures (700, 725, and 750)°C and at three constant stress applications (120, 130, and 140 MPa). Also, a time-temperature parameter method (Larson-Miller Method) was modified to be applied based on the results of the accelerated creep rupture tests to build life predicted master curve for austenitic stainless steel type 321H. It is found that creep rupture time for stainless steel alloy decreases as temperature or stress increase. Also, it distinguished from the creep curves for the serviced stainless steel alloy, that the onset of tertiary creep stage starts early (about 50% of creep curve), this reflects the reduction in creep strength of the alloy as a result of the degradation in alloy properties that take place during the service life. It is also found that the estimated remaining working life for the serviced tube samples made from austenitic stainless steel type 321H is about (54703 hr) based on the calculated stress level (40 MPa) and service temperature 570 °C. The difference between the estimated remaining life and the experimental creep test life is due to the differences between the applied stresses, where higher level of stresses in the experimental creep testes are used to accelerate failure of specimens. The application for the result of this work can be the petroleum industries that where heaters tubes serviced at such industry need to be estimated for the remaining life after the design life expire.

**Keywords:** austenitic stainless steel, creep life, remaining life, tube furnace, Larson-Miler parameter.

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# تقدير العمر المتبقي لانابيب افران وحدة انتاج البنزين العاملة الى ما بعد العمر التصميمي


## الخلاصة:

الهدف من هذا العمل هو دراسة نموذج لتراكم ضرر ظاهرة الزحف لغرض تقدير العمر الامن المتبقي لمواد انابيب تستخدم في وحدات الصناعة النفطية والتي تعمل منها بدرجات حرارة عالية ولفترة طويلة الى ما بعد العمر التصميمي. ثوابت المواد والبيانات الاخرى المطلوبة لتخمين العمر المتبقي تم استخراجها من النتائج التي تم الحصول عليها من اختبارات حقيقية للزحف بظروف معجلة تم اجرائها بثلاث درجات حرارة (700، 725، 750)°م، وبتطبيق ثلاث قيم للاجهادات الثابتة خلال كل اختبار وهي (120، 130، 140) ميكاباسكال. كذلك تم تطوير طريقة معاملات الزمن-حرارة والتي يطلق عليها بطريقة لارسن-ميلر وتطبيقها باستخدام نتائج اختبارات كسر الزحف المعجلة لبناء المخطط الرئيسي لتخمين العمر لسبيكة الفولاذ المقاوم للصدا الاوستنايتي من النوع 321H. من خلال البحث وجد ان سبيكة الفولاذ المقاوم للصدأ اظهرت نقصان الزمن اللازم للكسر الناتج عن الزحف عند زيادة درجة الحرارة او الحمل المسلط. كذلك يمكن تمييز ان بداية المرحلة الثالثة في منحنيات الزحف لسبيكة الفولاذ المقاوم للصدأ والتي كانت في الخدمة قد ظهرت بمرحلة مبكرة (تقريباً 50% من منحني الزحف)، وهذا يعكس النقصان الحاصل في مقاومة الزحف للسبائك كنتيجة للاضمحلال في خصائص تلك السبائك والحاصل خلال فترة عمر الاشتغال. كذلك وجد ان العمر المتبقي التخميني لعينات سبائك الفولاذ المقاوم للصدأ هي (54703 ساعة) عندما يكون الاجهاد المسلط بحدود (40 ميكاباسكال). ان الفرق بين العمر التخميني المتبقي و العمر الناتج عن اجراء اختبار الزحف ناتج عن الفرق في الاجهاد المسلط، حيث تم استخدام اجهادات بمستوى اعلى في اختبارات الزحف لغرض تعجيل الفشل في عينات الاختبار. يمكن تطبيق نتائج البحث في الصناعة النفطية على انابيب الافران الحرارية التي تحتاج الى تقدير العمر التشغيلي المتبقي بعد انتهاء العمر التصميمي.


## 1. Introduction:

Equipment such as furnaces operated in critical industries, such as oil, gas, energy, and nuclear industries are subject to types of failures that may cause disasters at various levels. Furnaces used to heat up hydrocarbons up to the required temperature to meet the requirement of the plant process, see Figure (1a). This equipment can be represented as the heart of the process in such plants. The engineering components (tubes) of that equipment are experience types of damages as a result of the service under severe conditions of temperature and pressure according to their design requirements and for long periods of time.[1] Such equipment usually designed for working life about (100000 hr) based on API-530 standard.[2] Since the effect of increasing the operational temperatures is destructive to engineering materials, it is necessary to deal with such problem and find solutions to keep up with these variables. The decision to replace tubes of furnace individually or totally in early stage of life design as a precaution procedure to eliminate the sudden failure is not a good idea, because each tube will cost several thousands of dollars. On the other hand, running the plant beyond the design life without any precautions is also a risky decision, because a probable failure may happen in tubes suddenly without any previous warnings that may lead to a catastrophic fire in the plant.[3] Good selection of materials is one

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method to deal with such problem, where the selected materials should have the ability to resist the accumulated damage resulting from the creep in addition to the corrosion and oxidation resistances at high temperatures.[4] Intergranular chloride stress corrosion cracking initiated in heater tube made from 321 stainless steel, serviced in crude distillation unit at elevated temperature for long term led to sensitization and high temperature sulphidation.[5] Creep is the time-dependent strain that occurs after the application of constant load, creep behavior usually occurs approximately when ($T > 0.4Tm$), where T and Tm are the absolute operating temperature and absolute melting temperature of that material, respectively. Creep Rupture is the failure of initially crack-free bodies under creep conditions, the failure can be creep ductile or creep brittle in nature.[6] Other method is the suggestion of new mathematical models with acceptable accuracy to predict the rupture life providing the possibility of economical replacement for these parts before a catastrophic failure can happen [7, 8], moreover it maximize the usefulness of the plants by reducing the unscheduled shutdown caused by service failure and also eliminating the unnecessary replacements.

Stainless steel type 321H is a kind of material with excellent stress rupture property and creep resistance of high temperature stress mechanical property. 321H austenitic stainless steel has good corrosion resistance in the atmosphere, and is widely used in petrochemical, electric power, bridge and automobile industries.

Alloy 321H (UNS S32109) is titanium stabilized austenitic stainless steel designed for high temperature applications with good general corrosion resistance. It has excellent resistance to intergranular corrosion after exposure to temperatures in the chromium carbide precipitation range of (427 – 816 °C). The alloy resists oxidation to (816 °C) and has higher creep and stress rupture properties than alloys 304 and 304L. It also possesses good low temperature toughness. [9]

Therefore, the aim of this work is to estimate the remaining service life for engineering parts (austenitic stainless steel tube type 321H) that service at high temperature for long time based on creep effect, this work will try to improve the existed technique (LMP Technique) for estimation. The application for the result of this work can be the petroleum industries that where heaters tubes serviced at such industry need to be estimated for the remaining life after the design life expire.

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## 2. Historical Background:

Reformer/Naphtha Hydrotreater plant at Daura Refinery is in operation since 1981. Subsequently, this plant exceeded its design life, which is 100000 hr. This plant has a number of furnaces in its process sequence with different shapes (Box and cylindrical). There are some examples of cases for mechanical failures lead to fires in furnaces as a result to the service life that exceeding the design lifetime, such examples the fire in 2006 due to tube fracture in furnace F101, see Figure (1b), also another fire happen in 2011 in furnace F102 of the same unit. At 2015, this plant was scheduled shutdown for routine inspection and check; samples of tubes were extracted from a Pretreater Reactor Feed Furnace F101 for remaining life estimation.


**Fig. (1): a) Typical vertical tube furnace b) Furnaces belong to Reformer unit at Daura refinery.**

## 3. Experimental Work:

### 3.1 Chemical Composition and Mechanical Properties:

Samples of tube that used in this work were examined for chemical analysis and mechanical properties. Standard uniaxial tensile test is performed to specimens of austenitic stainless steel 321H materials, using a universal tensile testing machine type Shimatzu AG-25TC. Specimens extracted from samples were made and tested according to the standard (ASTM E8).[10] The aim of these experiments is to record the, yield strength, tensile strength, and elongation. This

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machine is equipped with a device to control the rate of separation for the two heads of the machine during the test; this rate is specified in millimeter per millimeter (mm/mm) of the reduced section length per minute. The displacement rates during the test are:

Up to the yield point = 0.6 mm/min

After the yield point = 2 mm/min

The result of this examination was compared with the related alloy designation according to ASTM standard; see Tables (1) and (2):

**Table (1) Chemical Composition for Stainless Steel Tube Samples (%wt).**

| Element | C | P | S | Si | Mn | Ni | Cr | Ti | Fe |
|---|---|---|---|---|---|---|---|---|---|
| **A-312 TP321H (standard value)[11]** | 0.04-0.1 | 0.045 A | 0.03 A | 1.0 A | 2.0 A | 9.0 – 12.0 | 7.0–19.0 | H | Rem. |
| **Tube Sample (measured value)** | 0.04 | 0.033 | 0.004 | 0.49 | 0.61 | 9.24 | 15.87 | 0.29 | Rem. |

A Maximum

H The Titanium content shall be not less than four times the carbon content and not more than 0.60%.

**Table (2) Mechanical Properties for Stainless Steel Tube samples**

| **Element** | **Yield Strength, min. ksi [MPa]** | **Tensile Strength, min. ksi [MPa]** | **Elongation, min. [%]** |
|---|---|---|---|
| **A-312 TP321H (Standard Tube)[11]** | 25 [170] | 70 [480] | [35] |
| **Element** | **Yield Strength 0.2%, [MPa]** | **Tensile Strength, [MPa]** | **Elongation 32% [%]** |
| **New Tube Sample (measured value)** | [190] | [606] | [69] |
| **Used Tube Sample (measured value)** | [219] | [584] | [49] |

### 3.2 Creep Rupture Tests:

Accelerated creep rupture tests were performed at previous work.[12] Test machine (SATIC) Model JE (maximum capacity 10 ton) is used to carry out test experiments on specimens with a constant uniaxial tension load at two test temperatures (700 and 750$^o$C) and

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three uniaxial test stresses (120, 130, 140 MPa). Creep curves (creep strain versus time) were plotted as a result of these tests. A flat dog bone shape specimen with centerline holes at the two ends was used for creep rupture test experiments. The dimensions of these specimens were designed according to the British Standard B.S. 3500: Part3: 1969.[13] These specimens were extracted from tubes samples longitudinally and made according to (ASTM E-8).[10] Starting from the tubes which were cut longitudinally to strips with a specific width, the strips in this step reserve their outside and inside curvatures. The next step for each strip is grinding to remove the curved surfaces and get a flat strip with a specific thickness (3mm) using grinding machine. The heat generation during machining was inhibited using lubricant to keep the properties of the metal without change. A wire cut machine is used to have a dog bone shape specimen from the flat strips, see Figure (2).

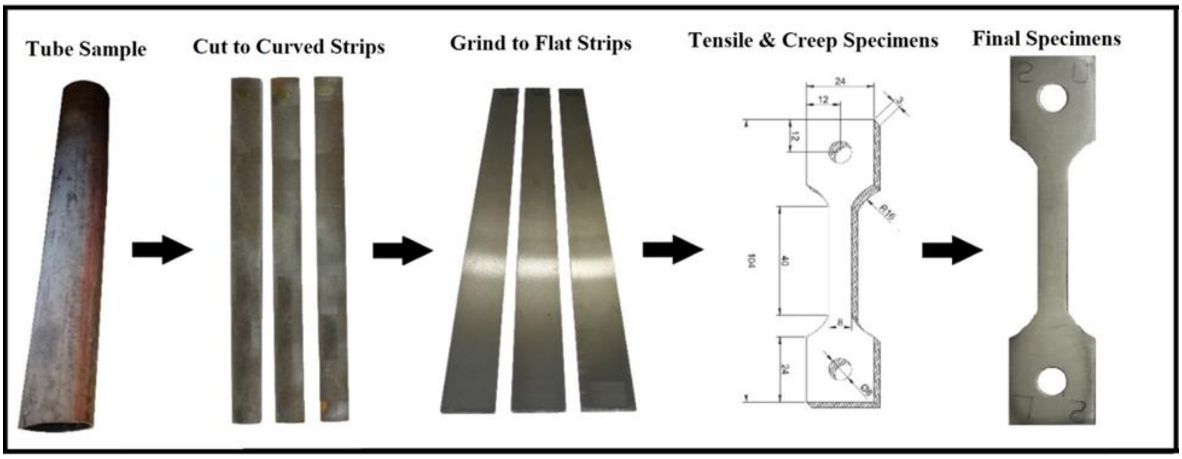


**Fig. (2): Preparing the tensile and creep test specimens (All dimensions are in mm)**

## 4. Modified Time-Temperature-Parameter Technique:

Creep tests were performed for steels at elevated temperatures for very long term (100000 hr) are very expensive and time consumable. In general, there is a need to perform such tests in a much shorter time by means of test acceleration. Time temperature parameter (TTP) approaches (Larson-Miller parameter) was modified and used to extrapolate the available short term creep rupture data used for the life assessment of viscoplastic models. This approach is based on Arrhenius equation, as shown in equation (1):[14]

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$$\dot{\varepsilon}^c = K\, t^m\, e^{-\frac{Q}{RT}}\, \sigma^n \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1)$$

Where, the temperature (T) measured in Kelvin, the time (t) in hours, ($\sigma$) is the stress, ($\dot{\varepsilon}^c$) is the creep strain rate, and ($K, m, n$) are material constant. Taking the logarithms of both sides for the above equation, and reviewing the results creep rupture tests, it can be seen that, at rupture time ($t_r$) the total strain will approximately equal a values from the range (0.35 to 0.45), this is will led to assume that the value of ($\log(\dot{\varepsilon}^c)$) will nearly to be constant, then the above equation will be after re-arranged:

$$T[C_{LM} + m\log(t_r)] = N - T\,[n\log(\sigma)] \qquad \ldots\ldots\ldots\ldots\ldots (2)$$

Where $C_{LM}$ is the Larson-Miller constant, and it is equal to $[C_{LM} = \log(K) - \log(\dot{\varepsilon}^c)]$, and N is equal to [$N$=0.4343$\frac{Q}{R}$ ], where N and n are material dependent factors. The above equation is based on a combination of temperature and the time to rupture, as long as the applied stress is constant, this parameter will remain constant. The equation above is similar to the Larson-Miller parameter equation with the addition of the time exponent (m) that improve the classical Larson-Miller Equation, where MLMP is the modification for Larson-Miler parameter that equal to:

$$MLMP(\sigma) = T[C_{LM} + m\log(t_r)] \qquad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (3)$$

## 5. Results and Discussion:

The following presented creep rupture tests (Strain-Time curves) for samples belong to stainless steel specimens (used and non-used) at different test temperatures and different stress applications. Acceleration of the creep ruptures tests can be achieved by increasing the test temperature up to the range (700 $^{o}$C - 750 $^{o}$C), and the applied stress up to the range (120 MPa-140 MPa), where it has been deduced experimentally that more than these ranges will give a failure due to a very rapid rupture, and less than these ranges give a deformation in a very slow rate which reflects to give a very long time to rupture. For a comparision Parameswaran, et.al.[4] used the same stress range and 650 oC for modified 9Cr-1-Mo steel, also, Mazaheri, et.al.[3] used test temperature between 650-700 $^{o}$C for 9Cr-iMo steel.

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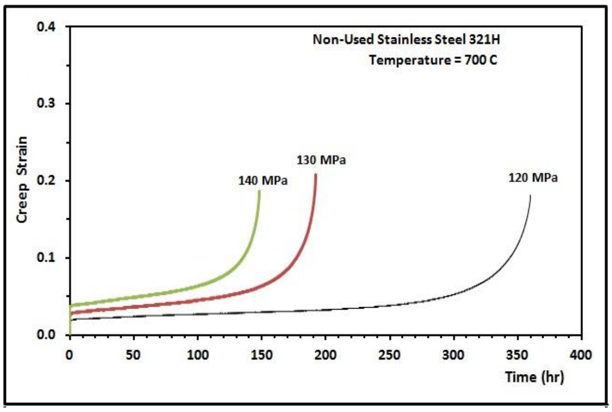


**Fig. (3): Creep rupture tests for a non-used material of stainless steel 321H at different applied stress and at temperatures 700 °C**

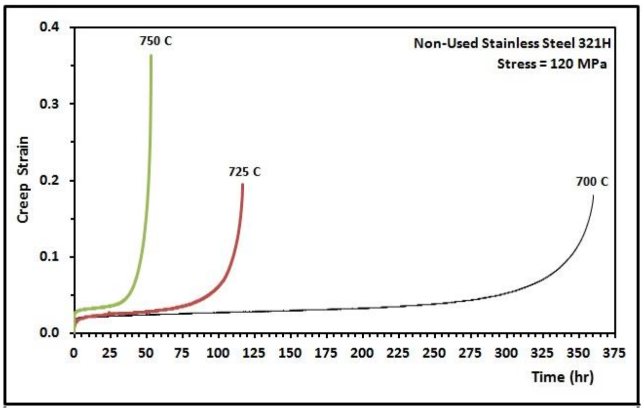


**Fig. (4): Creep rupture tests for a non-used material of stainless steel 321H at different test temperatures and at applied stress 120 MPa**

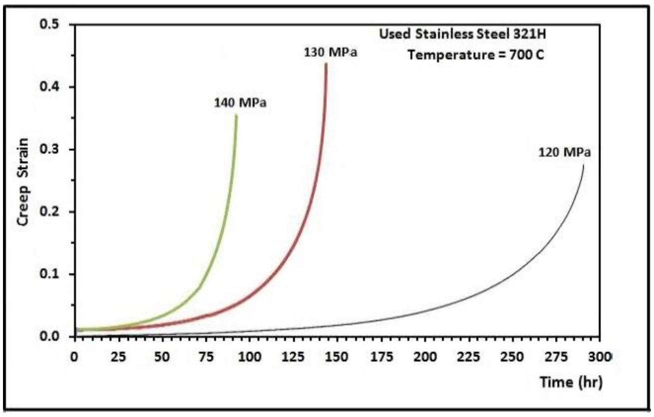


**Fig. (5): Creep rupture tests for a used stainless steel 321H (previous service life about 290000hr at temperature 570 °C) at different applied stress and test temperatures 700 °C**

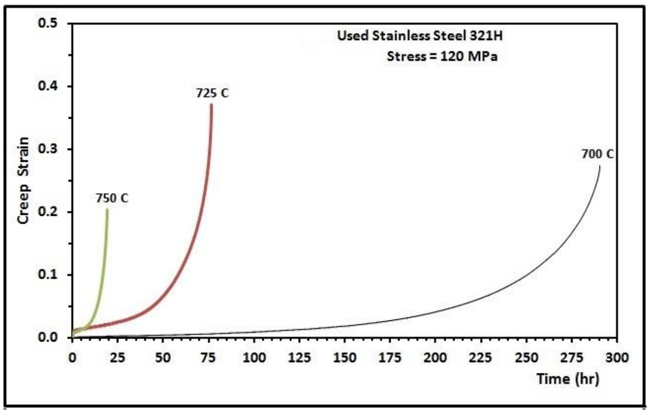


**Fig. (6): Creep rupture tests for a used stainless steel 321H (previous service life about 290000hr at temperature 570 °C) at different test temperatures and at applied stresses 120 MPa**

The non-used stainless steel 321H material (Figures (3) and (4)) nearly shows a typical creep curve that contains three distinguished creep stages, the longest stage is the secondary stage (minimum creep strain rate or steady stat creep stage).

The used stainless steel 321H material (Figures (5) and (6)), we can distinguish that the tertiary creep stages have the longest period of the three stages of such curves instead the secondary creep stage as usual with the typical creep curves. The reason beyond that related to the capability of metal to bear the applied load that decrease starting from this stage due to the reduction in the effective remaining area. This reduction can be attributed to two main reasons,

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the first is the necking which starts to happen in this stage, and the second is the total sum for the creep voids accumulated in the metal structure subtracted from the original cross-sectional area designed to withstand the applied load.[15] Figure (7 a & b) shows that creep cavities for 321H stainless steel start to be visible by optical micrograph at 60% from the creep rupture life, the damage accumulated inside metal can be represented as a creep cavity formation on grain boundaries.[12] Chromium carbides type $Cr_{23}C_6$ precipitate on grain boundaries, where the growth of these carbides with time causes the formation of creep cavities.[12].

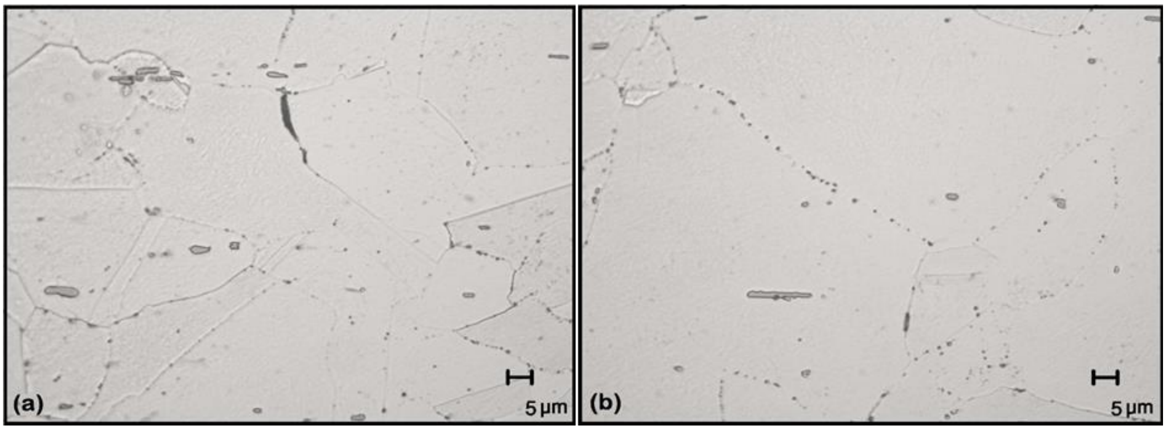


**Fig. (7- a, b): Creep cavity formation in microstructure of austenitic stainless steel type 321H after 60% of rupture life[12]**

The non-used stainless steel 321H material in Figures (3) and (4) and used stainless steel 321H material in Figures (5, 6) at different test temperatures and different stresses show a decreasing in rupture time when the test temperature, applied stress, and creep strain rate increased, which represent the normal behavior of materials when creep take place. It is believe that the decreasing in creep life is due the amount of chromium carbides that precipitated on grain boundaries leading to nucleating creep voids that started from such carbides.[16]

At high temperature and accompanied with the existence of creep in a form of plastic deformation, both work hardening and annealing effect take place. The value of creep strain rate change locally at every point on creep curve, it ruled by the balancing state between the strain hardening and annealing effects. In other word, the number of dislocation that can generated led to strain hardening formation and the number of these dislocations that can be annealed (dislocations that can annihilated by annealing).

In general, during the primary creep stage, creep strain rate values are diminishing starting from specific values up to the point of secondary stage, which exhibit a work or strain-hardening effect is the dominant during this stage. While, the secondary creep stage exhibits a balance in way that all the dislocations produced by strain hardening recovered by annealing. Beyond the secondary stage, the creep rate will increase up to rupture.[17]

Figure (8) illustrate a comparison between the used and non-used stainless steel of tube samples. Nearly all the plots exhibit an increase in the value of the total strain (strain value at rupture) for the used material compared to the non-used one. The creep curves for the used stainless steel material have less primary elastic strain values ($\varepsilon_o$), which reflects the decrease in its ability to elongate elastically.

The used stainless steel shows that rupture can happen in a time ($t_r$) less than the new stainless steel at exactly the same test conditions of temperature and stress, which reflects the reduction in creep strength of the stainless steel as a result of the degradation in material properties that takes place during the long service life. As shown in Table (2), the tensile strength and elongation decrease for the used stainless steel compared with the new stainless steel.

The trend of the creep curves for the used material is differ than the non-used that follows to build the creep curves, as mentioned early that the third part of the curve (tertiary creep stage) in the used metal represents the longest time period than the other stages.

Usually, the minimum creep rate stage represents the most important stage for design to have metals with high creep strength providing a type of metal to service in a high temperature condition for long-term operation. Secondary stage is characterized by its long period in creep curve without creep cavities formation.

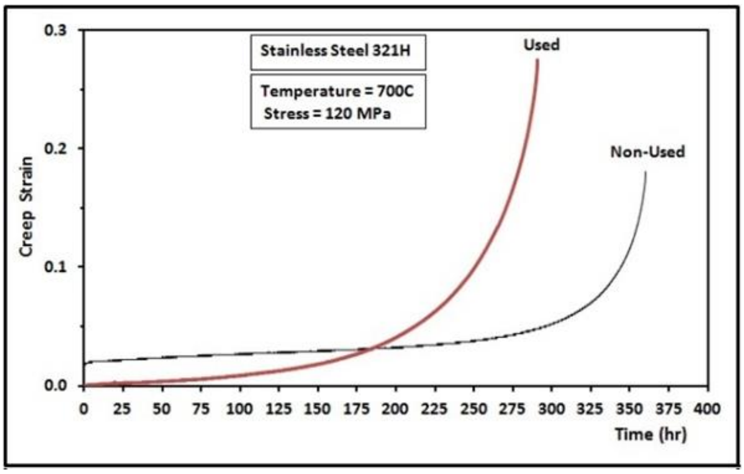


**Fig. (8): Comparisons of creep curve behaviors between non-used and used (previous service life about 290000hr at temperature 570 ºC) of stainless steel 321H at the same creep test conditions**

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The values of material constants that appear in equation number (3) at each test temperatures for the two life situations of stainless steel can be found using the accelerated creep rupture tests. The experimental data sets of stress, temperature, and time were substituted in the developed equation (equation no. 3) to construct a master curve for stainless steel type 321H, as shown in Figure (9).

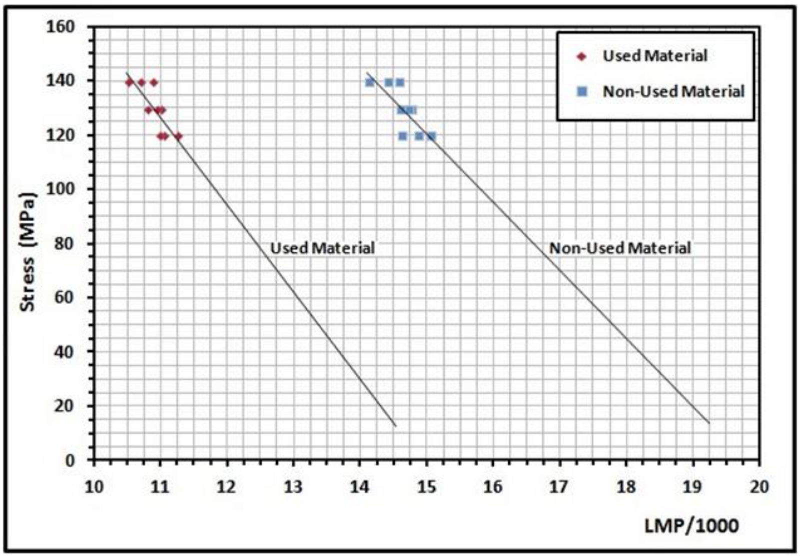


**Fig. (9): Modified Larson-Miller master curve for used and non-used austenitic stainless steel material.**

## 6. Conclusions:

1- Austinitic stainless steel type 321H can be tested for creep under the accelerated test conditions of temperature range (700-750 $^{o}$C) and load application range (120-140 MPa) to get a reasonable creep rupture life up to 360hr (15 days continuous) for non-used stainless steel.

2- It is found that for austenitic stainless steel 321H material, the rupture life decreased (68.24% for used material, 58.82% for non-used material) when applied stress increased from 120MPa to 140MPa.

3- For austenitic stainless steel 321H material, the rupture life decreased (93.21% for used material, 85.27% for non-used material) when test temperature increased from 700 $^{o}$C to 750 $^{o}$C.

4-The creep strain rate for austenitic stainless steel 321H material increased (148.19% for used material, 226.33% for non-used material) when applied stress increased from 120MPa to 140MPa.

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5- The creep strain rate for austenitic stainless steel 321H material increased when test temperature increased from 700 $^{o}C$ to 750 $^{o}C$.

6-The creep curve of austenitic stainless steel type 321H serviced for (290000hr) under temperature 570 $^{o}C$ revealed that the longest period and the dominant stage is the tertiary stage with less primary elastic strain value. In addition, the total creep strain (strain value at rupture) increased compared with the non-serviced stainless steel.

7-The estimated remaining working life for the serviced tube samples made from austenitic stainless steel type 321H is about (54703 hr) based on the calculated stress level (40 MPa) and service temperature 570$^{o}C$.

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