Prediction of work-rolls failure in hot ring rolling process

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Abstract
The work-rolls of the hot ring rolling process are subjected to various damages due to the contact with hot metal. Thermo-mechanical fatigue is one of these damages. In order to predict failure due to the thermo-mechanical stress in the work-rolls, the developed code in ABAQUS has been used. The comparison between three- and two-dimensional models and, also, thermal and thermo-mechanical response of work-rolls with variable boundary conditions has been investigated. The results have shown that by applying mechanical and thermal loads separately or simultaneously, the response of work-rolls is completely different. In the mandrel, the location of the maximum equivalent stress is on the surface, while the location of equivalent maximum stress is in the subsurface of the main-roll. By making use of cumulative damage rules and the stress life method, the thermo-mechanical fatigue life was estimated. The cumulated damage in the mandrel’s surface was higher than subsurface regions. In contrast to the mandrel, the cumulated damage in the main-roll’s subsurface was higher than surface regions. In hot ring rolling machines, these locations are prone to crack initiation as a result of the thermo-mechanical fatigue in the work-rolls.

Keywords
Ring Rolling; Thermo-Mechanical Stress; Script Code; Stress Life Method; ABAQUS

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1. Introduction

The thermo-mechanical fatigue is one of the damages affecting the life of work-rolls in hot rolling machines. The thermo-mechanical fatigue is a process in which crack propagation and initiation occurs in critical positions exposed to simultaneous thermal and mechanical strain. Up to now, numerous researches have been done on the hot rolling machines with various aspects and approaches. For example, the rolling of various metals and metal composites have been investigated [1,2]. Some others studies could be either related to the effects of rolling on mechanical and metallurgical properties of the work piece [3–5] or controlling and optimizing the rolling conditions[6,7]. Another interesting aspect of rolling that has been studied is the prediction of the thermo-mechanical response of work-rolls in various situations to evaluate the work-rolls service life. Song et al.[8] used finite-element software and developed a thermo-mechanical coupling model to form ring-shaped IN-718. By using the model, they calculated the work-roll surface temperature, ring temperature and the required loads for rolling. Shahani et al.[9] studied the effect of different process parameters on hot rolling of AA5083 aluminum alloy by making use of finite element method. Harrer et al.[10] investigated the failure in silicon nitride rings for hot rolling and suitable conditions for making highly alloyed steel and super alloy wires. Based on FEM models and various assumption, the thermal and mechanical response of strip and work-rolls during a hot strip rolling have been investigated [11,12]. Yadav et al.[13] presented an approximate method to estimate temperature distributions in the work-roll and strip in a rolling process. Benasciutti et al.[14] investigated a work-roll in hot flat rolling process by introducing a one-dimensional harmonic element and calculated the thermo-mechanical stresses in the work-roll more rapidly in comparison with their previous works. Koohbor[15] developed an integrated mathematical model to study the thermo-mechanical behavior of strips and work-rolls during the warm rolling process of steels. The
model was first employed to solve the thermo-mechanical response of the rolled strip under steady-state conditions and then used to apply proper boundary conditions for solving the thermo-mechanical response of the work-roll. Deng et al.[16] studied the thermal and oxidation behaviors of a HSS work-roll during hot flat rolling in actual service conditions. The effect of various parameters on temperature and thermal stress distributions within the work-roll has been examined. Weidlich et al. [17] analyzed the effect of operational parameters of a hot rolling mill in the degradation process of a roll surface by thermal fatigue. They presented a new coefficient to predict the thermal damage in work-rolls. Hanoglu and Sarler [18] simulated the hot rolling of various sections by means of meshless method. Palit et al. [19] tested progressive failure of a work-roll in a hot strip mill. The results showed that in a work-roll the crack initiation took place in subsurface and spalling occurred due to propagation of a circumferential crack through the shell. Hadizadeh et al. [20] inspected failure of repair welded continuous casting rolls by changing in microstructure.

In hot rolling process, Tolcha et al.[21] investigated creep-fatigue interaction damage. Their model consisted of three parts: mechanism of creep-fatigue interaction, elliptical crack growth rate, and H13 tool material response. The ABAQUS software has been used for the finite element simulations.

By considering the literature review, it is clear that the most former studies on the thermo-mechanical analysis of work-rolls focused on the flat rolling, and a few works have been conducted in the ring rolling process. It is important to note that the analysis and simulation of work-rolls in a rolling machine are often time-consuming procedure which is, most often, owing to the rotation of work-rolls and the variations of the boundary conditions during the process. Rotation of work-rolls makes the finite element matrices changed and updated in every increment. To reduce the computational cost of simulation, the work-rolls’ temperature and related thermal stress field have
been usually analyzed by researchers. Furthermore, it is evident that evaluating thermo-mechanical analysis has rarely been taken into consideration.

Figure 1 shows the schematic of a radial-axial ring rolling machine and a flat rolling machine. Ring rolling is a rolling machine in which the precise and seamless circularly-shaped metal parts are progressively forged. The mandrel, which is idle, moves to the main-roll. The main-roll is fixed and driven with a constant angular velocity. The axial rolls control the height of ring. The guide rolls guarantee that the ring remains circular during process. In flat rolling, the plate is passed through one or more pairs of work-rolls to reduce the thickness.

With respect to Figure 1, estimation of thermo-mechanical stresses in the work-rolls of a ring rolling machine is rather different from a flat rolling. A brief comparison between the flat rolling and ring rolling could be as follows: In the flat rolling, due to the symmetry of work-rolls, it is common to analyze one work-roll, while in the ring rolling the diameter, applied loads and boundary conditions of work-rolls are different, and the symmetry assumption is not valid. In the ring rolling process, the contact surface between the ring and work-rolls are time-dependent. During the process, the ring’s contact surface decreases with the mandrel and increases with the main-roll, while the contact surface in the flat rolling is constant. This feature of the ring rolling makes the applied forces and moments be time-dependent, which will affect the thermo-mechanical stresses. In the ring rolling, the temperature-dependent thermo-mechanical properties of the metal can be different because of repeated rolling and variation of temperature in the ring and work-rolls. In order to evaluate the process more accurately, the temperature-dependent thermo-mechanical properties of the metal (density, heat transfer coefficients, specific heat, work hardening, etc.) should be taken into account. To conclude, it is clear that the ring rolling process is time-dependent. At each moment, the work-rolls and the ring are in a specific condition that makes their analysis too complicated. In the current
research, by developing a scripting code in the ABAQUS, the magnitude of thermal and mechanical loads is extracted, computed and applied to work-rolls simultaneously and all time-and temperature-dependent properties taken into account.

2. Applying boundary conditions in Finite Element Method

Work-rolls in rolling machines are simultaneously influenced by mechanical and thermal stresses. The thermal stress is due to the non-homogeneous temperature distribution on the work-roll which is caused by being in contact with the hot metal and the coolant. The mechanical stress is due to rolling pressure and contact with supporting work-rolls. Thermo-mechanical stresses on the work-rolls cause elastic and plastic strains that lead to erosion, spalling and unexpected damages. To reduce the computational time and simplify the model, the ring is considered as a hollow cylinder with thickness and radius time dependent during the process. The shape of the main work-roll and mandrel are also cylindrical, so the general equation of heat transfer in cylinder coordinates is valid for them. The equations of thermo-elasticity could be obtained from kinematic relation, equations of motion, energy-scale equation, and constitutive equations[22]. The finite element formulation of a problem by making use of Galerkin weighted residual method is obtained in standard way[23].

\[
\begin{align*}
\left[ \int_\Omega \rho_n L_m dV \right] \dot{U}_{mi} + \left[ \int_\Omega G \frac{\partial N_i}{\partial x_j} \frac{\partial N_m}{\partial x_j} dV \right] U_{mj} + \left[ \int_\Omega G \frac{\partial N_i}{\partial x_j} \frac{\partial N_m}{\partial x_j} dV \right] U_{mj} \\
\left[ \int_\Omega \frac{\partial N_i}{\partial x_j} \frac{\partial N_m}{\partial x_j} dV \right] - \left[ \int_\Omega \beta \frac{\partial N_i}{\partial x_j} N_m dV \right] \theta_m = \int_\Omega \rho F_i dV + \int_\Omega t_i dA
\end{align*}
\]

\[ l, m = 1, 2, \ldots, n \quad i, j = 1, 2, 3 \tag{1} \]

\[
\left[ \int_\Omega k \frac{\partial N_i}{\partial x_j} \frac{\partial N_m}{\partial x_j} dV \right] \theta_m - \left[ \int_\Omega T_0 \frac{\partial N_i}{\partial x_j} N_m dV \right] \dot{U}_{mi} + \left[ \int_\Omega \rho c N_m N_l dV \right] \dot{\theta}_m \\
= \int_\Omega \rho R N_i dV - \int_\Omega (\bar{q} \bar{N}) N_i dA
\]

\[ l, m = 1, 2, \ldots, r \quad i, j = 1, 2, 3 \tag{2} \]
The finite element approximation of the equation of motion is expressed by Equation (1) and the finite element approximation of the coupled energy equation is defined by Equation (2). The general form of the equations (1) and (2) could be as follows:

\[
[M]\{\alpha\} + [C]\{\nu\} + [K]\{d\} = \{F\}
\]  

(3)

With respect to equation-3, if the speed and acceleration of the elements are ignored, some terms in matrices will be ignored and the amount of computing time will be reduced. So, the strategy is to rotate the boundary condition around the work-rolls and the work-rolls should be fixed. This assumption reduces the effective matrices in the finite element model. The boundary conditions required for simulation procedure can be considered according to Figure 2 as follows:

\[-k_r \frac{\partial T}{\partial r}\bigg|_{r=R_{\text{surf}}} = h^* (T_{\text{cooler}} - T_{\text{rollsurf}}) + \eta \Lambda \sigma_B \left(T_{\text{ambient}}^4 - T_{\text{rollsurf}}^4\right) \begin{cases} \eta = 0 & T_{\text{roll-initial}} = 30^\circ C \\ \eta = 1 & T_{\text{roll-initial}} = 500^\circ C \end{cases}\]

(4)

\[-k_r \frac{\partial T}{\partial r}\bigg|_{r=R_{\text{surf}}} = h_c C (T_{\text{ring}} - T_{\text{rollsurf}}) \quad C = C_1 \text{or} C_2\]

(5)

\[-k_r \frac{\partial T}{\partial r}\bigg|_{r=0.5 R_{\text{surf}}} = 0\]

(6)

\[p_{\text{contact-zone}} = \frac{F}{C_1} \quad C = C_1 \text{or} C_2\]

(7)

\[u_i\bigg|_{r=0} = 0\]

(8)

\(h^*\) is the convective heat transfer coefficient with different values in each regions (air, water or oil cooling region) except deformation zone. \(h_c\) is a property indicating the thermal conductivity between two bodies in contact. The radiation heat transfer is considered, when the initial work-roll’s temperature is at 500 °C. \(\sigma_B\) is Stefan-Boltzmann constant and \(\Lambda\) is radiative coefficient.

[[figure2]]
According to the non-symmetric and variable contact surface, the length of contact surface (C₁ and C₂) can be estimated by the research of Forouzan et al. [24]. The time dependent contact area during the simulation is calculated by using the above-mentioned values.

3. Estimation of Work-roll’s temperature with local cooling

The estimation of the surface temperature in a rolling process has a particular importance. Given these values, the rate of cooling and work-roll’s material and service life can be predicted. In a flat rolling, researchers usually use the plane strain assumption which has acceptable result. This assumption must be used carefully in a ring rolling process because the strain in the axial direction could not be neglected. Negahban et al. [25] studied the assumption of plane strain in the ring rolling and proposed a suitable range for using this assumption. The results showed that if the values of distribution ratio of feed amount [26] and mandrel’s velocity be small enough (less than 1 and 0.5 mm/s), the results of 2D simulations have a good agreement with three-dimensional simulation.

3.1. Flat rolling

ABAQUS software has the Film and D-flux subroutines for thermal analysis. These subroutines can be used to define a non-uniform film coefficient or heat flux as a function of position, time, temperature, etc. in a heat transfer analysis [27]. Therefore, thermal stress analysis needs another time-consuming simulation to convert this temperature field history to stress field. In order to conquer this problem and save time, a script python code has been developed. Two separate simulations were used to compare the results of the explicit and implicit algorithms. There is an important balance between the efficiency of an explicit algorithms based on lumped matrices and the accuracy of an implicit algorithm with consistent matrices. The lumped matrix approach has clear advantages in computational efficiency, but with some loss of accuracy. In problems where high accuracy of temperature distribution is required, the use of the more accurate through more
expensive consistent matrix is justified[28]. It should be noted that both methods have a critical
time step to avoid spurious oscillations (implicit) or divergence (explicit).
The proposed modeling procedure contains several sub-models in which boundary conditions are
changed. In these models, the cooling and heating zones are rotated in reversed direction by the
script code. In every step, the surface elements located on this zone are selected and the proper
boundary conditions are imposed, then a simple transient thermo-mechanical analysis is simulated.
Each time step is equal to one degree of work-roll’s rotation. The research conducted by Benasciutti
et al.[14] was used in order to simulate the local cooling and estimate the temperature field on the
work-roll. The work-roll FE model has a fine mesh, with a total of 10800 elements and 11161
nodes. The outer surface is divided into 360 segments. The radial partitions are divided by seed 30
and bias 15. The four nodes linear element (CPE4RT) is used.
The results have been obtained and variations of the node temperature in the work-roll’s surface
have been shown in the Figure 3. The same temperature trend has been predicted by the models. In
other words, the surface’s temperature rises rapidly in the heating zone. When roll surface leaves
this zone, surface’s temperature decreases with a specific trend. In cooling zone, the surface’s
temperature decreases rapidly; so, there is a cusp at the point where the cooling zone is started.
When the roll leaves this zone, the surface’s temperature rises slowly. This is due to heat transfer
from the internal nodes to external nodes.

[[figure-3]]

In the heating zone where the pick point occurred, the first model (implicit algorithm) predicted the
temperature a little more than the Benasiutti’s results. The second model (explicit algorithm) have
been predicted the temperature less than the Benasiutti’s results. In other locations, the predicted
temperature, in general, is higher (Max 10%). Comparison between models which prepared by
script code indicated that simulation time is almost the same. The simulation time with the personal
computer (Intel core i7-4790 3.5GHz, RAM-16G) took about 10 hours. This thermal stress simulation of the work-rolls by Benasciutti took 13 days [29] and in other work with a 1D parametric element, which allows the analysis of plane axisymmetric structures[14], required 5 hours.

The advantages of the proposed developed code in Abaqus and modeling procedure are ability to simulate 2D and 3D geometry without any simplification and also simultaneously simulate thermal and mechanical analyses. The other advantages are the ability to impose the mechanical and thermal loads history and variable contact surfaces into a model. With respect to simulation results, the implicit method was used to evaluate thermo-mechanical stress in the ring rolling process.

3.2. Ring rolling

As mentioned before, the simulation of the model using the typical software environment is not feasible. Therefore, the model and the steps with the variable boundary conditions are prepared by the script code. Each time step is equal to one degree of work-roll’s rotation. According to the history of loading and temperature, in each step the initial and boundary conditions on the work-roll are computed and added to the model. In other words, in each step, the boundary conditions such as rolling force, area of heating and cooling zones, etc. are changed. At the end of each step, the results are extracted and used as an initial state condition for the subsequent sub-model. Figure 4 shows schematic of work-roll’s modeling with a partial boundary condition and the algorithm used in the models. The angels α, γ, β are the angel of heating zone, the angle of cooling zone and the angle between two zones, respectively.

In order to apply thermal flux at each step, the current contact length and temperature of the work-roll and ring in the previous step are required. Using the developed code in ABAQUS, these values are obtained from the previous step and the empirical data[8], respectively. For the simulation, the
models are constructed with python code in ABAQUS. The dimensions and conditions are in accordance with the information as provided in Table 1.

According to the low velocity of work-rolls and small deformations in the ring, the assumption of the plane strain in the present simulation is acceptable[25]. In order to reduce the amount of computational cost, it is possible to isolate and analyze work-rolls individually. As mentioned before, the general strategy in this research is that instead of analyzing a work-roll under different boundary conditions caused by its rotation, the boundary conditions rotate around the work-roll. By doing this, a simple transient thermo-mechanical problem is solved in each step. Hence, the volume of effective matrices in the governing equation in finite element formulation are reduced.

As three-dimensional thermo-mechanical simulation of ring rolling need a huge computational cost, the thermal analysis with variable boundary conditions has been carried out. The results of the simulation are shown in Figure 5 where the temperature variation of the four different points on the work-rolls surface is shown. The initial temperature of the work-rolls is 30° C. The variation of temperature on the work-rolls surface depends on the location in axial direction. At every rotation of the work-roll, the graphs indicated that the maximum temperature occurs in contact zone. Point 1 is located on the axial symmetry plane of the work-roll. It is clear that the temperature at the symmetry plane of the work-roll is maximum. Due to the symmetry plane at point 1, the two-dimensional heat transfer occurs. At point 2, there is no symmetry and the heat flux is transmitted in three directions. Therefore, the work-roll’s surface temperature is slightly lower. At points 3 and 4 where the ring and the work-roll are not in contact, the temperature drop is further increased to reach the initial temperature of work-rolls.
As mentioned, in the three-dimensional model the maximum temperature occurs at the symmetry plane. To compare the temperature in two-dimensional and three-dimensional models, the variation of temperature in the symmetry plane of the 3D model was compared with the two-dimensional model.

Figure 6 makes a comparison between two- and three-dimensional simulations. As can be clearly seen, the two-dimensional model predicts a higher temperature than the three-dimensional one in the contact zone. In other locations, there is no significant difference between the models. In the three-dimensional model, the thermal flux which is transmitted from the ring to the main-roll is spread in three directions. In the two-dimensional model, the same thermal flux enters the work-roll, but the thermal flux is transmitted in two directions. This issue causes the nodes to show a higher temperature rise in the two-dimensional model. As was shown in Figure 6a, the temperature of the main-roll surface sharply increases and reaches its maximum in the contact region. By leaving this area, the temperature decreases by a specific rate to enter the forced convection zone (cooling zone). In this area, the temperature drop is higher and causes a cusp in the temperature profile. As the work-roll surface passes through this area, due to a higher reduction in the temperature of the surface nodes compared to internal nodes, heat flux transfers from the inside to the outside of the work-roll, and increase the surface’s temperature. The temperature of coolant is constant during the process, but during the process, temperature of the internal surfaces increases. This leads to an increase in temperature difference between the inner and surface elements. In each rotation of the work-roll, the mentioned condition is met. As a result, the total work-roll temperature experiences a little increase at each rotation. Figure 6b illustrates the situation in which the initial temperature of the main-roll is 500 °C and no cooling is performed on the surface. In this case, as mentioned earlier, the heat transfer of the work-roll is done by radiation and convection with the surrounding environment. Figure 6a shows that in the contact surface, the surface’s temperature of the work-roll
increases rapidly and decreases with a specific rate after leaving the area. In this case, there is no sudden change in boundary conditions at the work-roll surface except the contact area; no cusp in the temperature profile is observed.

[Figure 6]

According to these figures, when the main-roll’s temperature is 30°C, temperature increases in the contact surface in two- and three-dimensional models are about 170% and 70%, respectively. Each rotation of the work-roll causes 8% and 4% average increase in surface’s temperature in two and three-dimensional models, respectively. When the work-roll’s temperature is 500°C, the thermal flux entering the work-roll is reduced due to a decrease in the temperature difference. In this case, the temperature’s rise in contact area in the two and three-dimensional models are about 6% and 3% respectively, and each rotation provides the work-roll surface with less than 1% increase in temperature.

In the study conducted by Sonboli and Serajzadeh[11], the two-dimensional finite element model indicated higher temperature in the contact region compared to the measured value. Considering the results of their work and this research, in general, the prediction of temperature is higher in the two-dimensional model. Therefore, the 2D model predicted greater thermal stresses in the work-rolls.

4. Estimation of thermo-mechanical stresses

In this study, by making use of ABAQUS software and the developed code, mechanical and thermal loads are simultaneously applied to the work-rolls and thermo-mechanical stresses are calculated. By doing this, computational cost will drop dramatically, and the accuracy of the results will be higher.
As mentioned earlier, in order to investigate the thermo-mechanical stress and estimate the life of work-rolls in ring rolling process, two initial temperatures have been considered. In the first case, the work-roll’s temperature is at 30° C. In this case, in order to avoid temperature’s rise in the work-roll, and prolong its life, its surface is cooled down by water. This increases the life of the work-roll. In other case, the work-roll’s temperature is at 500° C to avoid chilling effect in the ring. In this case, the local cooling is not applied to the work-roll, and the work-roll transfers heat to the ambient by convection and radiation. The model was prepared based on plane strain assumption according to Table 1. The heat load at each step is determined according to the ring’s temperature at any moment. The value of the forces generated by the rolling process is derived from a separate dynamic analysis, and the history of the force applied to the work-roll is listed in Table 2. The magnitude of pressure load on each work-roll, estimated by the contact length and load history at any moment.

[[Table 2]]

The values of temperature and stress on the main-roll in the case where only the thermal loads are applied are illustrated in Figure 7a. According to this figure, it can be observed that the predominant variations of temperature occur on the main-roll surface, and lower surfaces experience less temperature variations. Severe changes in temperature and maximum temperature lead to higher thermal stresses on the surface. The maximum temperature and thermal stress variations occur at the main-roll surface in the contact area. This has been reported by various researchers in hot rolling process. The magnitude of temperature and thermal stress field in 22nd second of simulation have been shown in the Figure 7b. If only the heat load is applied to the main-roll, critical conditions occur on the work-roll surface. By applying mechanical and thermal loads on the main-roll (Figure 7c), similar to the previous case, the most significant temperature changes occur on the work-roll surface, however, the location of the maximum equivalent stress (MES) is transferred from the
surface to the lower in the contact area (Figure 7d). In other area, the obtained stresses are almost equal to the case where only heat loads were applied.

The values of plane strain stress’s components in radial direction along the work-roll with temperature of 30°C are illustrated in Figure 8. By applying the mechanical forces, normal stresses on the surface reach the maximum value. However, the maximum shear stress occurs in the subsurface. According to relation of the equivalent Von-Mises stress, it is obvious that the increase in shear stresses below the surface has a significant effect on the equivalent Von-Mises stress and makes this stress reach its maximum value below the surface. This phenomenon can be justified by the stress caused by the contact known as the Hertzian stresses. Under the surface, due to the increase in the Von-Mises stress, there is a possibility of crack initiation and propagation to the surface.

[[Figure 7]]

[[Figure 8]]

The variation of temperature and stress on the mandrel by applying thermal and thermo-mechanical loads in normalized distance 1 and 0.86 are illustrated in Figure 9. If the mechanical load is applied to the mandrel, the MES occurs in the normalized distance r/R=0.86. According to this figure, it is evident that the temperature’s rise in the mandrel is more than the main-roll. Therefore, the magnitude of thermal stress is higher than the main-roll. The variation of thermal stress in the internal surface is negligible. However, because of temperature’s rise in the mandrel during the forming process, the value of thermal stress increased. This graph shows that the trend of thermal stress and temperature are the same. By applying thermal and mechanical loads on the mandrel simultaneously, in contrast to the main-roll, the MES occurs on the surface of the mandrel. The results of simulation show that the thermal loads have greater effects than mechanical loads in the mandrel. The mechanical load tends to the MES occur under the mandrel surface, on the other hand,
the thermal load tends to the MES occur on the surface. These phenomena resulted in the hydrostatic pressure increase in the mandrel. Therefore, the amount of thermo-mechanical Von-Misses stresses are less than thermal stresses in the mandrel’s surface (Figure 9b). The magnitude of temperature and thermo-mechanical stress field in 22nd seconds of simulation are shown in the Figure 7c.
[[Figure 9]]
Overall, these opposing trends in the work-rolls indicated that the value and location of maximum thermo-mechanical stresses are completely different. The response of the mandrel to thermo-mechanical load is similar to work-rolls in a hot flat rolling.

In Figure 10, the history of the main-roll’s Von Mises stress is illustrated at an element’s integration point on the surface and a subsurface element with a ratio of \(r/R=0.985\). The Figures 10a and 10b are related to main-roll with initial temperature of 30 °C and 500 °C, respectively. It is evident from these figures that during the process, with the increase of mechanical load, Von Mises stress increases. The value of equivalent stress below the surface is on average 50 percent higher than the surface. The mechanical forces in the contact area have a significant effect on the equivalent Von Mises stress, and the rest of the regions are affected by thermal loads. In Figure 10b, due to the absence of cooling on the work-roll’s surface, there is no cusp in the thermo-mechanical stress.
[[Figure 10]]

In Figure 11a the history of the mandrel’s Von Mises stress is illustrated at an integration point on the surface and a subsurface element with a ratio of \((r/R=0.86)\) at a temperature of 30 °C. The figure depicts that the thermo-mechanical stress trend in the mandrel is different from the main-roll’s. The consequent effect of the temperature rise in the mandrel is shifting the location of MES. At the early stage, the maximum thermo-mechanical stress occurs on the subsurface that is related to the mechanical load. During the process and more heat transfer to the mandrel, the thermal stress overcome the mechanical stress and location of MES is shifted to the surface. The mandrel with the
initial temperature of 500 °C has been simulated to investigate the effect of work-roll initial temperature on thermo-mechanical stress. The history of the Von Mises stress at an integration point on the mandrel surface and below it (r/R=0.86) is shown in Figure 11b. From this figure, it is obvious that without cooling practice on the mandrel the value of mean stress increases gradually. These figures also depicted that, the magnitude of the amplitude stress decrease slightly and remain almost steady during the process. In the another research, effect of various initial temperature and cooling practice on the thermo-mechanical stress are investigated[30]. The results indicated that to reduce the thermal stresses, it is necessary to maintain the temperature of the work-roll in the initial temperature as far as possible with proper cooling. A proper cooling minimizes the amount of thermo-mechanical stresses and the heterogeneous temperature field in the work-roll.

[[Figure 11]]

A cycle is equal to 24 seconds of loading history; therefore, it is the time that the ring needs to form completely. It is assumed that the delay time between the forming processes of rings is long enough to the work-rolls return to initial condition. So, this history is considered as a loading block. During a cycle, the Von Mises stress in the contact region of the work-rolls suddenly change. This change is due to the mechanical and thermal loads. As the work-rolls pass this region, the equivalent stress experiences sudden and significant drop. This phenomenon is related to the absence of mechanical loads and conduction heat transfer. In non-contact regions, thermal stresses have a greater effect on thermo-mechanical stresses. For example, in the main-roll, the equivalent stress on the surface is higher compared to the inner surfaces because of the higher temperature on the surface. In the subsurface elements, the heat transfer is delayed, so this heat flux does not have a sudden effect on the value of stress.
5. Estimation of thermo-mechanical fatigue life

The stress-based methods are one of the oldest approaches to estimate life, which have become conventional since the mid-nineteenth century and are also known as S-N method. In the cases where cyclic stresses are significant parameters and plastic deformations are insignificant in the parts, stress based methods have acceptable accuracy in the life of more than $10^3$-$10^4$ cycles[31]. The work-rolls are made of H-13 alloy and its thermo-mechanical properties are according to the references[32–34]. If required, the curve, which was fitted based on experimental values, was used for some thermo-mechanical properties. Proper correction coefficients and thermo-mechanical properties are shown in Table 3.

[[Table 3]]

The standard S-N diagram for this alloy which is produced by the ESR method and heat treatment, in $R = -1$ is extracted using the research conducted by Philip on this alloy[35]. By applying suitable coefficients, and by considering the geometry, production method and work-roll temperature, the stress-life diagram is prepared for the desired working conditions. The standard and modified S-N curves are shown in Figure 12.

[[Figure 12]]

According to the figures 10 and 11, the stresses are within the range of high cycle fatigue. Each block has specific destructive effect, so the cumulative damage hypotheses will be used to estimate the damage caused by each load in the block. In the present research, the cumulative damage hypotheses include the Palmgren-Miner[36], modified Palmgren-Miner (Haibach)[37] and Manson-Halford[38] methods. In these methods, it is assumed that the failure occurs when the sum of damage reaches to a specific value. This relationship is as follows:

$$\sum \frac{n_i}{N_{fi}} = D_{PM}$$ (9)
Where \( n_i \) and \( N_{fi} \) are the number of loading and fatigue life in a specific range of stress respectively. \( D_{PM} \) is the critical value of damage. If the critical value of damage reaches 1, the work-piece would be failed. However, it has been determined that the value of this coefficient varies for materials and alloys. Haibach [39] offers a value of 0.3 for steels. The value of \( N_{fi} \) estimated by making use of S-N curve. The theories of Palmgren-Miner, Haibach and Manson-Halford are summarized in Table-4. As has been mentioned before, most of the amplitude and mean stresses are below the fatigue limit; so, the Haibach rule is suitable. On the other hand, for load-sequence effect Manson-Halford is used.

\[
[\text{Table 4}]
\]

\( S_a, S_e, N, n, N_D, n_{eq}, N_{eq}, k \) are stress amplitude, endurance limit, number of cycles until failure at a specified stress level, number of loading cycles at a given stress level, number of cycles at the deflection point, equivalent damage cycles, shortest life of life levels, slope factor of S-N curve, respectively[38,40]. In each block, the value of equivalent mean and alternating stresses will be determined. The Equation 9 will be changed as follows in order to estimate the number of blocks until failure:

\[
\sum n_b \left( \frac{n_i}{N_{fi}} \right) = D_{PM}
\]

(10)

Where \( n_b \) is the number of loading blocks until the failure.

There are several methods for estimating the limited life and the effect of mean stress on fatigue life. To estimate the effect of mean stress, the methods Goodman, Morrow and Gerber are chosen. According to the loading history, the value of fatigue safety factor is assumed to be 1.5. By making use of the modified S-N curves, the damage caused by each loading cycle on and below the surface was examined.
The estimated damage by Palmgren-Miner linear damage accumulative rule in the MES location in the main-roll and mandrel with initial temperature 30°C at first block with Goodman, Morrow and Gerber methods are zero. This value indicated that Palmgren-Miner method predicted infinite life for the work-rolls.

The estimated damage by modified Palmgren-Miner (Haibach) linear damage accumulative rule in the main-roll (initial temperature 30°C) with Goodman, Morrow and Gerber methods at first block are 2.83E-08, 4.67E-09, 1.47E-10, respectively. These values in the mandrel are 1.34E-10, 1.77E-11 and 1.27E-13, respectively. It should be underlined that Goodman relation predicted higher equivalent fully reversed stress amplitude. Therefore, the relative damage is higher than other mentioned relations. Furthermore, equivalent fully reversed stress amplitude computed by Gerber relation is less than Morrow relation. The one block’s cumulative damage in the work-rolls shows that the damage in mandrel is less than the main-roll. The numbers of tolerable blocks can be predicted by adding the cumulative damage in each block to reach critical value.

The estimated damage by Manson-Halford-Haibach power damage accumulative rule in the main-roll (initial temperature 30°C) with various methods at first block is 1.27E-08, 2.04E-09, 5.98E-11, respectively. The estimated damages in the mandrel by this rule are 3.67E-11, 4.67E-12, 1.13E-13, respectively. In the first block, the results show that the magnitude of damage by Manson-Halford-Haibach rule is less than previous linear damage rules. It is notable that the computed damage at the end of process became higher than previous rules. This rule considers the effect of loading sequence and gradually predicted higher damage at subsequent loading history. Therefore, the predicted tolerable blocks are less than other rules. The numbers of tolerable blocks by means of mentioned methods and rules are summarized and shown in Table 5.

The estimated damage by Palmgren-Miner linear damage accumulative rule in the MES location in the main-roll with initial temperature 500°C at first block with Goodman, Morrow and Gerber
methods are $2.29E-05$, $2.87E-06$ and zero, respectively. These values in the mandrel are $5.66E-06$ and zero. The initial impression from the computed damages is that the higher initial temperature of the work-rolls decreases the strength of material and leads to higher damage.

The estimated damage by modified Palmgren-Miner (Haibach) linear damage accumulative rule in the main-roll (initial temperature $500^\circ C$) with various methods at first block are $2.79E-05$, $5.60E-06$, $4.19E-07$, respectively. These values in the mandrel are $1.52E-05$, $1.23E-07$ and $6.34E-10$, respectively. The estimated damage by Manson-Halford-Haibach power damage accumulative rule in the main-roll (initial temperature $500^\circ C$) with various methods at first block is $8.37E-06$, $2.12E-06$, $1.56E-07$, respectively. The estimated damages in the mandrel by this method are $3.66E-06$, $1.97E-08$, $1.79E-10$, respectively.

With respect to the value of predicted damages in the work-rolls it is clear that the value of damage in the mandrel is less than the main-roll. Also, it is evident that the life of the subsurface elements is far less than the surface elements in the main-roll and vice versa in the mandrel. This causes the initiation of cracks occurs below the main-roll surface, which moves continuously toward the work-roll surface. This causes sudden failure due to thermo-mechanical stresses in the main-roll. On the other hand, in the mandrel, the initiation of cracks related to thermo-mechanical stress occurs on the surface.

As mentioned before, the main-roll is mostly affected by the mechanical stress and the mandrel affected by thermal stress. By making use of cooling practice on work-roll’s surface, the amount of mean thermal stress on work-roll and cumulative damage decreases. For increasing life of work-rolls with initial temperature $500^\circ C$, it is necessary to apply cooling practice on work-rolls. However, it has not considerable effect on reducing the thermo-mechanical stresses in the main-roll.
In the mandrel with initial temperature 500°C and cooling its surface by oil with the same temperature, the estimated damage by modified Palmgren-Miner (Haibach) in the MES location at first block with Goodman, Morrow and Gerber methods is 1.69E-06, 5.90E-08 and 4.29E-10, respectively. The estimated damage by Manson-Halford-Haibach with mentioned methods at first block is 4.74E-07, 1.35E-08, 7.34E-10, respectively. By mandrel’s oil cooling, an average reduction of 60% is achieved in the amount of the cumulative damage.

As mentioned before, the amount of cumulative damage in first loading block with Haibach rule is higher than Manson-Halford rule. However, in the Manson-Halford rule the cumulative damage in each block rise rapidly. Therefore, the predicted number of tolerable blocks with this method is less than the Haibach method. In the mentioned rules, when the total damage with respect to the alloy reaches to 0.3, it is expected that the work-roll fails. The results are shown in Table 5.

[[Table 5]]

6. Conclusion

In this research, the two- and three-dimensional simulation of the hot ring rolling process are compared. The thermo-mechanical response of work-rolls with variable boundary conditions are studied by making use of the developed code in ABAQUS software. In the following, the effect of thermo-mechanical stresses on the life of the work-rolls in hot ring rolling process has been investigated. Usually the damages caused by corrosion, oxidation, wear, etc. have destructive effects on the surface, and the damage caused by them can be observed with regular inspections. The results indicated that the effect of thermo-mechanical stresses on fatigue life cannot be easily observed. The results of the research can be summarized briefly as follows:
• The plane strain and three-dimensional simulation of ring rolling process provide approximately the same temperature prediction if it is carried out in the mentioned allowed range. Overall, the plane strain simulation predicts higher values for temperature.

• The simulation of hot ring rolling process by applying thermal or thermo-mechanical loads offers completely different results.

• Thermal stresses have a greater effect on the work-roll’s surface. The extreme temperature variations occur in this region. At subsurface, change of thermal stress is reduced due to less temperature variations.

• Mechanical stresses have a greater effect on the work-roll’s subsurface. By applying mechanical forces on the work-roll’s surface, the Von-Mises stress reaches to the maximum value in the subsurface, which is in agreement with the Hertzian stress theory.

• The main-roll’s response to thermo-mechanical stresses in hot ring rolling is the same as work-rolls in the cold flat rolling. In contrast, the mandrel’s response is mostly the same as work-rolls in a hot flat rolling.

• The predicted life in subsurface of the main-roll is much less than the surface of the work-roll. This causes the initiation and propagation of cracks in the subsurface. It leads to a sudden failure by thermo-mechanical fatigue.

• Thermal stresses have a greater effect on the mandrel. By appropriate cooling practice on work-roll’s surface the amount of service life considerably increases. The results show that the failure in the mandrel due to thermo-mechanical stress occurs on the mandrel surface.

7. Nomenclature

<table>
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<th>Symbol</th>
<th>Description</th>
<th>Symbol</th>
<th>Description</th>
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<tr>
<td>( a )</td>
<td>Generalized acceleration vector</td>
<td>( n )</td>
<td>Number of loading cycles at a given stress level</td>
</tr>
<tr>
<td>Symbol</td>
<td>Description</td>
<td>Symbol</td>
<td>Description</td>
</tr>
<tr>
<td>--------</td>
<td>-------------------------------------------------------</td>
<td>--------</td>
<td>--------------------------------------</td>
</tr>
<tr>
<td>$C$</td>
<td>Generalized damping matrix</td>
<td>$q$</td>
<td>Heat flux per unit area</td>
</tr>
<tr>
<td>$C_{1,2}$</td>
<td>Length of contact zone</td>
<td>$R$</td>
<td>Strength of the internal heat source per unit mass</td>
</tr>
<tr>
<td>$c$</td>
<td>Specific heat per unit mass</td>
<td>$r$</td>
<td>Total number of nodal points</td>
</tr>
<tr>
<td>$D$</td>
<td>Critical value of damage</td>
<td>$S_a$</td>
<td>Stress amplitude</td>
</tr>
<tr>
<td>$d$</td>
<td>Generalized displacement vector</td>
<td>$S_e$</td>
<td>endurance limit</td>
</tr>
<tr>
<td>$F_i$</td>
<td>External force per unit mass</td>
<td>$T_0$</td>
<td>Initial temperature</td>
</tr>
<tr>
<td>$F$</td>
<td>External force vectors</td>
<td>$t_i$</td>
<td>Prescribed traction component on the boundary surface</td>
</tr>
<tr>
<td>$G$</td>
<td>Shear modulus</td>
<td>$u_i$</td>
<td>Displacement vector with respect to coordinate (i)</td>
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<td>$h^*$</td>
<td>Convective heat transfer coefficient</td>
<td>$v$</td>
<td>Generalized velocity vector</td>
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<tr>
<td>$h_c$</td>
<td>Contact thermal conductivity coefficient</td>
<td>$\alpha$</td>
<td>Coefficient of thermal expansion</td>
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<td>$K$</td>
<td>Generalized stiffness matrix</td>
<td>$\beta$</td>
<td>Thermoelastic constant</td>
</tr>
<tr>
<td>$k$</td>
<td>Coefficient of thermal conductivity</td>
<td>$\theta$</td>
<td>Temperature difference</td>
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<td>$N_D$</td>
<td>Number of cycles at the deflection point</td>
<td>$\Lambda$</td>
<td>Radiative coefficient</td>
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<tr>
<td>$N_{ref}$</td>
<td>Shortest life of life levels</td>
<td>$\rho$</td>
<td>Mass density</td>
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<tr>
<td>$N_{i,m}$</td>
<td>Shape function</td>
<td>$\sigma_B$</td>
<td>Stefan-Boltzmann constant</td>
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<td>$N$</td>
<td>Number of cycles until failure at a specified stress level</td>
<td>$\sigma_p$</td>
<td>Flow stress</td>
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<td>$n_{i,eq}$</td>
<td>Equivalent damage cycles</td>
<td>$\varepsilon_p$</td>
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<tr>
<td>$n_b$</td>
<td>Number of loading blocks until the failure</td>
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<th>Ring material</th>
<th>Feed rate (mm/s)</th>
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<td>Outer radius of mandrel (mm)</td>
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<td>Colling zone (deg)</td>
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<td>Inner radius of mandrel (mm)</td>
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<td>Initial rolls temperature (°C)</td>
<td>30 or 500</td>
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<td>Outer radius of main-roll (mm)</td>
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<td>Inner radius of ring (mm)</td>
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<td>air convection coefficient</td>
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<td>Height of rolls (mm)</td>
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<td>height of the contact area (mm)</td>
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<td>Coolant convection coefficient (W/(m²°C)) - oil</td>
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<td>Contact heat conductivity (W/(m²°C))</td>
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<td>Time(s)</td>
<td>Force(N)</td>
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<td>25.50</td>
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<td>Table 3 work-roll correction coefficients and thermo-mechanical properties</td>
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<td>---------------------------------------------------------------</td>
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<tr>
<td>Work-rolls material</td>
<td>H-13 tool steel</td>
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<tr>
<td>Elastic module $(GPa)$</td>
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<tr>
<td>Ultimate tensile strength $(MPa)$</td>
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<td>Yield tensile strength $(MPa)$</td>
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<tr>
<td>Poisson coefficient</td>
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<td>Initial rolls temperature $(^\circ C)$</td>
<td>30-500</td>
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<td>Specific heat $(J/\text{kg} \cdot ^\circ C)$</td>
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<td>Density $(kg/m^3)$</td>
<td>7840</td>
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<tr>
<td>Thermal conductivity as a function of temperature $(W/(m \cdot ^\circ C))$</td>
<td>$k = 10^{-7} \cdot T^3 - 10^{-4} \cdot T^2 + 5.78 \cdot 10^{-2} \cdot T + 16.131$</td>
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<tr>
<td>Thermal expansion as a function of temperature $(10^{-3} / ^\circ C)$</td>
<td>$\alpha = 3 \cdot 10^{-7} \cdot T^2 - 10^{-4} \cdot T + 1.0971$</td>
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<tr>
<td>Flow stress as a function of plastic strain $(MPa)$</td>
<td>$\sigma_p = -268.72 \cdot \varepsilon_p + 1795.5 \cdot \varepsilon_p^2 - 4676.9 \cdot \varepsilon_p^3 + 5995 \cdot \varepsilon_p^4 - 3943.2 \cdot \varepsilon_p^5 + 1334.7 \cdot \varepsilon_p^6 + 693.05$</td>
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<tr>
<td>Surface treatment factor</td>
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<tr>
<td>Reliability correction factor</td>
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<tr>
<td>Temperature correction factor $(500{^\circ}C)$</td>
<td>0.768</td>
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Table 4: Summary of Cumulative damage rules

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<tr>
<th>Condition</th>
<th>Damage Rule</th>
<th>Damage Accumulation</th>
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<tr>
<td>$S_u \geq S_e$</td>
<td>$N_i = N_D \left( \frac{S_u}{S_e} \right)^4$</td>
<td>$D = \sum n_i / N_i$</td>
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<tr>
<td>$S_u &lt; S_e$</td>
<td>$N_i \rightarrow \infty$</td>
<td></td>
</tr>
<tr>
<td>$S_u \geq S_e$</td>
<td>$N_i = N_D \left( \frac{S_u}{S_e} \right)^4$</td>
<td>$D = \sum n_i / N_i$</td>
</tr>
<tr>
<td>$S_u &lt; S_e$</td>
<td>$N_i = N_D \left( \frac{S_u}{S_e} \right)^{24-1}$</td>
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<tr>
<td>$D_i = \frac{n_i}{N_i}$</td>
<td>$n_{eq} = N_i \left[ D_{ref} \right]^{0.4}$</td>
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<tr>
<td>$D_i = \left[ \frac{n_{eq} + n_i}{N_i} \right]^{0.4}$</td>
<td>$N_i$</td>
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Table 5: Work-roll’s life estimation in different temperature

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<th>Manson-Halfod-Haibach</th>
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<tr>
<td></td>
<td>$n_b \ (500^\circ C)$</td>
<td>$n_b \ (30^\circ C)$</td>
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<tr>
<td>Goodman</td>
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<td></td>
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<tr>
<td>Main-roll (r/R=0.98)</td>
<td>9462</td>
<td>&gt;1E7</td>
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<tr>
<td>Mandrel (r/R=1)</td>
<td>14530</td>
<td>&gt;1E7</td>
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<td>Morrow</td>
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<td>Main-roll (r/R=0.98)</td>
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<td>&gt;1E7</td>
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<tr>
<td>Mandrel (r/R=1)</td>
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<td>&gt;1E7</td>
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<td>Gerber</td>
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<tr>
<td>Main-roll (r/R=0.98)</td>
<td>609433</td>
<td>&gt;1E7</td>
</tr>
<tr>
<td>Mandrel (r/R=1)</td>
<td>&gt;1E7</td>
<td>&gt;1E7</td>
</tr>
</tbody>
</table>

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