INVESTIGATION OF HEAT LOSS AND FEASIBILITY OF REHEATING IN LARGE RADIAL-AXIAL RING ROLLING PROCESSES

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06/06/2013

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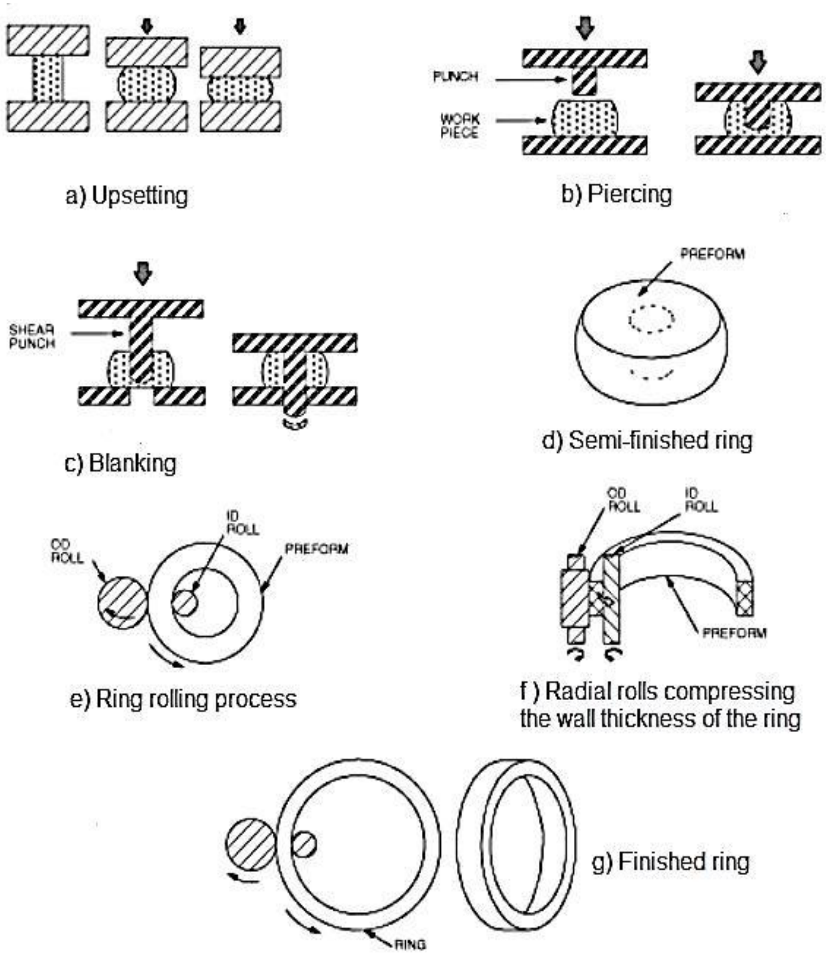
Introduction

Ring rolling process

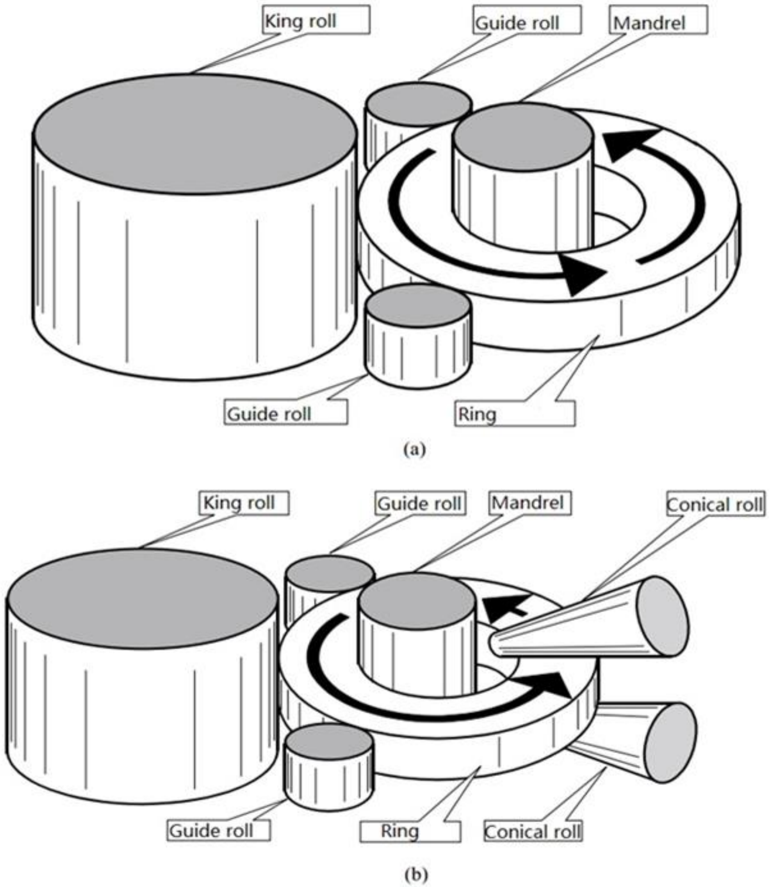
- First Modern ring rolling mill invented in England by Bodmer in 1842
- Rings are used in power plants, aircraft, railway equipment etc.
  - Size ranges from mm to meters
- T-Shape, H-Shape, Pure radial, Radial- axial
- Ring rolling research started 1960s

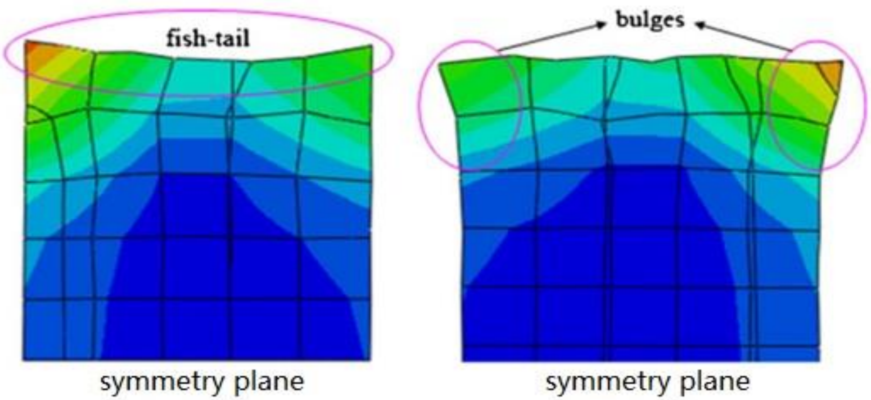


Introduction

Radial-axial ring rolling process

- Key components: King roll, mandrel, conical rolls, guide rolls





(a) fish-tail (b) bulges

Introduction

Problem statement

- Based on increased surface area during ring rolling and large temperature gradient (radiation, convection, conduction).
- Cooling during hot rolling necessitates large ring rolling process divided into two parts due to chilling. Significant time and energy are wasted due to the need for reheating during ring rolling.
- This problem is most significant in large diameter rings (> 1000mm)

Radial-axial ring rolling at Scot Forge McHenry, Illinois

Introduction

Research objective

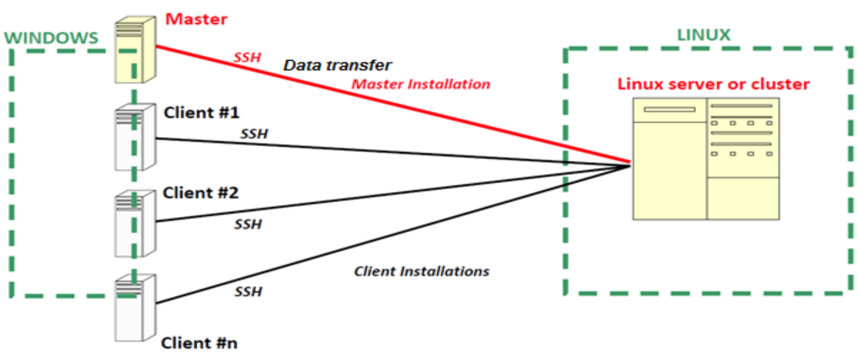
- Understand heat loss in the ring rolling process
- Investigate a reheating methodology for large metal rings which can maintain the ring temperature during the rolling process:
- Achieve a more uniform temperature distribution and microstructural response
- Would result in more efficient mill utilization through elimination of reheating step and reduction of processing costs (faster turn around time from order-shipment)

Introduction

Research methodology

- Build up FE model based on the ring rolling data from Scot Forge
- Simulate and analyze the ring rolling process using FEM software FORGE HPC 2011
- Run the simulation computation using Linux64Redhat3 OpenMpi Cluster system at Marquette University

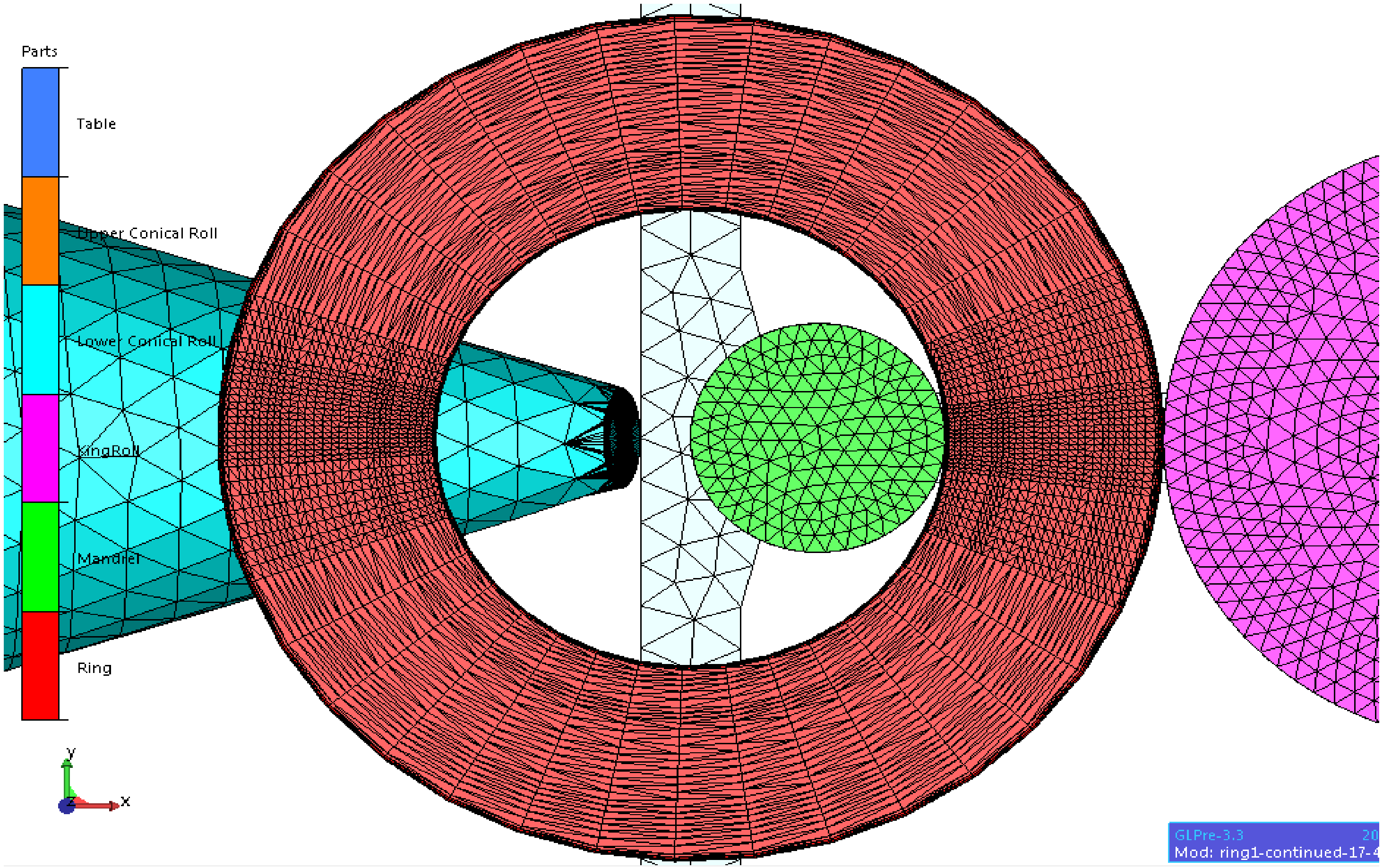
24 node operation Enables simulation times on order of 8-12 hours instead of 2 days



Simulation Model

- Most industrial processes
- Full model required
  - Can not exploit ring symmetry due to table support
- ALE Algorithm required for efficient simulation
  - Eulerian formulation used to model roll gaps and minimize excessive remeshing
  - Lagrangian formulation used to model free surface and define limits of free/contact surfaces
  - Mesh Design Important for Simulation Model

Mesh Design


Parts
Table
Upper Conical Roll
Lower Conical Roll
KingRoll
Mandrel
Ring
y
x
GLPre-3.3
Mod: ring1-continued-17-4

Roll and workpiece dimensions used in the initial ring rolling model development

	Items	Dimension
Roll dimensions	Diameter of king roll	88.90 cm
	Diameter of mandrel	38.18 cm
	Taper of conical roll	35 degrees
Initial ring dimensions (hot)	Outer diameter(OD)	142.24 cm
	Inner diameter(ID)	72.60 cm
	Height	30.48 cm
	Wall thickness	33.02 cm
Final ring dimensions (hot)	OD	304.8 cm
	ID	245 cm

FE model – Mechanical

Material Constitutive model(Hensel-Spittel)

$$\bar{\sigma} = \mathrm{K} \cdot e^{m_2/\bar{\varepsilon}} \cdot \bar{\varepsilon}^{n} \cdot \dot{\bar{\varepsilon}}^{m_1} \cdot e^{\beta/T}$$

$$\bar{\sigma} = A e^{m_1 T} T^{m_9} \varepsilon^{m_2} e^{\frac{m_4}{\varepsilon}} (1+\varepsilon)^{m_5 T} e^{m_7 \varepsilon} \dot{\varepsilon}^{m_3} \dot{\varepsilon}^{m_8 T}$$

Values of coefficient used the Hensel-Spittel constitutive model for AISI 4340 steel

Coefficient	Value
A (strength coefficient)	1530.96
m1 (Temperature term)	-0.00261
m2 (Sensitivity to Strain-hardening)	-0.1461
m3 (Sensitivity to strain rate)	0.13956
m4 (Strain softening coefficient)	-0.05778
m5, m7, m8, m9 (Unused coefficients)	0

FE model – Mechanical

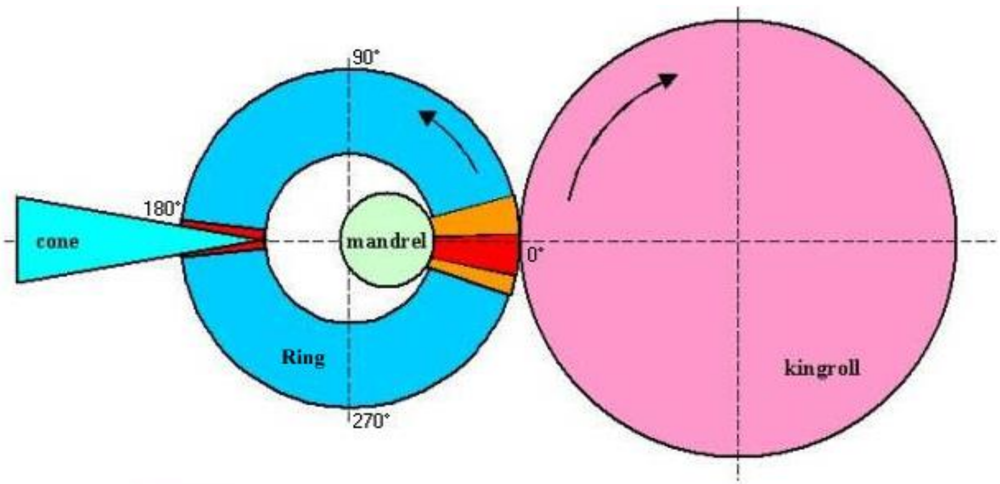
Friction model(Coulomb)

$$\tau_f = \begin{cases} \mu N, & \mu N < \tau_s \\ \tau_s, & \mu N \geq \tau_s \end{cases}$$

- Where μ is the coefficient of friction, τ_s is the shear yield stress and N is the normal contact pressure.

- As no lubricant is used in ring rolling, dry conditions can be assumed so that the friction coefficient μ between the workpiece and radial roll, was set equal to 0.4[5] in the FE model.
- μ was set as 0 between the workpiece and conical rolls

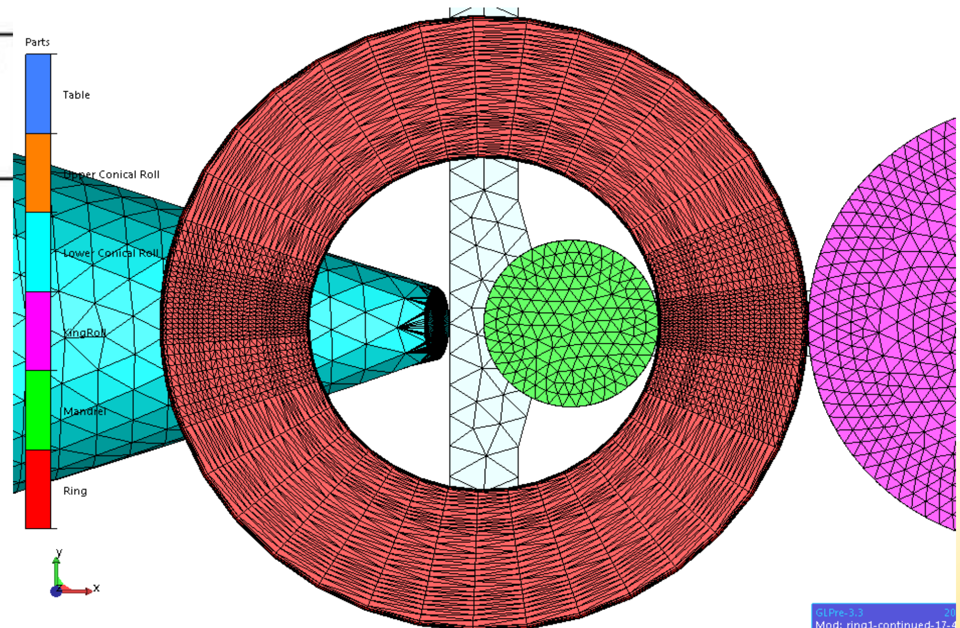
FE model – Mechanical
Mesh design



Accurate mesh		
↑	1	**Area in contact** with the kingroll / **Area in contact** with the cone
	2	**Area around contact** with the kingroll.
	3	**Rest of the billet.**

- Deformation is concentrated at two roll gaps. Reasonable mesh design can make the FE model more efficient.

- Deformation and heat transfer occurs simultaneously in roll gaps, higher accuracy is needed than the non-contact areas where only heat transfer occurs



FE model – Thermal

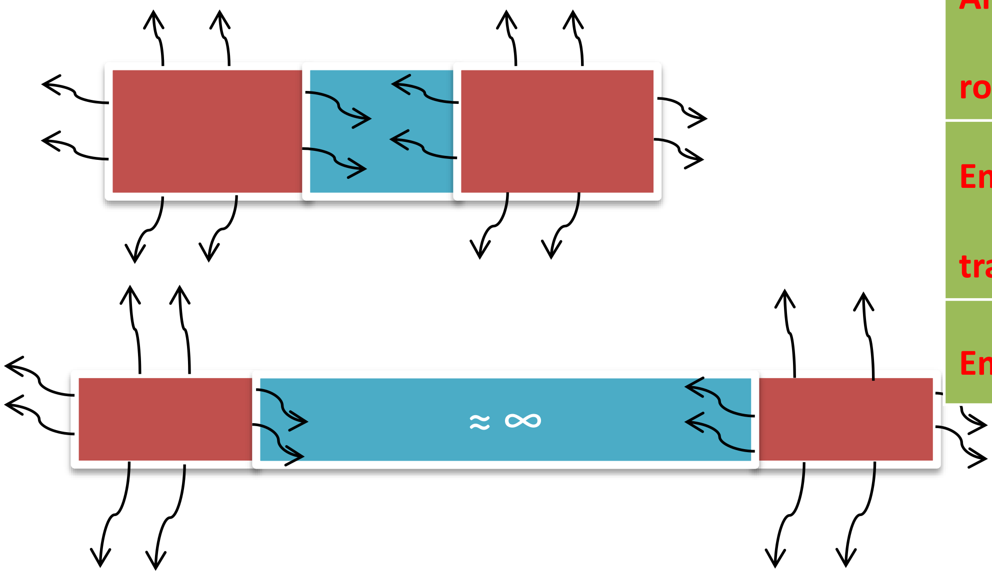
- The ring was heated up to 1288C(2350F) uniformly, then transported to the rolling mills during 2 minute interval.
- Chilling during transport from the furnace to the rolling mill was modeled as a simple transient thermal simulation.
- Rolling was simulated with heat loss and analyzed

FE model - Thermal

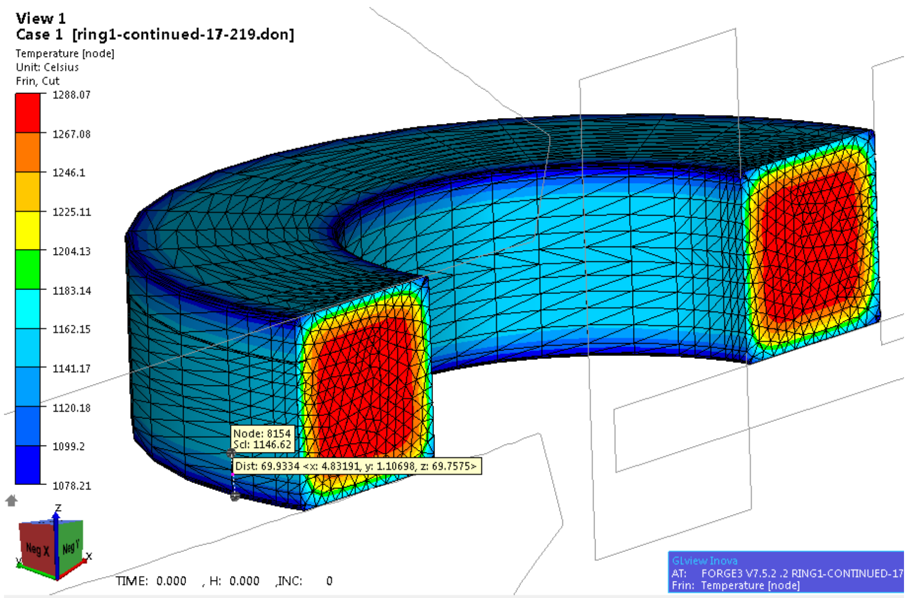
Thermal exchange assumptions

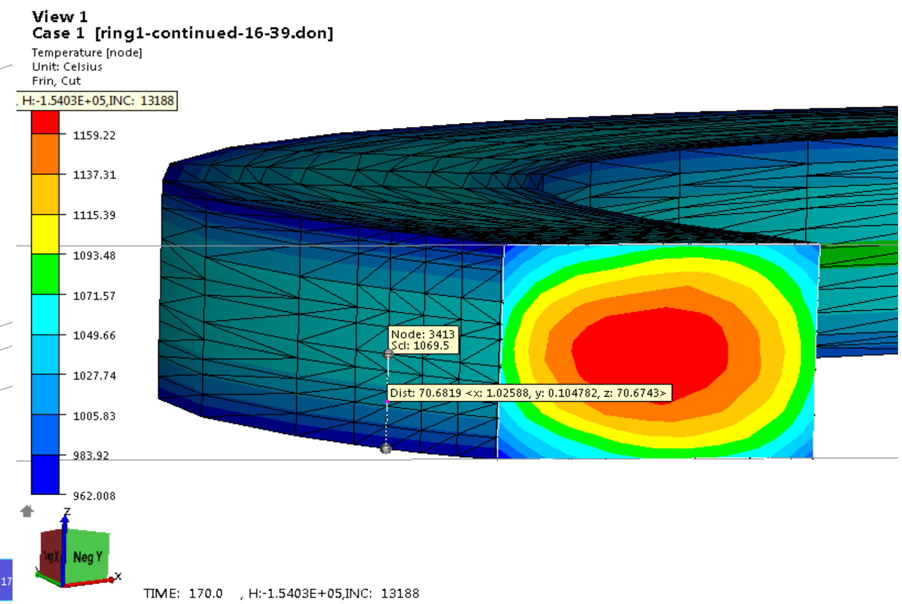
- convection, radiation and conduction (including inter object)
- No re-radiation

Items	Value
Contact heat conductivity k_h	35.5 $(\mathrm{W}/(\mathrm{m}\cdot K))$
Convection coefficient, h	10 $(\mathrm{W}/(m^2\cdot K))$
Initial temperature of ring when out from furnace	1288C (2350F)
Temperature of rolls	66C (150F)
Ambient temperature in rolling	30C (86F)
Emissivity during transportation	0.5
Emissivity during rolling	0.6



Results
Validation of surface temperature

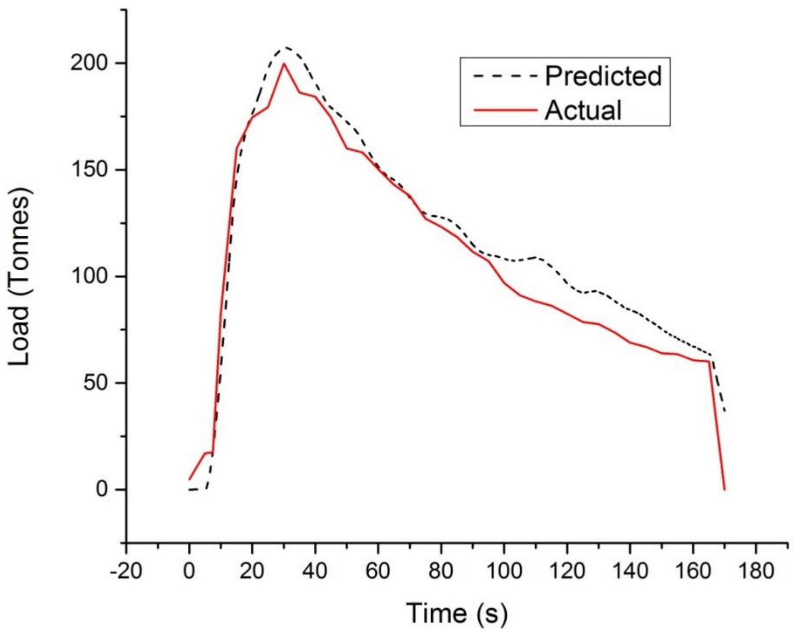


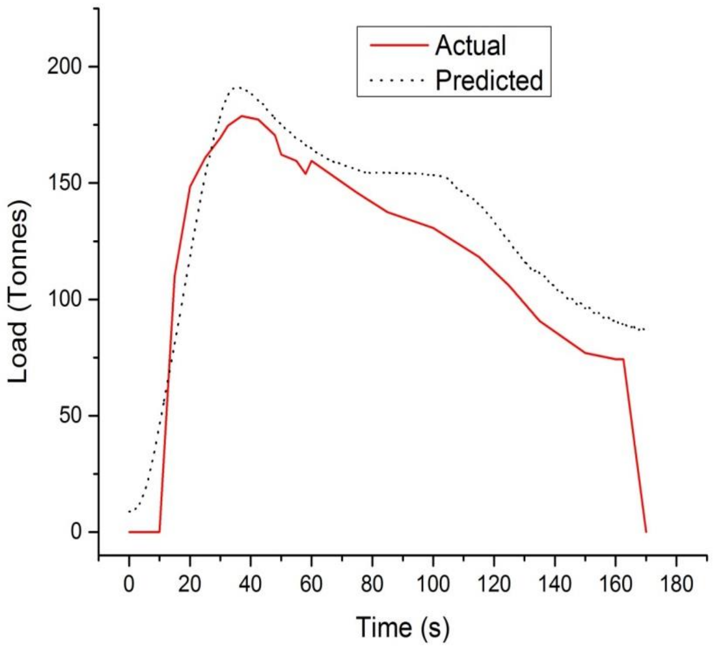


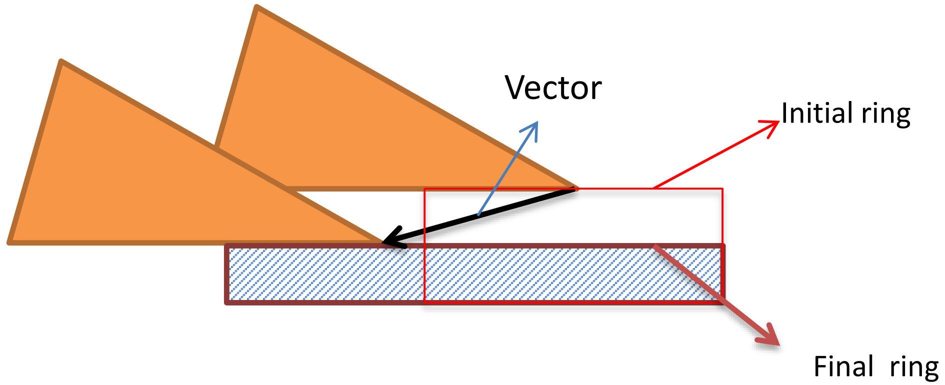
The comparison of the predicted and measured surface temperatures during transportation and rolling

	Predicted	Measured	Error
Transportation	1146.6C	1166C	1.67%
Rolling	1069.5C	1077C	0.70%

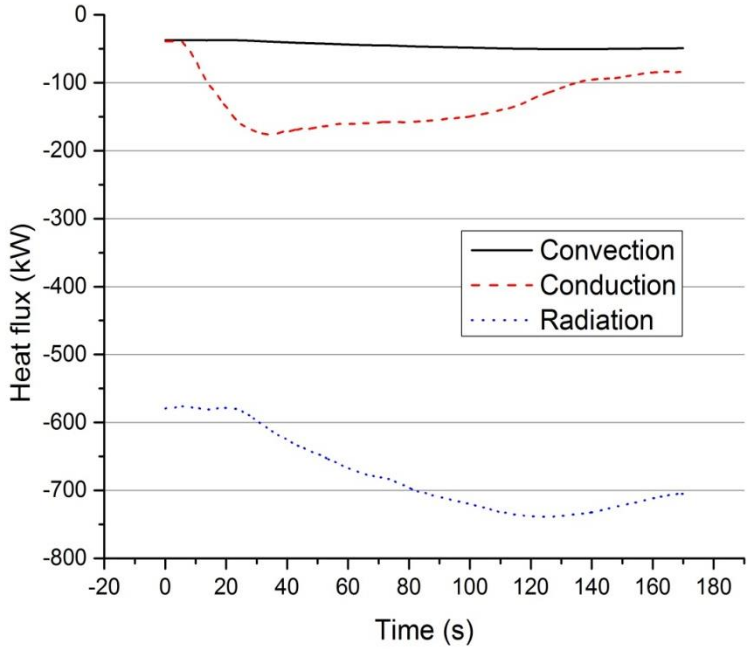
Results
Validation of mill loads







Results
Break-down of heat losses in ring rolling

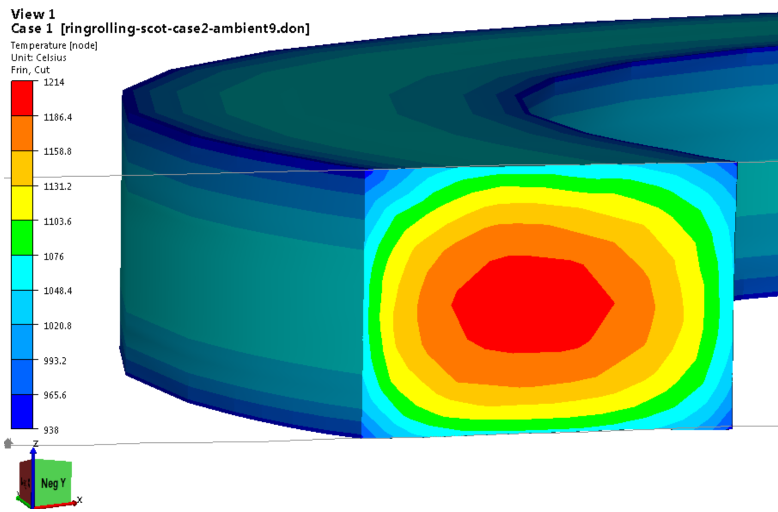


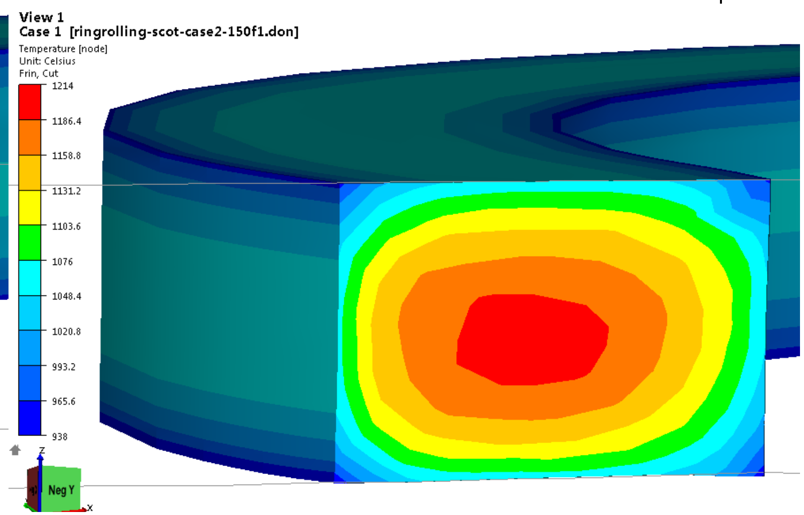
- The heat loss profile of each mode during the ring rolling from the FORGE simulation.
- The average heat loss flux of the three heat transfer modes are 80% in radiation, 16% in convection and 4% in conduction where a negative value indicates that heat was lost from the ring.

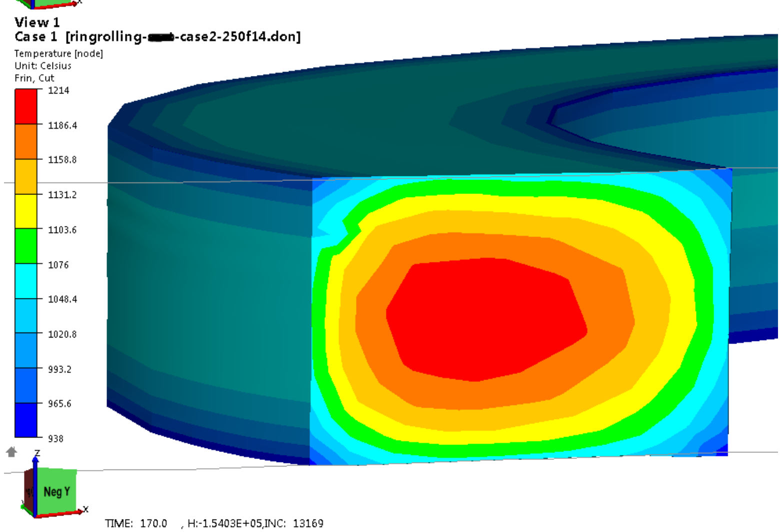
Discussions

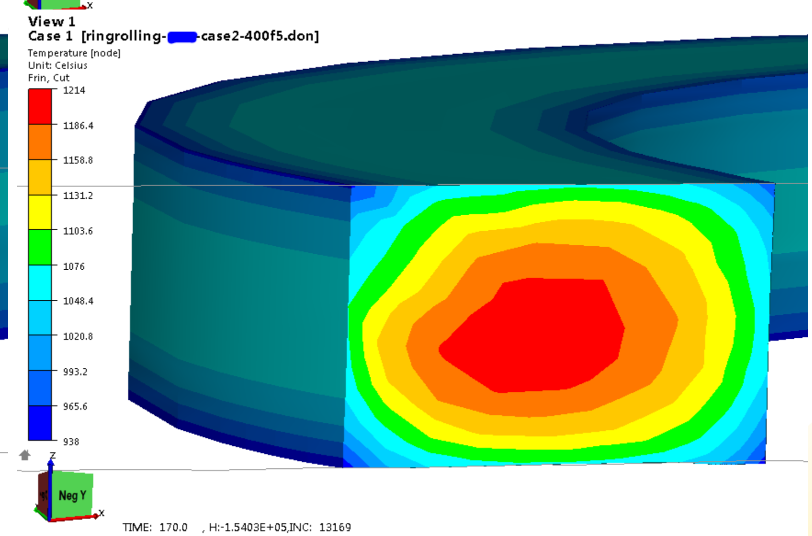
The effect of the roll temperature on the ring temperature

86F	150F
250F	400F

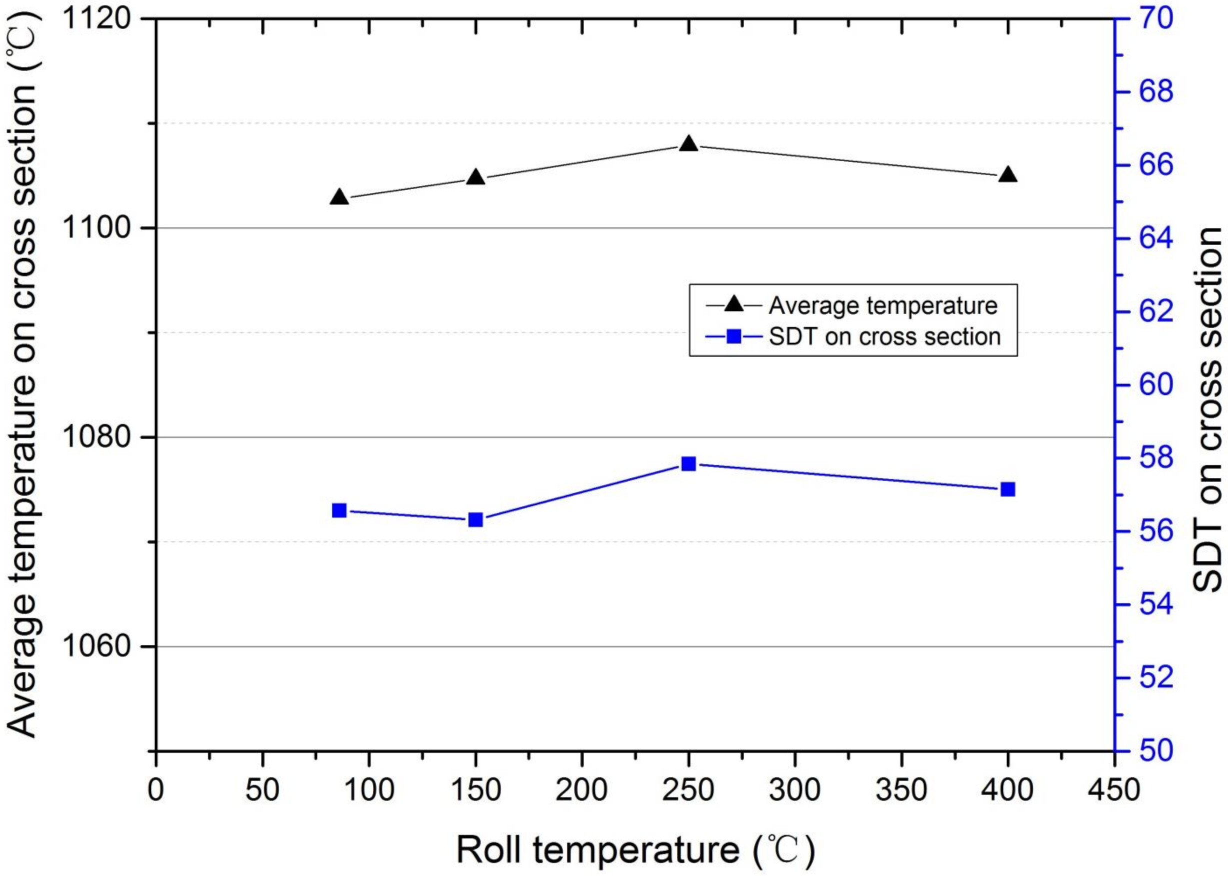






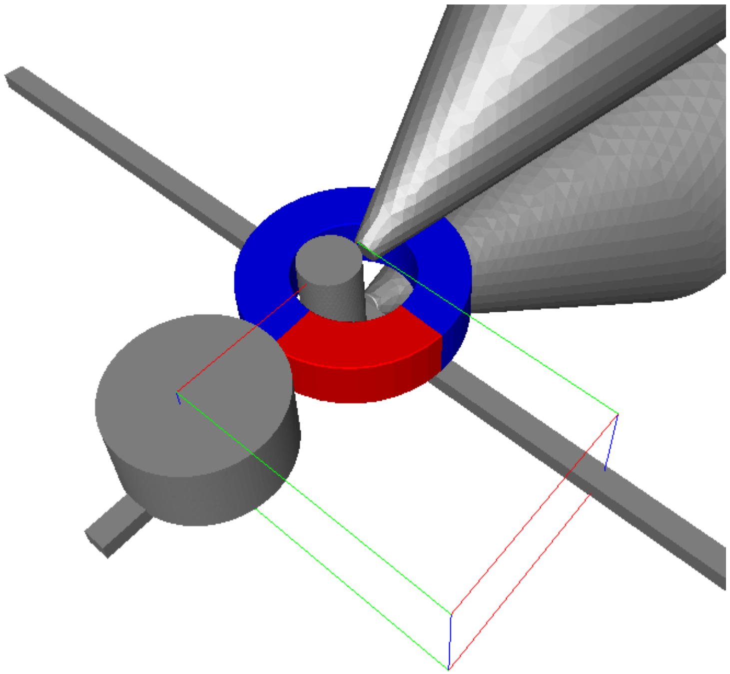


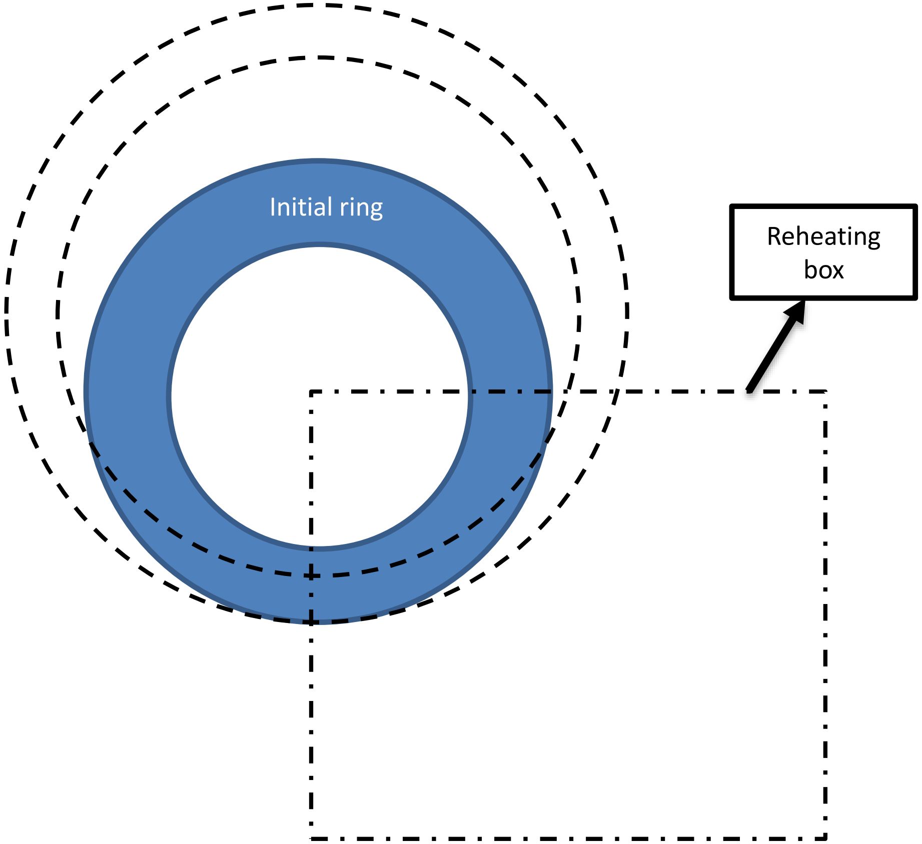
Average temperature and SDT on cross section



FE model - Reheating

Development of simulation methodology used to model reheating in FORGE

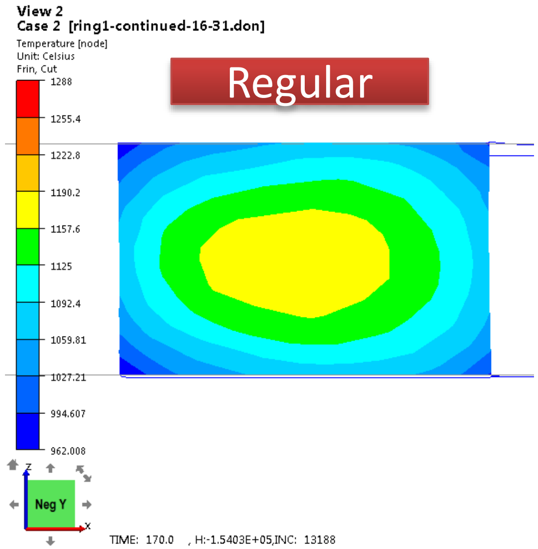


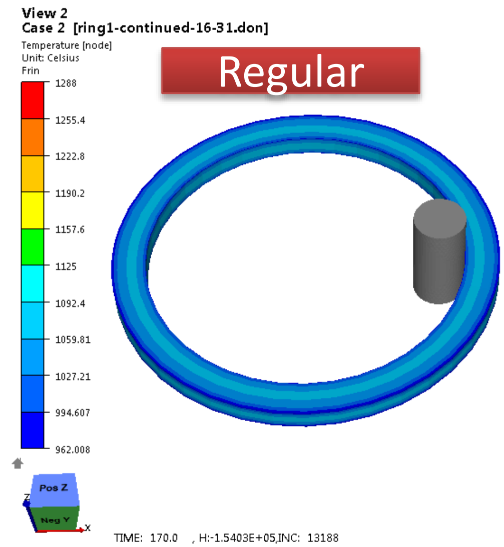


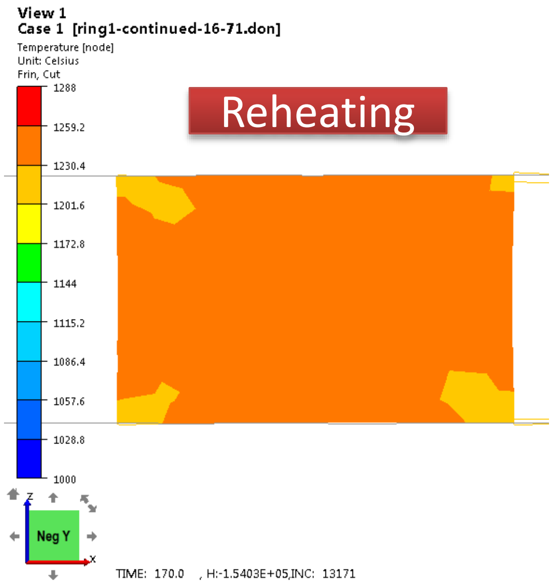
- In the reheating box, the ambient temperature was set as 1927°C, convection coefficient was 80 $W/(m^2 \cdot K)$, the emissivity was 1.
- The reheating box was fixed at a position, and the ring went through the box in each round.

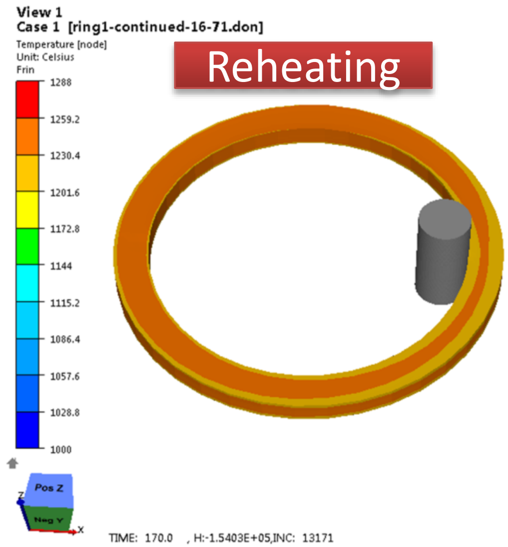
Reheating

Effect on the uniformity of the thermal profile by reheating

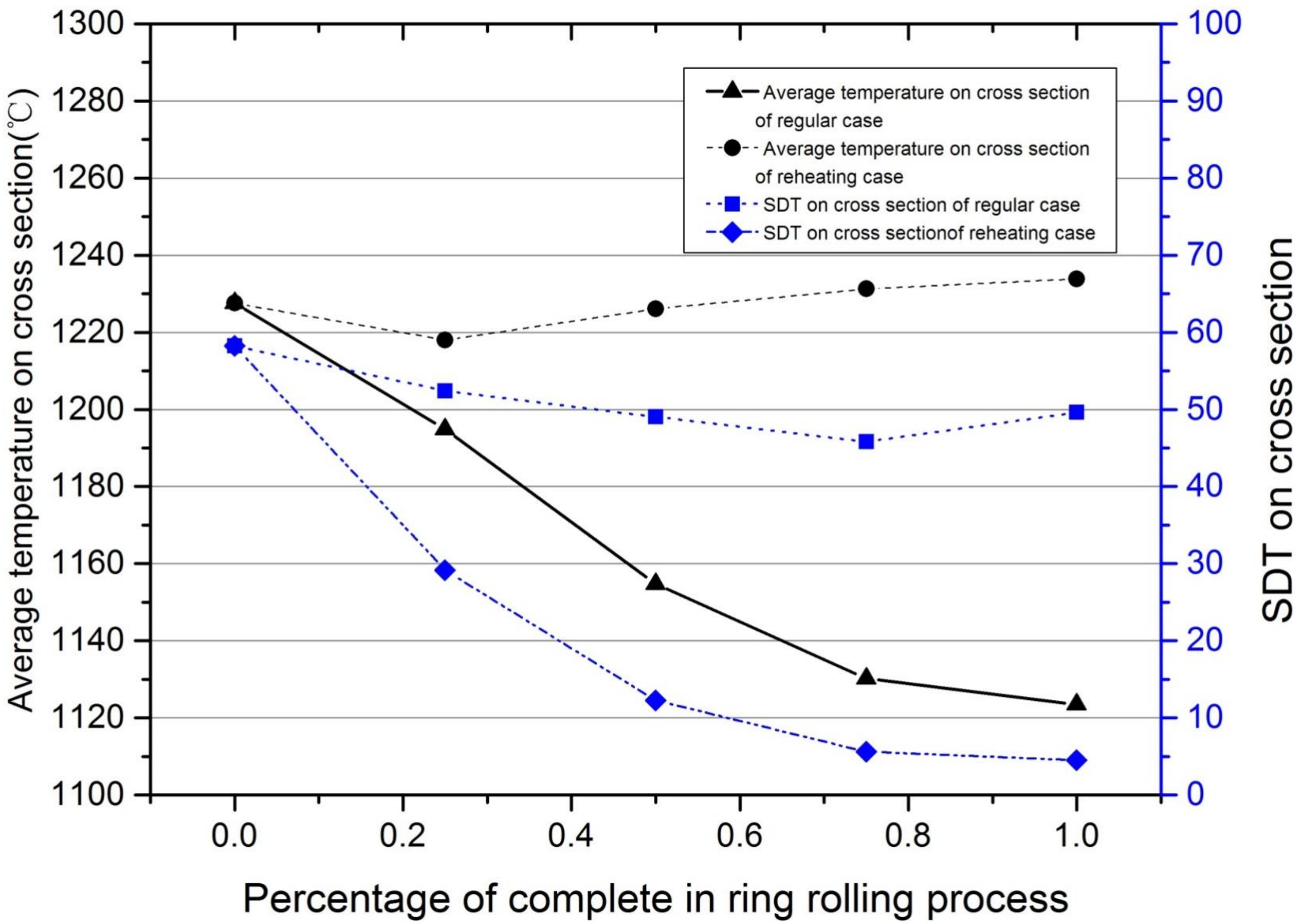




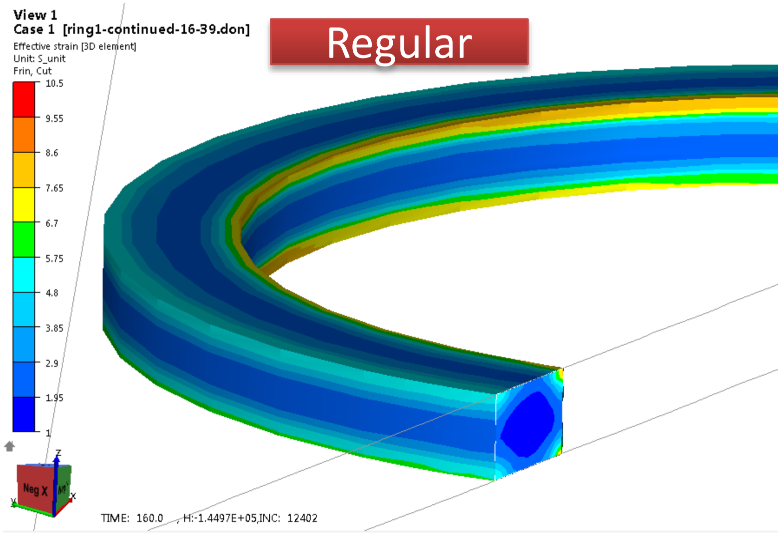


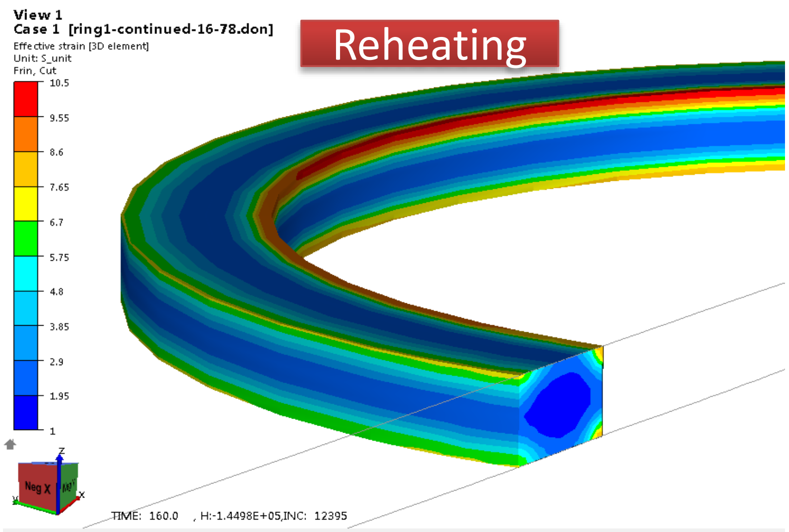


SDT (Standard Deviation of Temperature) and average temperature on transverse cross section

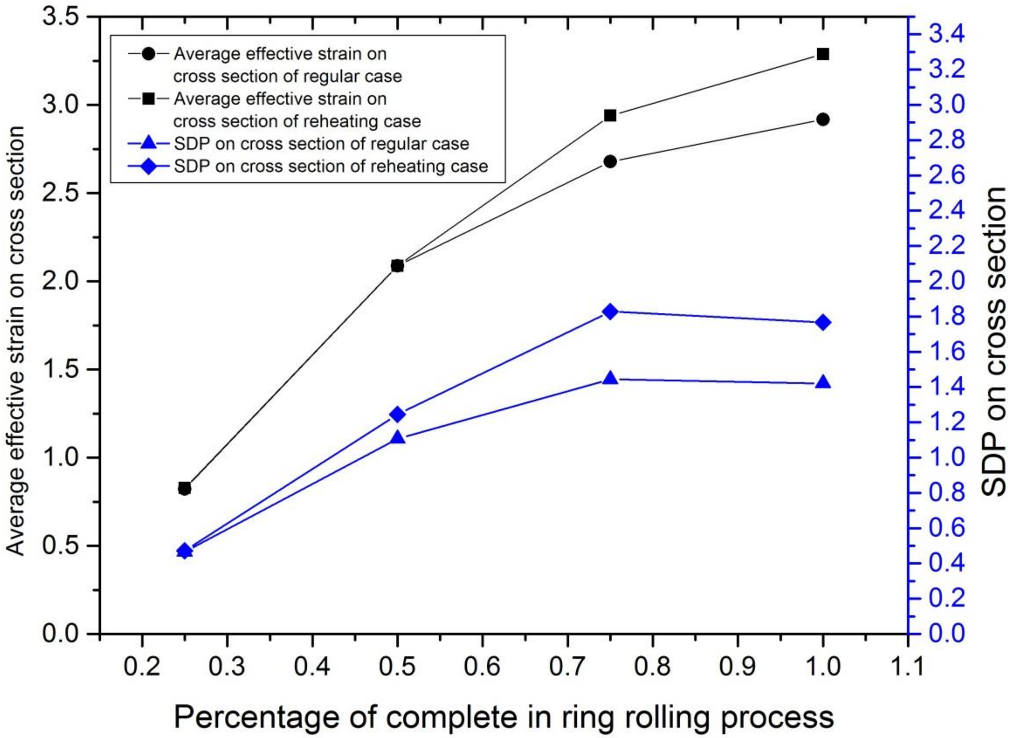


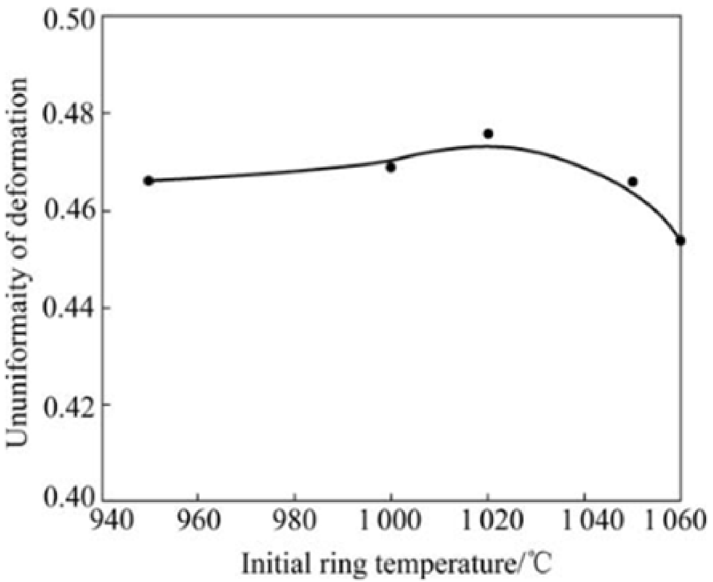
Effect of reheating on the effective strain distribution





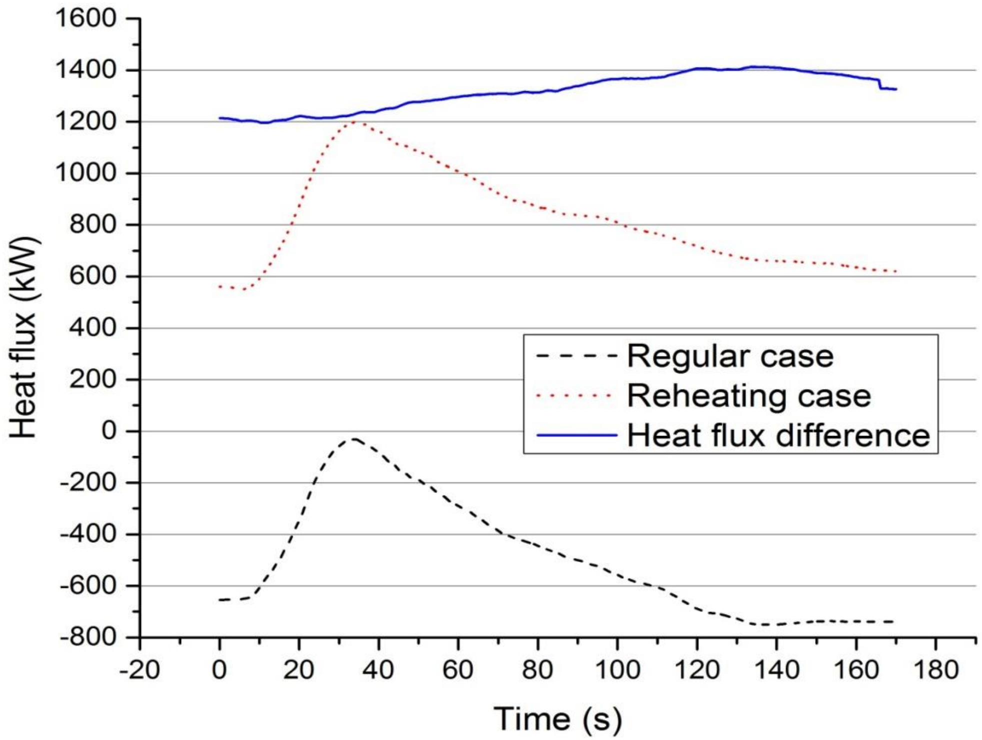
SDP(Stand Deviation of Effective Plastic Strain) and average affective on transverse cross section





- Sun, Z.; Yang, H.; Ou, X., Thermo-mechanical coupled analysis of hot ring rolling process. *Transactions of Nonferrous Metals Society of China* **2008,** *18* (5), 1216-1222.

Cost estimation for the reheating during the ring rolling



- The heat transaction difference curve was plain enough to estimate an average value for the heat gain from reheating box, and it was estimated as 1300kW.
- The amount of energy obtained from reheating box $E_{reheating}$ = 1300kW*$\frac{170s}{3600s/h}$= 61.4kW-h.
- Assume the efficiency of the real reheating device $\eta = 50\%$, then the total electricity needed would be 122.8kW-h per ring.
- Based on the industrial electricity rate $0.23 per kW-h[29], the reheating cost for the candidate ring simulated is $28.24.

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CONCLUSIONS

1. The predicted dimensions, surface temperature of the ring and mill loads in the FE model were in good agreement with the actual values of the real ring rolling process.
2. The final ring temperature profile is not significantly dependent on the roll temperature.
3. The reheating box greatly improved the uniformity of the temperature profile on the ring, the standard deviation of the final temperature decreased from 45 to 4.5.
4. The reheating didn’t significantly change the uniformity of effective strain on the ring.
5. The estimated reheating cost per ring was $28.24 (< 180 RMB).

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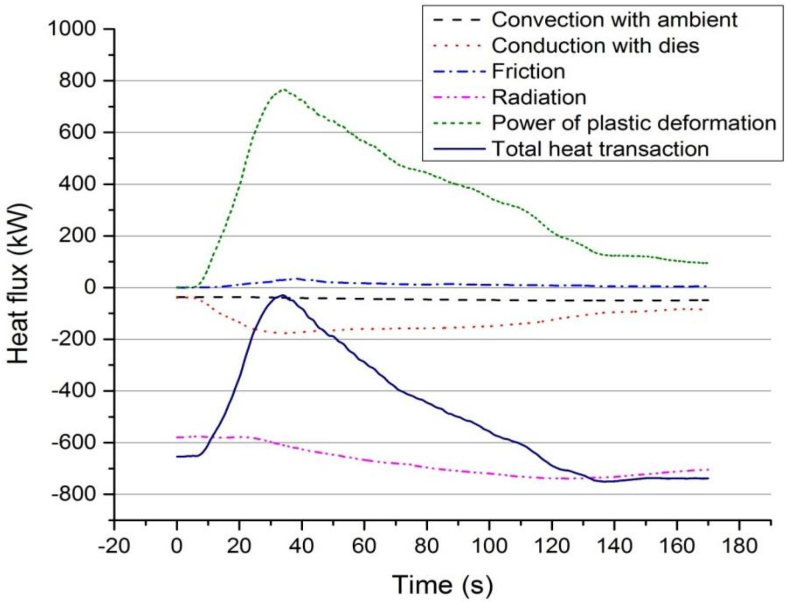
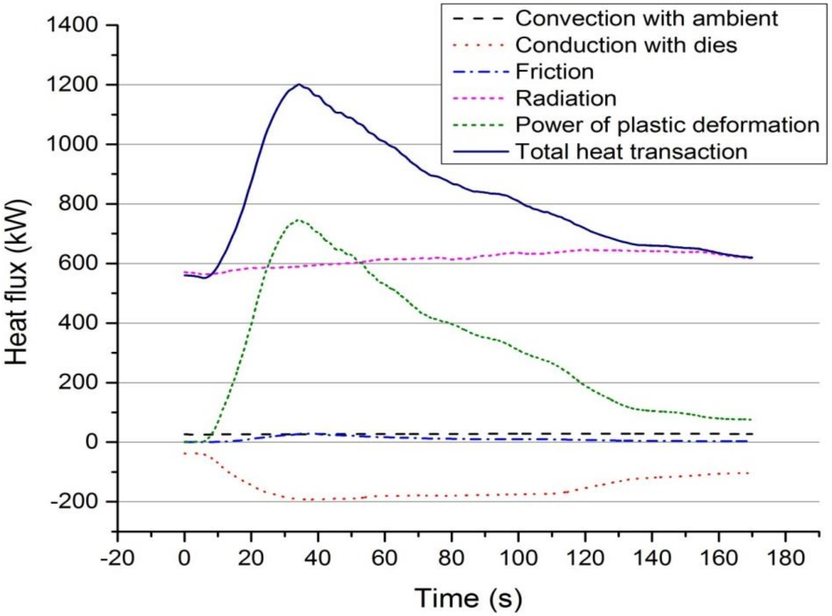
Future work

1. More efficient ring rolling FE model
2. Test methodology on a super alloy ring
3. Test methodology with different modes of heating furnaces
4. Development of reheating model based on induction heating
5. Microstructure modeling using reheating and validation

Heat flux of different methods during regular and reheating ring rolling process





FE model - Thermal

Estimation of heat loss

$$\dot{Q}_{total} = \dot{Q}_{rad} + \dot{Q}_{h} + \dot{Q}_{kh}$$ Eq. 4.4

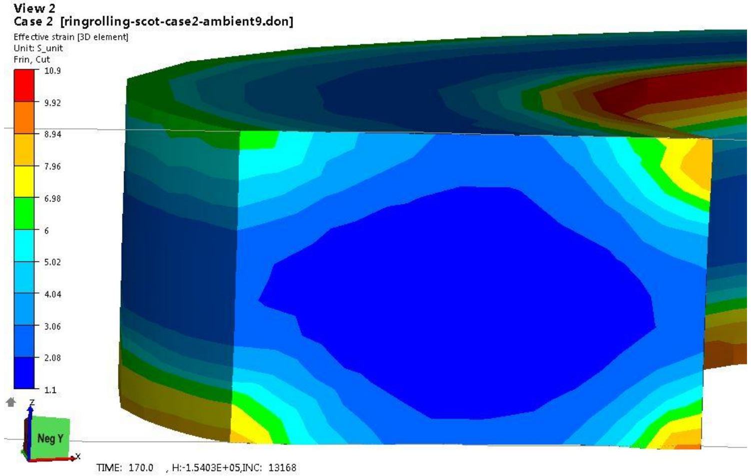
$$\dot{Q}_{rad} = A_{surf,0} \cdot \varepsilon \cdot \sigma \cdot \left[T_{ring,\mathrm{surf}}{}^{4} - T_{surr}{}^{4}\right] \cdot \left|0.001 \cdot \frac{kW}{W}\right|$$ Eq. 4.5

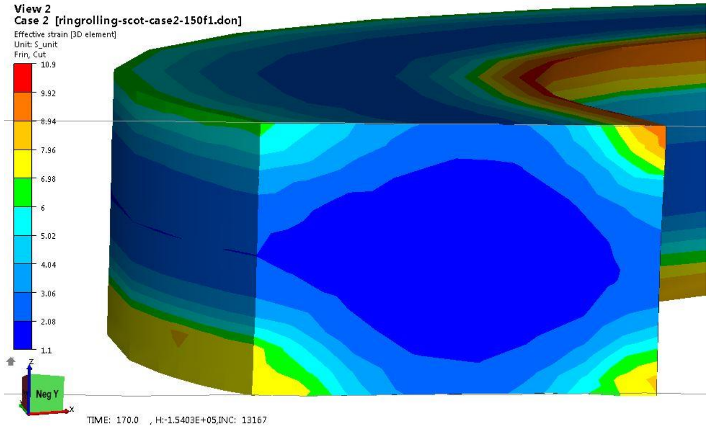
$$\dot{Q}_{h} = A_{surf,0} \cdot h \cdot \left[T_{ring,\mathrm{surf}} - T_{surr}\right] \cdot \left|0.001 \cdot \frac{kW}{W}\right|$$ Eq. 4.6

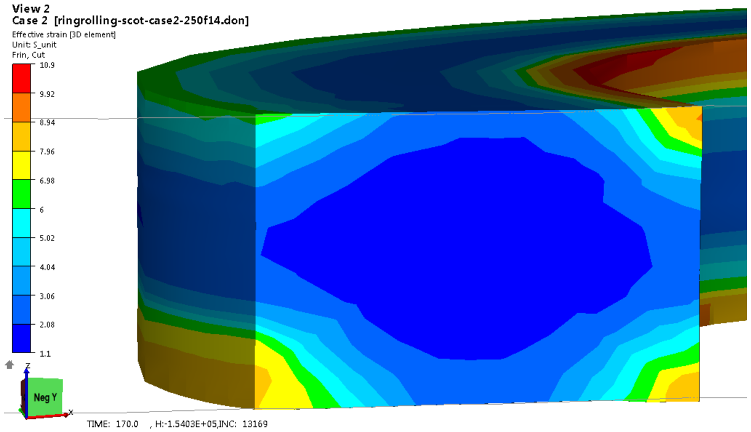
$$\dot{Q}_{cond} = A_{contact,0} \cdot k_{h} \cdot \left[T_{ring,\mathrm{surf}} - T_{roll}\right] \cdot \left|0.001 \cdot \frac{kW}{W}\right|$$ Eq. 4.7

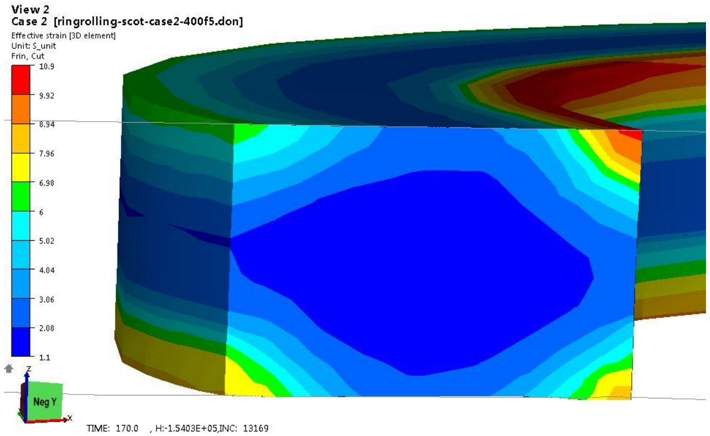
Effect of roll temperature on the effective strain

86F	150F
250F	400F









Average effective strain and SDP on cross section