Control of continuous strip annealing for copper and copper alloys by means of real-time recrystallisation modelling

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Introduction

Worldwide some 100.000 MTPA of Cu and Cu-alloy sheet metal are produced as a semi-finished product with a thickness less then 5 mm down to 50 µm or even less. The main material properties, the sheet metal has to meet, are characterized by strength, hardness, ductility, grain size, electrical conductivity and surface quality (reduction of oxides). These properties, except surface quality, depend on the final microstructure of the metal, which is achieved by short time annealing, the last production step after cold rolling. While short time annealing, the material is recrystallised. In the case of alloys additionally phase transformations might occur, e.g. α-brass and β-brass. For more advanced alloys, a solution annealing and subsequent precipitation hardening procedure is performed. The final properties of the material depend strongly on the annealing parameters, i.e. the temperature versus time curve applied to the material, the so called “recipe”. These recipes are based on laboratory trials and experience. If the product shows deviations of the final properties compared to the required properties, the operator usually tries to compensate for these deviations by manual readjustment of the process parameters. The success depends on his experience.

The investigations presented in this paper are performed solely for recrystallisation annealing. Two models, set in contrast with each other, are presented which predict the change of material properties during recrystallisation for non-isothermal heat treatment. The models combine the material model with the furnace model, which is able to calculate the strip temperature versus time very accurately. The models allow for automatic control of the annealing process. The benefits can be seen in certain everyday production situations.

The Production Process

Short time annealing is mainly performed in continuous strip annealing furnaces. High heating and cooling rates with an order of magnitude of 10 to 100 K/s and in some cases a short soaking period at a defined temperature is required. This annealing process, which is described by a precise temperature versus time curve, lasts only a short time of about 10 to 100 seconds. The radiant heat transfer is low because of the poor radiant emissivity of Cu (ε about 0.03). Thus the basic concept of heat transfer is high gas convection achieved by gas jets impinging on the strip surface. The jets are generated by nozzle systems driven by hot gas fans. The process gas is usually air or where a bright surface of the strip is required, nitrogen mixed with hydrogen or even just pure hydrogen. Using pure hydrogen increases the heat transfer by a factor of 1.9. In order to avoid explosions using hydrogen concentrations higher than 5 %, however, demands safety measures. The furnaces can be built both vertically or horizontally. With the horizontal type, the jet impulse is also used to levitate the strip and guide the strip contact free through the furnace.

The main process parameters, which determine the heating and cooling curve, are the gas temperatures of the individual heating and cooling sections, the nozzle exit velocity of the gas jets, which depends on the fan speed, and lastly, the strip velocity and the strip geometry. The required material properties will determine these process parameters, the so-called “recipe”.

During production, the common method of quality control is as follows:

1. Production of a new coil is started.
2. A material sample is taken from the first part of the strip leaving the furnace.
3. The hardness is measured.
4. In the case where the deviation of hardness is to large, the process parameters are readjusted.

Of course each step is performed while the production is running. In the worst case, the first part of the strip has to be scrapped. The most common parameter to be readjusted is the strip speed. A more ambitious method is readjustment of the fan speed which controls the heating or cooling power applied to the strip by changing the heat transfer. The fan speed n correlates with the heat transfer α to the power of 0.7 ($\alpha = n^{0.7}$). The heating or cooling power correlates linearly with α. Thus a 100 % higher fan speed means a 62 % higher heating or cooling power. Of course this method is limited in order not to lose strip stability, since the impinging gas jets have an impact on the levitation forces. Readjustment of the furnace temperature is inappropriate since this takes too much time. The amount of readjustment depends on the experience of the staff.

Additionally some working situations occur which require adjustment of the annealing parameters in order to achieve the same product quality. The most important are:

1. Change of coil at decreased strip speed.
2. Change of heating-sections temperature before starting a new production campaign. Sometimes the downtime period is shortened and production starts with a suitable strip speed before the individual temperature set points are reached.
3. Change of material thickness from coil to coil.

The “recipes” are mostly formulated based mainly on laboratory annealing trials and optimized by the production. However, with laboratory furnaces, e.g. salt bath or sand bath furnaces, it is hard to achieve similar temperature versus time curves as in the continuous strip annealing furnace. Common laboratory furnaces are suitable for performing isothermal annealing.

To optimize the production process a predictive material model based on metallurgical physics, which describes the change of material properties depending on the annealing process and the initial properties of the material, is required.

The benefits of a predictive material model would be:

- Minimization of scrap
- Optimization of process parameters
- Improvement of material quality control during transient phases, i.e. coil change with decreased strip speed, product change
- Maximization of material throughput

The Furnace Model

The basic requirement for reliable material modelling is the precise knowledge of the heating and cooling curves of the material. Unfortunately, in the case of Cu and Cu-alloys it is not possible to acquire the temperature versus time curve by contact-free measurement during the process. Pyrometers are not suitable because of the poor radiant emissivity of Cu.

The most suitable method is by calculation of the strip temperature with a furnace model. The most important parameter for the calculation is the convective heat transfer coefficient α, which is a characteristic parameter for each high convection heating system. The heat transfer coefficient of jet nozzle systems depends mainly on the nozzle field geometry, the distance of nozzle field to strip, the gas atmosphere and the gas temperature. The heat transfer coefficient is expressed by Nußelt's law of Similarity. WSP specifically determines Nußelt's law relevant for each type of nozzle system, which is assembled in a WSP high convection furnace. The strip temperature can easily be calculated employing Nußelt's law. So, further explanations of the furnace model need not be the subject of this paper.

Predictive Material Models

Generally three types of predictive material models are available:

1. Micromodels, e.g. cellular automaton, Monte Carlo simulation or models based on the phase field theory. Some of the models require an extensive thermo physical database.
2. Statistical models determine "recipes" from a database by means of interpolation (e.g. DOE-method). The database is a collection of all successful "recipes".
3. Macromodels, the change of material properties is expressed through analytical equations, which are based on physics. The material is assumed to be homogeneous, thus having the same properties in every position.

Micromodelling consumes a lot of calculating power and calculation time (hours). To use the software, experts are required. Thus micromodelling is not suitable for real-time process control. Micromodelling is suitable for fundamental research. In the production field it might be useful to generate basic recipes.

The use of statistical models is a helpful interim solution for creation of recipes by means of interpolation. Creation of recipes by extrapolation is unreliable, because it is outside the range of experience. Thus to enlarge the operating window, further empirical trials are necessary.

Macromodelling is the more appropriate solution. The speed of calculation is very fast even on a standard personal computer. Perhaps, in the near future, even PLC's will provide sufficient calculation power to run the macromodel. The macromodel is beneficial for the creation of recipes and additionally it enables real-time process control in situations where the recipe set points deviate from actual values.

Recrystallisation

The recrystallisation process and the phenomena occurring during recrystallisation will be summarized briefly before attempting to describe the macromodel.

Recrystallisation is referred to as a reconstruction of the microstructure during a heat treatment of deformed metals. It proceeds by the creation and motion of high angle grain boundaries. According to this the deformed grains are replaced by undeformed grains that nucleate and grow until the original grains have been entirely consumed. Recrystallisation is usually accompanied by a reduction in the strength and hardness of a material and a simultaneous increase in the ductility.

In many processes recrystallisation is accompanied by recovery, which starts at lower temperatures, compared to recrystallisation, and subsequent grain growth. Recrystallisation is about 2 orders of magnitude faster when compared with grain growth.

There are several largely empirical observations related to recrystallisation, the most important are listed below:

1. *Thermally activated*.

   The rate of the microscopic mechanisms controlling the nucleation and growth of recrystallised grains depends on the annealing temperature. Arrhenius type equations indicate an exponential relationship.

2. *Critical temperature*.

   To start recrystallisation, a critical temperature has to be exceeded which depends also on the amount of previous deformation (e.g. for pure copper $\vartheta_{crit,Cu} \cong 250°C$ or for brass $\vartheta_{crit,brass} \cong 400 - 450°C$).

3. *Critical deformation*.

   The initial deformation applied to the material must be adequate enough to provide nuclei and sufficient stored energy to drive their growth.

4. *Deformation affects the critical temperature*.

   Increasing the magnitude of the initial deformation, or reducing the deformation temperature will increase the stored energy and the number of potential nuclei. As a result, the recrystallisation temperature will decrease with increasing deformation.

5. *Deformation affects the final grain size*.

   Increasing the deformation increases the rate of nucleation. As a result the final grain size is reduced by increased deformation.

6. *Recrysallization time.*

   The recrystallisation time decreases with increasing annealing temperature. The impact of the annealing temperature on the recrystallisation time is large.(e.g. for pure Cu, magnitude of deformation 62%: $t_{recr.}(300°C) \cong 1000s$, $t_{recr.}(500°C) \cong 10s$).

7. Impurities

   Impurities can have a major impact on recrystallisation, because they slow down the recrystallisation velocity, since they influence the mobility of the high angle grain boundaries

Where other microstructural effects such as precipitation hardening after solution annealing or phase transformations, i.e. brass with a higher Zn content, occur, the phenomena which lead to the final properties of the material are more complicated. Thus the macromodels introduced are describing recrystallisation effects only.

The Predictive Material Model

The approach of the macromodel is to consider recrystallisation during non-isothermal conditions to be equivalent to a lot of short isothermal recrystallisation treatment steps performed one after another. The final properties the material reaches in one annealing step are the initial properties for the following annealing step. The better the change of material

properties are described at isothermal conditions the better the result of the calculation, which is basically an integration of the isothermal equations.

The first basic equation used is the JMAK-equation, developed by Johnson, Mehl, Avrami and Kolmogorow. The JMAK-equation can be applied to describe the evolution of the recrystallised volume fraction for isothermal conditions. The model assumes a statistical distribution of the initial spherical nuclei. The recrystallisation nucleation is assumed to be site-saturated, meaning all nuclei are present at t=0.

A second basic equation is needed, which expresses the correlation between either the recrystallised volume fraction or the recrystallisation time with a certain material property such as e.g. the hardness. The hardness is the preferred property, since the hardness is a parameter which can easily be measured within a short time. This is required in order to be able to control the process in real-time.

> **Comment concerning hardness:**
> At this moment in time, it has to be accepted that hardness is not the most scientific parameter to represent material properties, but determination of more significant parameters such as grain size distribution, tensile strength or ductility, with the present day measurement methods would be very time consuming. It is important to take into consideration that material hardness is not uniform when measuring the hardness. When the point of measurement is closer to the centre of a grain, the hardness is smaller compared to the hardness measured nearer the grain boundaries. The number of measuring points to be taken in order to get a reliable value has to be carefully chosen.

Firstly the JMAK-equation is introduced. The JMAK-equation is written in the general notation:

$$X(t)_{iso} = 1 - \exp(-K \cdot t^{K_3}) \qquad [1]$$

with

$$K = K_1 \cdot \exp\frac{-K_2}{T_{iso}} \qquad [2]$$

X:	volume fraction which has been recrystallised
t:	recrystallisation time
T_{iso}:	isothermal annealing temperature
K	1/K is the characteristic recrystallisation time (at 63 % recrystallised volume fraction)
K_1, K_2	fit-parameters
K_3	Avrami or time exponent

Transformation of [1] to t expresses the recrystallisation time:

$$t(X)_{iso} = \sqrt[K_3]{\frac{\ln(1-X)}{k}} \qquad [3]$$

The exponent K_3 is commonly given a value between 2 and 4; see Gottstein, Günther and see Humphreys, F.J. and Hatherly, M. (K_3 = 4: the nucleation rate and the growth rate are constant; K_3 = 3: the number of nuclei and the growth rate are constant; K_3 = 2: the number of nuclei and the growth rate are not constant).

Due to the exponential term, the result is very sensitive to small changes of the parameters. Two examples should demonstrate this. In both examples, the exponent K_3 of the time is chosen to be 3:

1. Assuming K_1 is increased by a factor of 10, the total recrystallisation time to achieve X = 1 is reduced to about 50%.

   Assuming K_1 is decreased by a factor of 10, the total recrystallisation time to achieve X = 1 is increased by about 110%.

2. Increasing the absolute temperature by 10% decreases the total recrystallisation time to 10%.

Looking closer at the Avrami-equation, the terms:

$$K_1 \cdot \exp\frac{-K_2}{T_{iso}} \qquad [4]$$

with

$$K_2 = \frac{Q}{R} \qquad [5]$$

Q: activation energy for recrystallisation
R: gas-constant (8,314 J/molK)

is representing the Arrhenius equation, which expresses the reaction rate as a function of the temperature. K_1 is assumed to be a constant factor initially. It is important to note, that one set of parameters K_1 and K_2 is only valid for a certain amount of initial deformation.

When comparing measurements and calculations, this type of function is a good approximation of the transient recrystallisation behaviour, Figure 1.

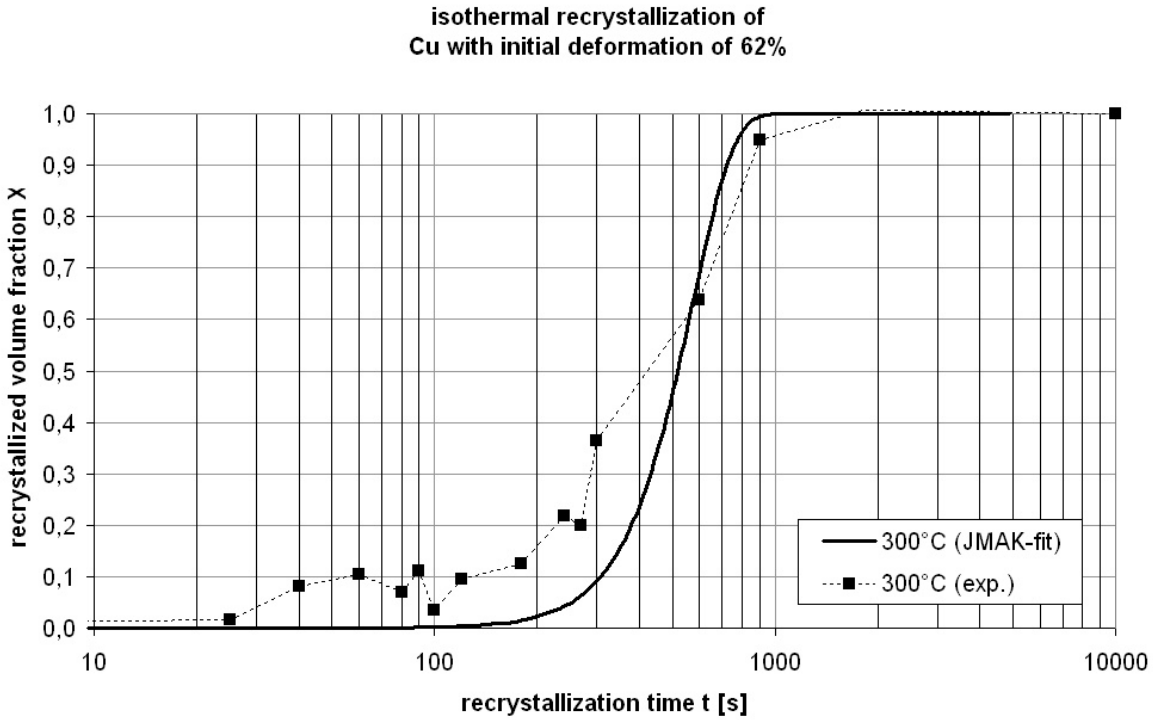


Figure 1: Experimentally achieved hardness curve compared to calculated hardness curve. Parameters of the JMAK-equation: $K_1 = 4{,}159 \cdot 10^{19}$; $K_2 = 68.16$; $K_3 = 3{,}619$

The second equation correlates either the recrystallisation time or the recrystallised volume fraction with the hardness. Following the first approach leads to the first model presented.

Model 1

This recrystallisation model is based on the investigations published by P. Neidel. Under the assumption of isothermal annealing, the hardness was related to the recrystallisation time. At a certain isothermal reference temperature the reference curve of hardness versus recrystallisation time is achieved experimentally. For the examples presented in this paper, this experimental reference curve has been adapted [6], Figure 2.

$$HB(t_{ref}) = 91.5 - 3.9 \cdot t_{ref} \qquad [6]$$

(recrystallisation of SE-Cu at T_{ref}=773K)

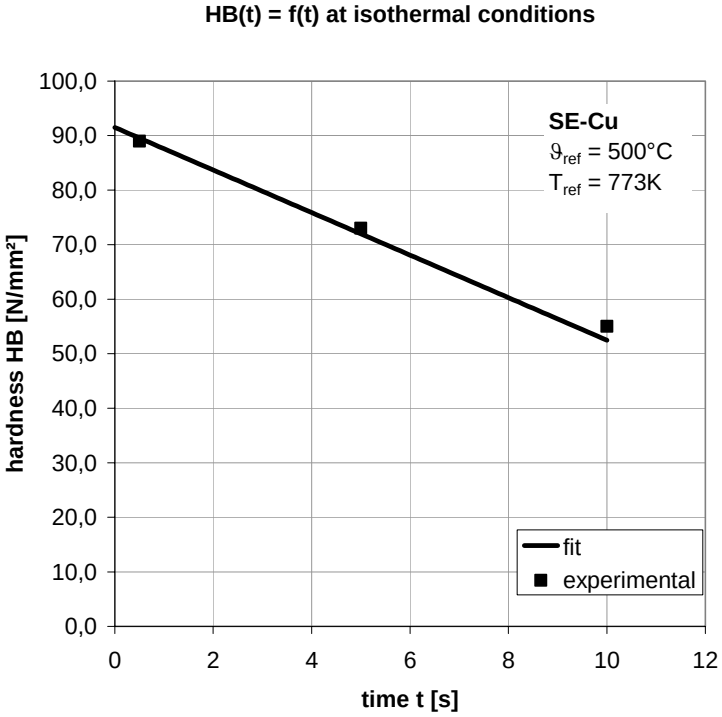


Figure 2: Reference hardness curve for Cu (amount of deformation: 20%)

P. Neidel transformed equation [3] by relating the crystallization time t(X), which is needed to recrystallise a volume fraction X at an isothermal temperature T, to a recrystallisation time $t(X)_{ref}$ at reference temperature. This leads to an integral which can easily be solved by numerical methods:

$$t_{red}(t) = \int_0^t \exp\left[-\frac{Q}{R} \cdot \left(\frac{1}{T(t)} - \frac{1}{T_{ref}}\right)\right] dt \qquad [7]$$

The integration over the process time t delivers for any temperature-time relationship T(t), the reduced time $t_{red}(t)$. t_{red} is the time which is needed to recrystallise the same volume fraction at isothermal reference conditions as is needed for recrystallisation during time t at process conditions. Putting t_{red} into equation [6] delivers the development of the hardness versus process time t.

Summarizing:

To apply model 1 to a realistic production process, the following information has to be known:

1. The development of temperature versus time, $\vartheta(T)$
2. The decrease of hardness versus time at a reference temperature: $HB(T_{ref})$

NB: a) T_{ref} should be in the range of the maximum process temperature
b) The model is only valid to predict the hardness for material with similar history compared to the material on which the reference hardness curves are based. The similar history is related to the initial amount of deformation but also the prior heat treatment may have an impact.
c) The model is valid for recrystallisation without any additional phase transformations

3. The activation energy Q depends on the material and the amount of deformation

The benefits of model 1 are demonstrated in four typical production scenarios:

Model furnace

For all calculations, the preconditions assume a vertical continuous strip annealing furnace with a heating section length of 8.4 m and a cooling section length of 8 m. At 100% fan speed, a nozzle exit velocity of 55 m/s is reached in the heating section, which corresponds to a heat transfer coefficient of 161 Wm²/K at the maximum section temperature of 700°C. The maximum nozzle exit velocity in the cooling section at 100 % fan speed is 45 m/s corresponding to a heat transfer coefficient of 188 W/m²K at 80°C section temperature.

Example 1, Model 1, Variation of the strip thickness:

The task is to find the optimal production speed for different strip thicknesses but at the same furnace temperature. To achieve total recrystallisation of a strip of 1 mm thickness at a heating section temperature of 700°C, the strip speed is 33 m/min, Figure 3. The final hardness HB of 52 N/mm² is achieved. It is obvious that for smaller strip thickness the production speed has to be increased. Without using the model, a first approach is to keep the product of strip speed and strip thickness, the so called (v x s)-value, constant. This strategy leads to the same strip temperature at the end of the heating section. Using this rule, the strip speed for strip thickness of 0.5 mm is 66 m/min, Figure 4, thus the recrystallisation time is reduced and the final hardness is 60 N/mm². This is due to an incomplete recrystallisation. Using this model, the optimal strip speed for total recrystallisation of a 0.5 mm strip is 55 m/min, Figure 5.

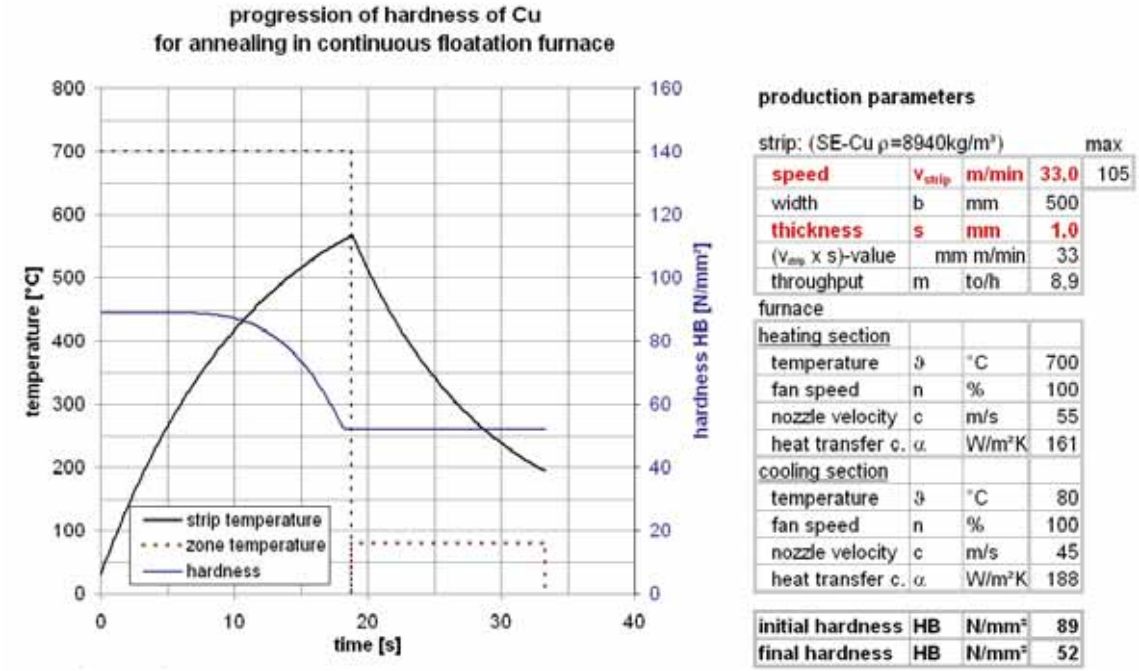
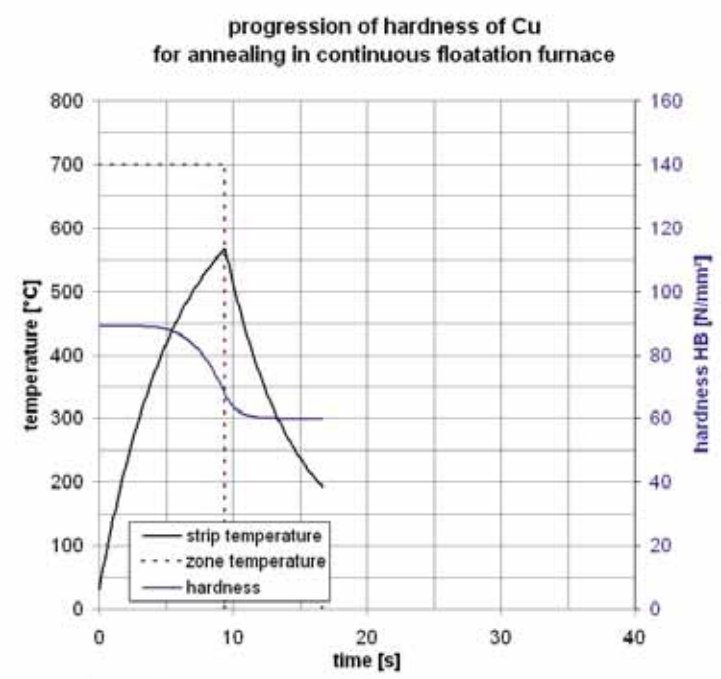


Figure 3: Example 1a (model 1) variation of strip thickness

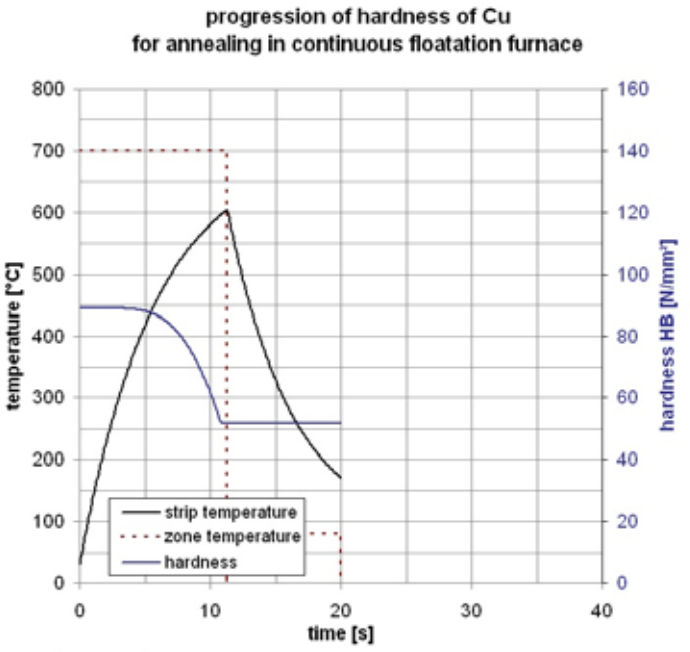


production parameters

strip: (SE-Cu ρ=8940kg/m³)

				max
speed	v_{strip}	**m/min**	**66,0**	105
width	b	mm	500	
thickness	**s**	**mm**	**0,5**	
(v_{strip} x s)-value		mm m/min	33	
throughput	m	to/h	8,9	
furnace				
heating section				
temperature	ϑ	°C	700	
fan speed	n	%	100	
nozzle velocity	c	m/s	55	
heat transfer c.	α	W/m²K	161	
cooling section				
temperature	ϑ	°C	80	
fan speed	n	%	100	
nozzle velocity	c	m/s	45	
heat transfer c.	α	W/m²K	188	
initial hardness	**HB**	**N/mm²**	**89**	
final hardness	**HB**	**N/mm²**	**60**	

Figure 4: Example 1b (model 1) variation of strip thickness



production parameters

strip: (SE-Cu ρ=8940kg/m³)

				max
speed	v_{strip}	**m/min**	**55,0**	105
width	b	mm	500	
thickness	**s**	**mm**	**0,5**	
(v_{strip} x s)-value		mm m/min	27,5	
throughput	m	to/h	7,4	
furnace				
heating section				
temperature	ϑ	°C	700	
fan speed	n	%	100	
nozzle velocity	c	m/s	55	
heat transfer c.	α	W/m²K	161	
cooling section				
temperature	ϑ	°C	80	
fan speed	n	%	100	
nozzle velocity	c	m/s	45	
heat transfer c.	α	W/m²K	188	
initial hardness	**HB**	**N/mm²**	**89**	
final hardness	**HB**	**N/mm²**	**52**	

Figure 5: Example 1c (model 1) variation of strip thickness

The optimization of the strip speed for strip thicknesses from 0.2 mm to 1.0 mm leads to the following correlation:

$$v_{strip} = 32.9 \cdot s^{-0.73} \qquad [8]$$

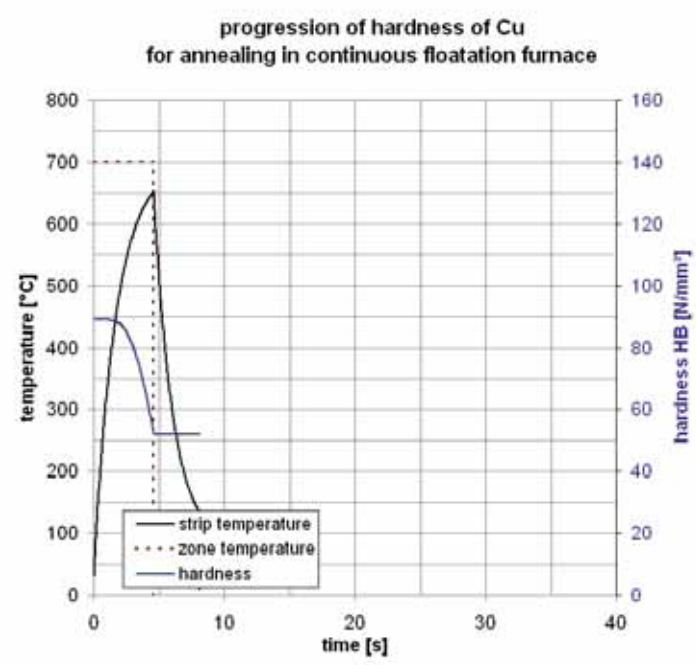
The parameters in [8] depend on the initial material state, i.e. the initial hardness and/or the amount of deformation, and the furnace characteristics (section length, set points for temperature and fan speed). Correlations of this type are sometimes used in production practice.

Example 2, model 1, maximum strip speed limit is reached

A very thin strip of 0.15 mm is to be annealed at the same furnace temperature compared to example 1, Figure 6. The model delivers a production speed of 135 m/min. This exceeds the limit of the facility, which is assumed to be 105 m/min. In this situation, the strip speed is set to maximum and the fan speed has to be decreased to a setpoint calculated with the help of the model. The fan speed has to be decreased to 65%, Figure 7.

Example 3, model 1, change of coil at reduced strip speed

In many facilities the strip accumulator length is undersized for small strip and high production speed. Assuming the strip speed is limited to 50 m/min while changing the coils. A strip of thickness 0.3 mm with a nominal production speed of 83 m/min, Figure 8, achieves the same hardness at a speed of 50 m/min (during the coil change), when the fan speed is reduced to 38 %, Figure 9. Of course, when decreasing the fan speed the levitational forces in a vertical furnace will be affected. Thus the lower fan speed limit has to be considered, which guarantees strip stability.



production parameters

strip: (SE-Cu ρ=8940kg/m³)

				max
speed	v_{strip}	m/min	135	105
width	b	mm	500	
thickness	s	mm	0,15	
(v_{strip} x s)-value		mm m/min	20,3	
throughput	m	to/h	5,4	
furnace				
heating section				
temperature	ϑ	°C	700	
fan speed	n	%	100	
nozzle velocity	c	m/s	55	
heat transfer c.	α	W/m²K	161	
cooling section				
temperature	ϑ	°C	80	
fan speed	n	%	100	
nozzle velocity	c	m/s	45	
heat transfer c.	α	W/m²K	188	
initial hardness	HB	N/mm²	89	
final hardness	HB	N/mm²	52	

Figure 6: Example 2a (model 1) maximum strip speed level is reached

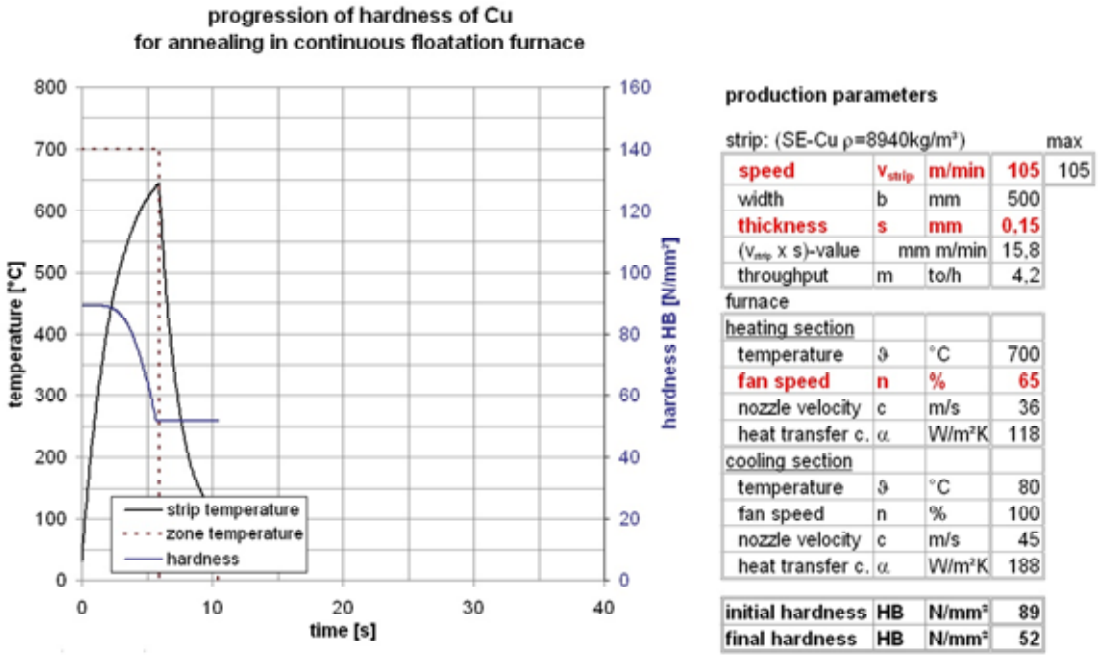


Figure 7: Example 2b (model 1) maximum strip speed level is reached

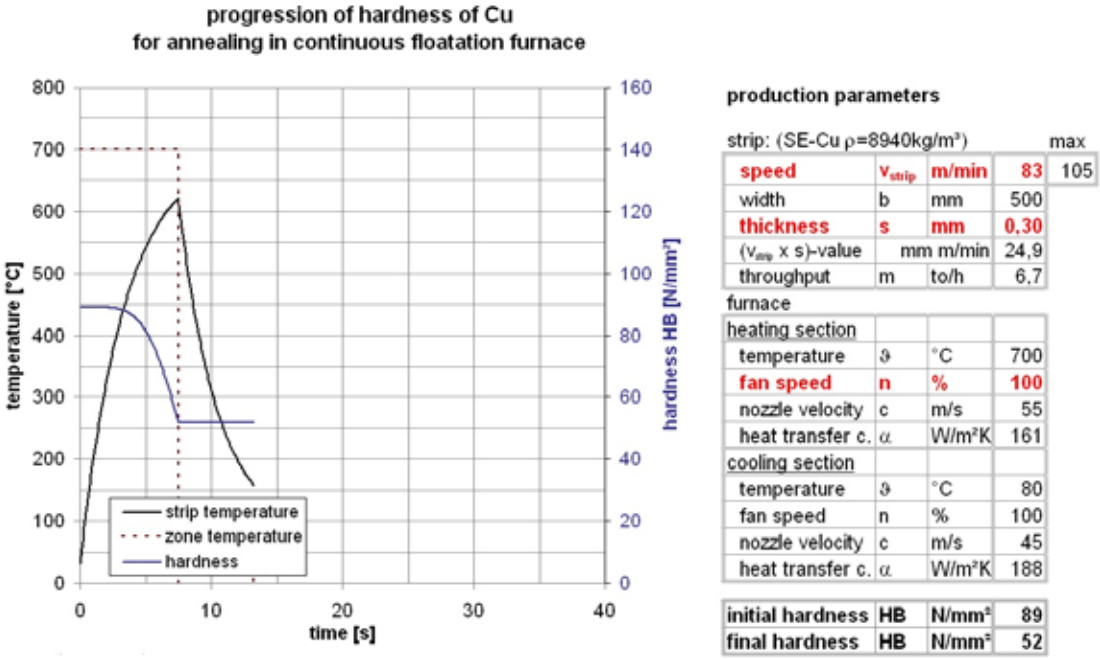


Figure 8: Example 3a (model 1) change of coil at reduced strip speed

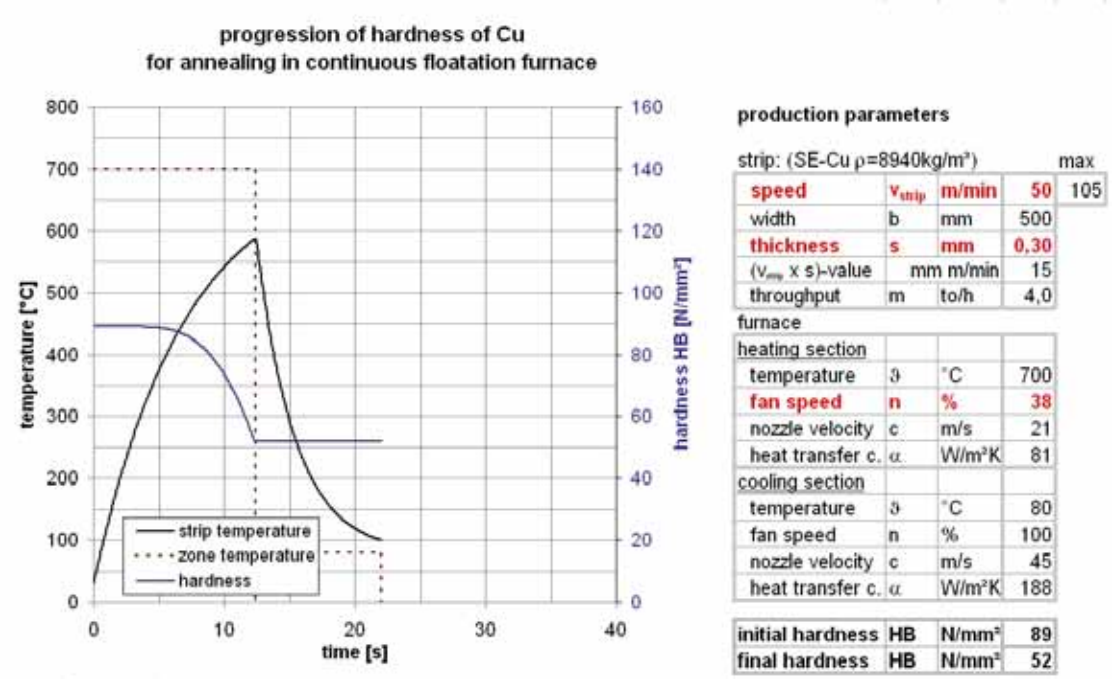


Figure 9: Example 3b (model 1) change of coil at reduced strip speed

Example 4, Model 1, Furnace temperature has not reached the setpoint value

In production practice the furnace temperature set point has to be changed from time to time. This depends on the material quality which is to be produced. Between two production-campaigns, which need different heating section temperatures, a downtime of 1 or 2 hours can occur. With help of the model, production of material which needs higher temperatures for full throughput can already be started before the set point is reached.

E.g. a strip of 0.4 mm thickness is nominally produced at 700°C at a strip speed of 65 m/min, Figure 10. Even at an actual heating zone temperature of 620°C this strip can be produced at a decreased strip speed of 54 m/min, Figure 11. With increasing heating section temperature, the strip speed has to be continuously increased.

In the opposite situation, in which the heating zone temperature has to be decreased in-between two campaigns, production can be partially maintained. In this case the strip also acts to speed up cooling of the heating section.

More production scenarios are possible, where the model could be beneficial. One of these is the annealing of strip with poor flatness after cold rolling. Such strips are disposed to becoming unstable in a levitation furnace. They tend towards oscillation or flapping at the strip edges. To control and reduce these movements, it maybe necessary to vary the fan speed. This has an impact on heat flow and hence the heating curve of the material. With help of the model, the strip speed can be adapted in such a way as to achieve material properties similar to those which would have been achieved with the initial recipe.

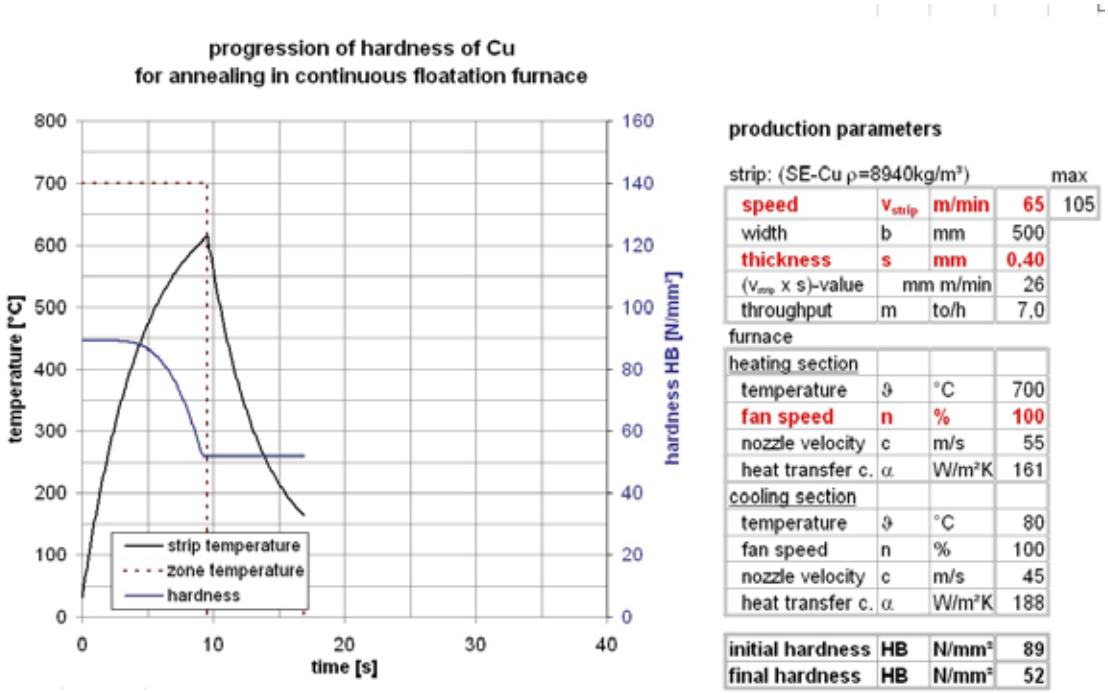


Figure 10: Example 4a (model 1) furnace temperature has not reached the set point value (nominal case)

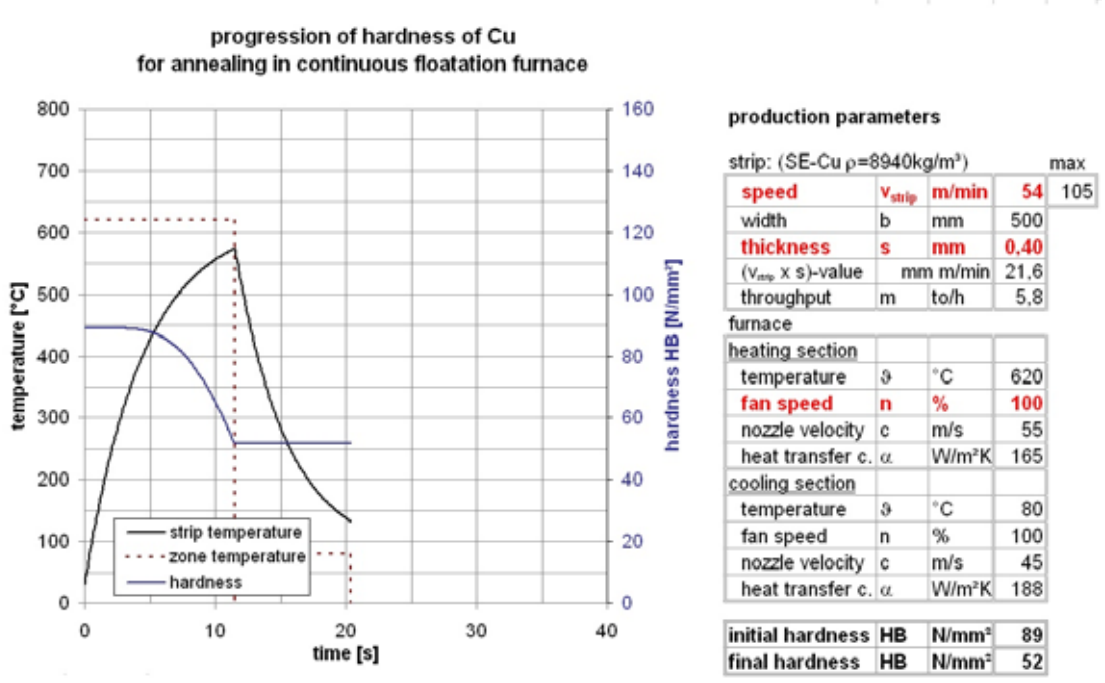


Figure 11: Example 4b (model 1) furnace temperature has not reached the set point value (transient case)

Model 2, improved

During recrystallisation, the annealing temperature level has a significant impact on the recrystallisation time needed for complete recrystallisation and on the final material properties with respect to the final hardness. The experience shows that a higher annealing temperature leads to a shorter recrystallisation time and lower hardness. This behaviour is not taken into account in model 1.

In order to take this into account, in the first instance, model 2 is based on two reference hardness curves achieved at isothermal conditions at two different temperatures. Additionally it is assumed, that the final hardness and the isothermal annealing temperature are linearly correlated. This relationship was found, while analyzing isothermal recrystallisation curves of Cu. Additionally the correlation between the recrystallised volume fraction and the hardness is assumed to be linear. This correlation was also observed, when analyzing isothermal recrystallisation curves of Cu.

NB: when model 2 to is applied to other materials, i.e. brass, it has to be carefully investigated in order to ascertain as to whether these linear correlations for the hardness in respect of X and temperature T_{iso} are still valid.

The two reference curves should be chosen, one at a temperature close to production temperature level and one close above the critical temperature where recrystallisation starts. All isothermal hardness curves in between these reference temperatures can now be calculated. Actual extrapolation to a slightly higher temperature in comparison with the upper reference temperature delivers feasible results.

$$H(X,\vartheta) = H_{initial} - X\left[H_{final,ref1} + (\vartheta - \vartheta_{ref1})\frac{H_{final,ref1} - H_{final,ref2}}{\vartheta_{ref2} - \vartheta_{ref1}}\right] \quad [9]$$

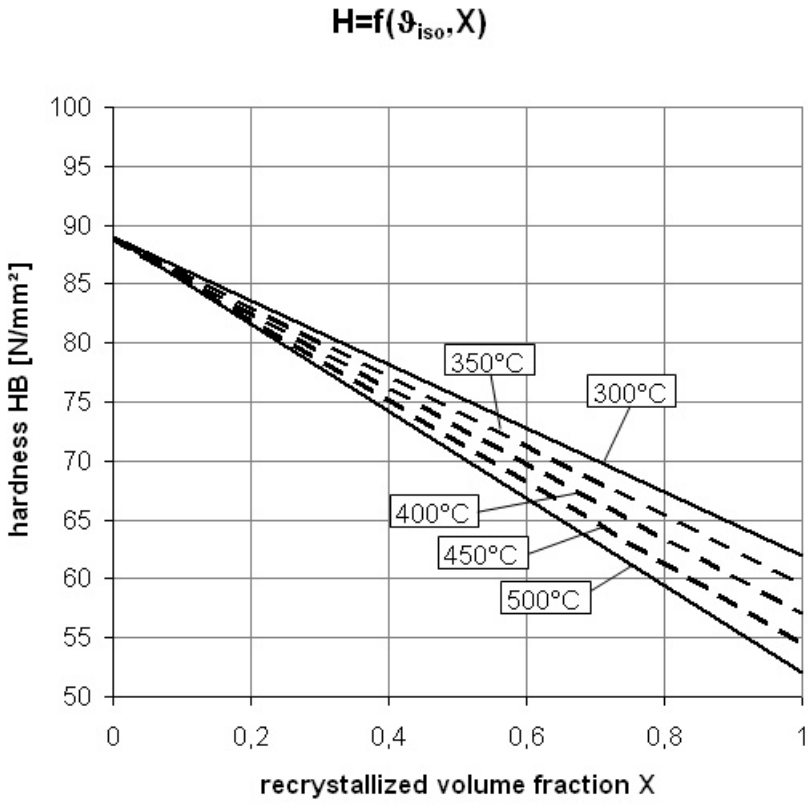


Figure 12: Reference hardness curves for different isothermal recrystallisation temperatures ϑ_{iso} as a function of the recrystallised volume fraction X (calculated)

In the next step, the recrystallisation time normalized to one of the reference curves is calculated by using equation [7], the model 1 integration method. In the examples shown later, the reference curve at higher temperatures has been used for this step. The result of this step is the progression of the recrystallised volume fraction X, which is assumed to be the same for reduced time and process time: $X(t_{red}) = X(t)$.

The task of the last step is to determine the hardness, which is related to X and to the elapsed process time, t. The approach is to use the recrystallisation time, which is actually the process time, as a link between isothermal and non-isothermal conditions. It is assumed that the modality of the microstructural transformation during recrystallisation, is basically determined by the recrystallisation time since this time is implicitly associated with the temperature versus time curve.

The following case study should make this clear:

During a certain annealing trial, the time required to achieve total recrystallisation is relatively long. This indicated that the temperature level during the annealing trial has been relatively low. The final hardness that is achieved is higher when compared to an annealing trial at a higher temperature level.

The calculation procedure is as follows: The progression of X(t) is calculated. For each discrete value of X(t), the isothermal recrystallisation temperature is determined, which leads to the same amount of recrystallised volume fraction. Basically this is done by rewriting the JMAK-equation [1] in terms of the isothermal temperature T.

The recrystallisation behaviour as mentioned above in this paragraph can only be expressed realistically, when the parameter K_1 of the JMAK-equation [1] is related to the total decrease of hardness $\Delta H(T_{iso}) = H_{initial} - H_{final}$ at isothermal conditions. For the examples calculated later, a linear correlation is assumed:

$$K_1 = \left(K_1^{'} + K_4 \cdot \Delta H\left(T\right)\right) \qquad [10]$$

Even though, from the material science of view, it is well known that the correlation should be a function with potential characteristic:

$$K_1 = K_1^{'} \cdot \Delta H\left(T\right)^{K_4} \qquad [11]$$

Substituting the linear approach for K_1, [10], into the JMAK-equation [1], the following equation is achieved:

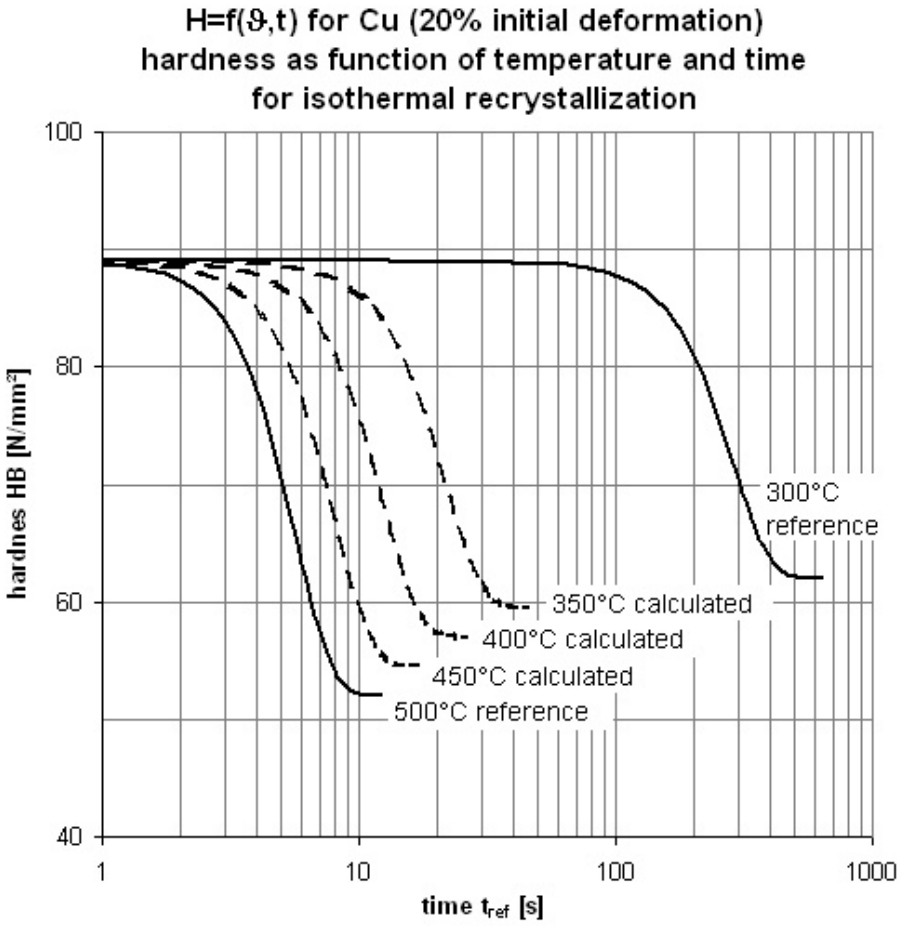
$$X(t,T)_{iso} = 1 - \exp\left(-\left(K_1^{'} + K_4 \cdot \Delta H\left(T\right)\right) \cdot \exp\left(\frac{-K_2}{T}\right) \cdot t^{K_3}\right) \qquad [12]$$

with

$$\Delta H\left(T\right) = H_{initial}\left(T\right) - H_{final}\left(T\right) \text{ at isothermal conditions} \qquad [13]$$

The linear approach delivers feasible isothermal hardness curves for Cu, Figure 13.

Since rewriting of the equation in terms of T is not easily done, the task to determine T for a given X and a given t is solved numerically by means of iteration. The advantage of applying numerical methods to this step is that the type of equation for K_1, whether linear or potential, can easily be modified.



parameters for equation [13]:

K_3		3	assumption
$K_2=Q/R$	K	8420	assumption
K_4	mm²/N	29,51	fit
K_1'		-796,54	fit

Figure 13: Reference hardness curves for different isothermal recrystallisation temperatures ϑ_{iso} as a function of the recrystallisation time t (calculated)

Example 1, model 2

Model 2 predicts with the same production parameters in comparison to model 1, an increased hardness on completion of recrystallisation, Figure 14. Using model 1 calculations, the fact that only an isothermal reference curve at 500°C is employed, will always lead to a final hardness of 52 N/mm². Since the recrystallisation time predicted by model 2 is about 20 s, the final hardness has to be higher in comparison to the final hardness achieved at reference temperature 500°C after only 10 s.

Lowering the strip speed does not lead to further decrease in hardness, when grain growth is not taken into consideration. This is obvious, owing to the fact that the heating rate of the strip is independent of the strip speed.

Under similar heating section conditions, thinner strips heat up faster. As a consequence, these strips achieve a lower final hardness.

Only strips up to a thickness of 0.4 mm can achieve an end hardness of 52 N/mm² equivalent to subjecting them to an isothermal annealing at 500°C. In this case even the fan speed has to be decreased in order to decrease the heating power; otherwise an even lower hardness would be achieved. For summary of all model 2 results, Figure 15.

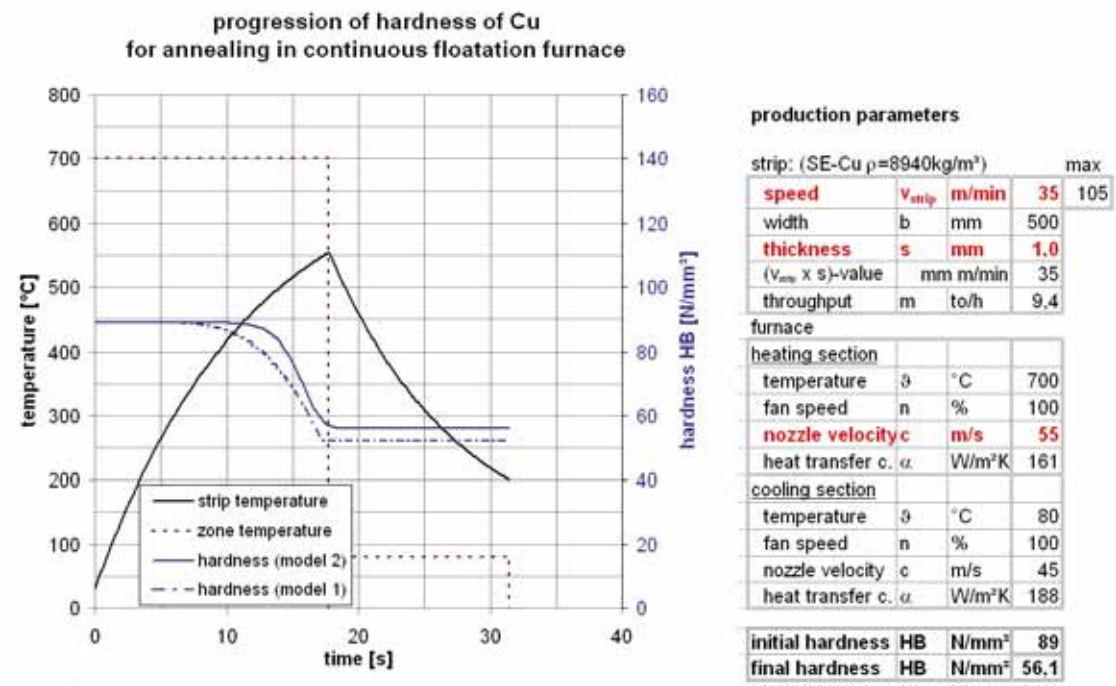


Figure 14: Example 1 (model 2) the diagram demonstrates the difference of hardness when applying model 2 in stead of model 1 to the same production conditions

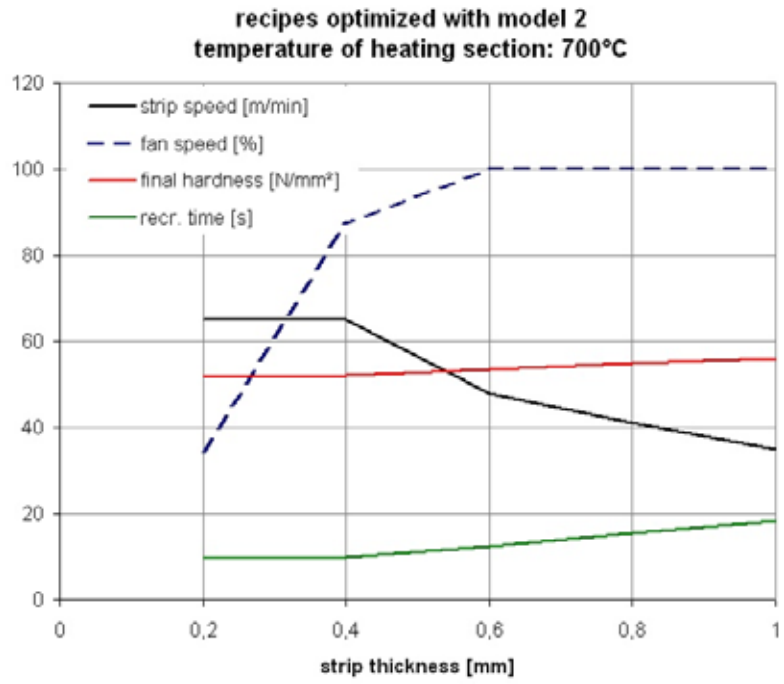


Figure 15: Overview of optimized process parameters for the recrystallisation of Cu-strip with different thickness

Summary and Discussion

The presented investigations show that a material model, describing recrystallisation, can be very beneficial for the process control during continuous strip annealing of Cu and Cu-alloys. It has to be taken into account that up to now the material model is valid for recrystallisation phenomena only. The modelling of additional effects occurring during precipitations hardening or phase transformations is much more complex. This will be a task for future investigations.

The improved predictive model 2, which is presented, is not yet ready for use. There are a number of points which have to be discussed and investigated:

1. In order to be of practical use, the model needs to be extended to include recovery and grain growth mechanisms.
2. What influence does the total recrystallisation time have on the final hardness? Is the impact of recrystallisation time on the final hardness overvalued in model 2? A better verification with experimental results is mandatory.
3. In order to verify the predictive model for short time annealing, hardness reference curves versus time gained under isothermal conditions at higher temperatures are necessary. Due to the resulting short recrystallisation times, it will be necessary to improve standard laboratory facilities in order to achieve reliable results.
4. Similarly, with regards the non-isothermal heat treatment, verification of the model requires special laboratory facilities, which are able to reproduce similar conditions as in the production. Up to now it is only possible to compare calculated results with results from the production. This makes the development and the verification process of the model difficult and time consuming. A laboratory facility for non-isothermal heat treatment is under construction at WSP.

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