Heating of dies in a vacuum furnace, part II

In the first part of the heating, we achieved that the inserts are heated to a temperature corresponding approximately to the setup furnace temperature **Tp = 650 °C.** However, the surface temperature **Ts** may not reach the furnace temperature **Tp** and will lie somewhere in the interval **Tp> Ts> Tc**. The temperature in the core **Tc** then decides on the start of the hold time countdown. It does not have to be significantly long; the goal is to heat the parts in full cross-section above **600 °C** so that the material of the insert goes into a plastic (ductile) state. Usually, after reaching the difference **Tp - Tc < 50 °C**, when the condition **Ts - Tc <110 °C** is automatically met, a holding of 15 minutes is set. Its extension makes no sense and is uneconomical, because by reducing the temperature difference **Tp - Ts** and **Ts - Tc**, the heating efficiency is reduced. Our interest is not only the proper heating of components in the furnace, but also the economics of this heating.

Just to give you an idea, for possible calculation it is necessary to take into account the heat transfer by radiation between the heating elements and the heated parts, expressed by the equation in which the temperatures are in the fourth power $\mathbf{Q = \sigma * \varepsilon * S * (Tg^4 - Ts^4)\ [W]}$, where **Tg** is the temperature of the graphite heating elements, **σ** represents the Stefan-Bolzmann constant, **ε** the emissivity of the surface, and **S** then the irradiated area.

Furthermore, it is necessary to take into account the heat transfer from the gaseous medium to the surface of heated parts according to the equation for convection heating $\mathbf{Q = \alpha * S * t * (Tp - Ts)\ [W]}$, where **α** is the heat transfer coefficient for the given environment, and at the same time heat inside the components according to the relation $\mathbf{Q = \lambda * S * (Ts - Tc) / d\ [W]}$, where **λ** is the coefficient of thermal conductivity for a given steel, which is not constant and changes with the heating temperature, and **d** is the wall thickness.

In all these equations, therefore, there is a difference in temperature, but most significantly in the transfer of heat by radiation, when the temperatures are in the fourth power. Therefore, more important than dealing with the theoretical calculation is to measure temperatures with thermocouples **Ts** and **Tc**, and to control the heating process from these thermocouples.

When programming the individual heating steps on a vacuum furnace, the so-called conditional dwell is usually used. In practice, this means that meeting a condition triggers the required step. However, since most vacuum furnaces do not have such programming capabilities, it is necessary to find a heat treatment supplier who has furnaces so programmable. The usual trigger for the heating step is one of the thermocouples, in our case **Tc**. When the difference **Tp - Tc < 50 °C** is reached, the step time starts automatically.

Whether **Ts** in the first step reaches a temperature **Tp = 650 °C** is therefore not decisive, it is decisive that the previous condition **Tp - Tc < 50 °C** is fulfilled. After its fulfillment, it is possible to continue heating, regardless of the temperature **Ts**, but with the knowledge that the optimal temperature difference between the heating elements and the surface **Ts** will be guaranteed. Thus, the heating will be sufficiently efficient according to the above equation for heat transfer by radiation.

However, since by fulfilling the condition **Tp - Tc < 50 °C** it is confirmed that **Tc > 600 °C**, it is thus also confirmed that the heated material is already over the transit temperature of the transition from solid to plastic (ductile) state and is therefore heated to the temperature range, where it is no longer necessary to take into account **dT**, and thus also the stress from the temperature difference **dT = Ts - Tc.**

In the next heating phase, for a hold on **Tp = 850 ° C**, we can heat the parts at any speed and the heating ramp for this second delay can be significantly higher than for heating up to **650 °C**. If in the first step up to **650 °C** it is usually **6 -10 °C/min**, and it is additionally controlled and limited by a ramp to **Tc <220 ° C / hour = 3.66 ° C/min,** then in the second heating step to **850 °C** we can set a ramp of **10 to 20 °C/min** on the furnace and we no longer have to check the ramp on **Tc**.

The aim of the second hold at 850 °C is therefore not to reduce the stress in the heated parts, but only to thermally homogenize the material before we start heating it to the austenitization temperature.

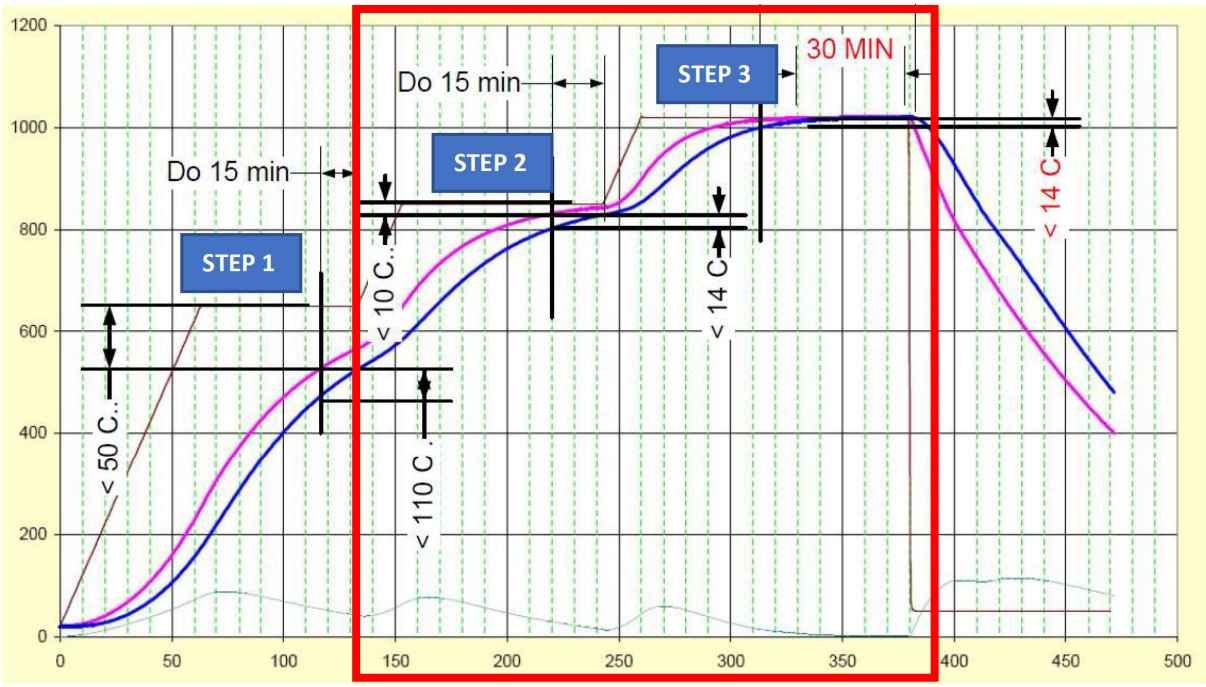

Fig. 1 – Theoretical (ideal) diagram of heating of dies in a vacuum furnace

Simultaneously with the heating of the material of the parts, some other properties of the steel also change. Above all, its thermal conductivity changes. It increases for high-alloy steels, but decreases for low-alloy steels. However, once we reach temperatures above **700 °C** (Fig. 2), the thermal conductivity for all types of steels is essentially the same and stabilizes at **25 - 30 W / (m.K).** This is also an advantage for further heating, since all types of steels can be processed in the same way from the point of view of heating at this stage.

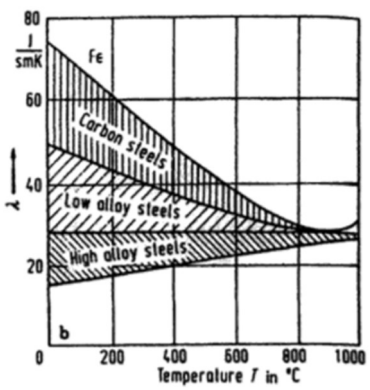

Fig. 2 – Dependence of thermal conductivity of steel on temperature *(Totton's* Steel Heat Treatment Handbook*)*

The hold at **850 °C** is again controlled from the thermocouple **Tc**. However, as soon as we reach the temperature **Ts - Tc < 14 °C** on the part, we should start counting down the dwell time. However, since usually the conditional delay evaluates the difference **Tp - Ts** or **Tp - Tc**, and not the difference **Ts - Tc** as Nadca 207 says, we will deal with the fact that again the condition of the transition to the next step will be reaching the temperature on **Tc**.

The surface temperature **Ts** will again be in the interval between **Tp> Ts> Tc**, but the temperature difference range will be narrowed to only **14 °C**. Even in this phase of heating we do not have to wait until **Ts** reaches the furnace temperature **Tp**, but it is likely that the temperature difference **Tp - Ts** will be less than **10 °C**. The holding timer at temperature can again be minimized, eg for 15 minutes.

The last heating step is heating to the austenitization temperature. This is the most important temperature of the entire heating process. We must ensure that the heated parts reach this temperature as far as possible over the entire cross-section, the holding time must be long enough to dissolve the carbides in the steel as best as possible, and at the same time not long enough for the primary grain growth. Nadca 207 therefore defines this heating phase as **30 minutes** from the moment when **Ts - Tc < 14 °C**, and at the same time states that it must not be longer than **90 minutes** from the time when **Ts** reaches the temperature **Tp**.

If we work in the mode of Nadca 207, then the austenitization temperature is not defined by the temperature range From-To, but only by a single temperature according to Nadca 207. It is necessary to be very careful. The material sheets of steel manufacturers always refer to the temperature range for austenitization, but this range cannot be applied to die-castimg inserts processed according to Nadca 207. The specification of austenitization temperatures, as well as the determination of heating delays are given in the Nadca 207 table on page 34.

NADCA Grade	Trade Name	Type	Preheating Temp, °F(°C)	Austenitizing/Hardening Temp. °F(°C)
A	Type H13- Premium*	A1885	1100-1250 (595-675) 1500-1560 (815-850)	1885 (1030)
B	Type H13-Superior	B1885	1100-1250 (595-675) 1500-1560 (815-850)	1885 (1030)

Fig . 3 – Part of the table with temperature specifications from Nadca 207, page 34

As an example, I mention steel W300 ISOBLOC from Bohler (Nadca 207, type H11 / 2343, steel group D), where in the material sheet the range of hardening temperatures from 1000 to 1040 °C is allowed, but Nadca 207 allows only one temperature, 1000 °C.

D	Type H11/2343			
	Bohler W300 ISOBLOC	D1830	1100-1200 (595-650) 1500-1560 (815-850)	1830 (1000)
	Schmolz+Bickenbach Thermodur 2343	D1830	1100-1200 (595-650) 1500-1560 (815-850)	1830 (1000)
	Uddeholm Vidar Supreme	D1830	1100-1200 (595-650) 1500-1560 (815-850)	1830 (1000)

The ramp for heating to the austenitization temperature can be chosen again significantly higher, as in the previous step, there is no danger of stress from the temperature difference **Ts** and **Tc**.

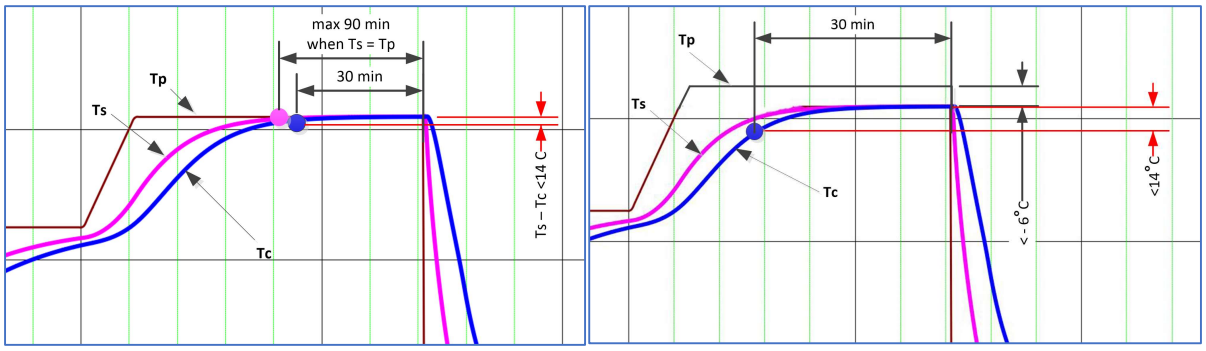

Fig. 4 – Ideal heating process
Fig. 5 – Heating process, when the load thermocouples never reach the required temperature

The ideal heating process is shown in **Figure 4**, where **Tp** is the programmed furnace temperature, **Ts** is the surface thermocouple temperature and **Tc** is the core temperature. All 3 temperatures meet at the required temperature, e.g. 1000 °C. The austenitization time **30 minutes** from reaching **Ts - Tc < 14 °C** starts to count down as expected, as well as the limit time of **90 minutes** from when **Ts** reaches temperature **Tp**.

But **Figure 5** shows another, not unusual, example. The furnace does not heat up and neither **Ts** nor **Tc** ever reach the desired temperature **Tp**. Because Nadca 207 does not give us the possibility the austenitization temperature tolerance, failure to reach the value **Tp = 1000 °C** can be considered as faulty austenitization. The condition that the austenitization time will be a maximum of **90 minutes** from reaching the temperature **Ts = Tp** will never be met, only the condition **Ts - Tc < 14 °C** and the time **30 minutes** will be met and the process will require manual intervention by the operator.

Because the vacuum furnace is usually validated according to **AMS 2750 F**, it can be assumed that the desired and actual temperature in the furnace, controlled by a control thermocouple, will actually be **1000 °C**. However, since the furnace is in **Class 2**, with a temperature tolerance of **+/- 6 °C**, a situation may occur where the part with **Ts** will be loaded in the furnace heat chamber, where the temperature is within the tolerance band for **TUS,** but with the limit temperature near deviation **-6 °C**. The processed part itself will therefore not be at a temperature of **1000 °C**, but only at a temperature of **994 °C.** However, this is only provided that the batch thermocouples show the correct temperature. However, other cases may occur.

- The furnace does not have a valid **TUS** or **SAT**, so it is possible to doubt the furnace temperature,
- The control thermocouple is incorrectly positioned in relation to the heating elements and therefore the furnace does not heat correctly or overheat
- Load thermocouples are without calibration, so it is not clear if there is a measurement error in them
- The offsets setup for the individual thermocouples are incorrect or no longer valid
- The furnace was overloaded for the given processing, so the temperature was not actually reached at the place of measurement by load thermocouples
- Improperly prepared holes for inserting Ts and Tc

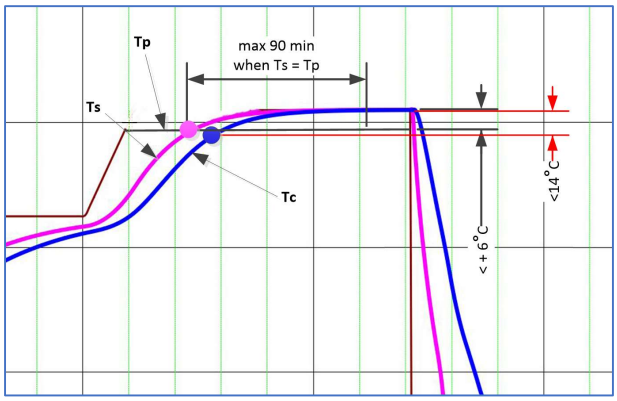

Fig. 6 – Heating process when the load thermocouples exceed the required furnace temperature

Just as the furnace does not heat, in case of incorrect calibration it can overheat (**Figure. 6**). At the set furnace temperature **Tp = 1000 °C** the parts will be heated to a temperature +**6 °C** higher than the furnace temperature. Thus, instead of the required **1000 °C**, they will have **1006 °C**. The opposite problem occurs. As soon as **Ts** reaches the furnace temperature **Tp**, a time of **90 minutes** is started, checking that the maximum austenitization time. However, since the condition that **Ts - Tc < 14 °C** be met later, the step may end after **90 minutes** have elapsed, even before the austenitization time of **30 minutes** has elapsed. The consequences can be fatal, e.g., in that the hardness after hardening will be significantly heterogeneous, precisely due to the premature termination of austenitization.

How to deal with this? Because Nadca 207 does not set a tolerance band for austenitization temperatures, this tolerance is **ZERO**, so it must be taken as a critical condition. However, Nadca 207 says that the furnace must be maintained in a calibrated state according to **AMS 2750** in the latest version, with maintained temperature recording devices, with load thermocouples validated also according to AMS 2750, and inserted in heat treated parts according to Nadca 207. Furnaces for hardening inserts for die casting, they should not be overloaded and the batch should not exceed 50% of the allowable weight of the furnace.

If these conditions are met, it is likely that the hardening cycle will take place according to Figure 4, while the austenitization temperature will be reached within the tolerance of furnace **Class 2**, **+/- 6 °C**. However, since the processing quality according to Nadca 207 is based on individual impact tests, these impact tests will show whether the austenitization temperature in the range of **994 to 1006 ° C** had an impact on the processing quality. It is then up to the heat treatment shop to assess the resulting risks, because if the impact tests are not in the required values, the heat treatment provider is authorized to perform one repeated hardening, after previous soft annealing, and if even after this re-hardening the impact values are not correct, the heat treater will cover both the costs and the resulting damages. Of course, provided that the entrance tests of the material at the entrance to the tool shop were OK.

However, there are other, technical possibilities related to the application of **AMS 2750 F**. As soon as new load thermocouples are used, today usually type N, the furnace should have new **SAT** with these thermocouples, and if required by the test results, then set corresponding offset. However, the condition applies that the offset must not exceed the tolerance range of the furnace, in this case **Class 2, +/- 6 °C.**

There are other software options to circumvent this problem, e.g., by setting allowed **dT** in the austenitization program step to reach the furnace temperature **Tp** on the load thermocouple **Ts** in the range **+/- 6 °C**. In the case of the cycle according to **Figure. 5**, i.e., for a furnace that does not heat, this means that the time of **90 minutes** starts after reaching **Ts = Tp - 6 °C**. This will allow the cycle to run

automatically, but will not change the fact that the austenitization temperature will be only **994 °C** and not the required **1000 °C**.

The cycle can be approached in the same way with an overheating furnace. On **Ts** we set the condition **Ts = Tp + 6 °C**, and in that case the time of **90 minutes** starts to count down when **Ts** reaches a temperature of **1006 °C**. Again, the austenitization time will be respected, but the temperature of the parts will not be **1000 °C**, but **1006 °C**.

Although I believe that Nadca 207 should tolerate non-compliance with the austenitization temperature within the temperature tolerance for furnace **Class 2**, as this is not the case, care must be taken very carefully to calibrate the furnace on all thermocouples entering the process and make every effort to so that the resulting records from the process run according to the ideal state in **Figure 4**.

In any case, at the moment when the furnace shows the state according to **Figure 5 or 6**, it is necessary to perform at least a new **SAT** and verify how the furnace actually behaves according to **AMS 2750 F**. The heat treatment plant must keep records of all these facts, as well as of the set offsets. If necessary, testify to the customer that the furnace validation is performed at the prescribed intervals and that the set offsets are current and do not deviate from the values according to AMS 2750 F.

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