Use of thermochemical data in inductive melting

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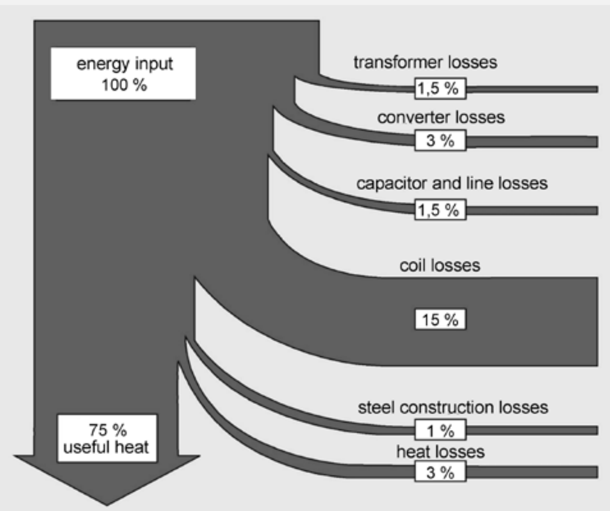
Minimizing the energy consumed during inductive melting of metal alloys is an ongoing concern for plant constructors and operators. Surprisingly enough, little thought is given to the potential provided by the enthalpy of the melt in question. It is demonstrated below that the composition of the input materials has a considerable influence on the heat content of alloy melts and therefore on their energy consumption. Enthalpies for different input materials can be derived from tabular thermochemical data and these can be used in inductive melting. This particularly applies to the production of cast iron melts made from scrap steel and various silicon carriers and also to brass melts made from copper and zinc as feed components compared to input materials made of brass.

The heat content (i. e. the specific enthalpy of the melt) is assumed when calculating the energy consumed during inductive melting of metals. For example, it is 385 kWh/t for melting 1 t of cast iron to 1,480 °C, as shown in **Fig. 1** [1]. The end energy requirement is then determined by the efficiency of the system and any technical process action taken until the melt is tapped. Plant constructors and operators constantly work to improve furnace efficiency and the process engineering in order to minimize the energy consumed. The potential here can be recognized from the relatively broad spectrum of consumption values in iron foundries, which range from 570 kWh/t to over 700 kWh/t.

At first glance, the specific enthalpy value may not seem to be amenable to influence. In what follows, it is shown that an appropriate selection of input materials drawing on thermochemical data can also be used to optimize this baseline value for the energy required to melt metal alloys. In this context, the feeding and melting processes deployed in modern, convertor-fed induction furnaces with weight-controlled loading of the charging vehicle (**Fig. 2**) and the tapping of the entire melt charge (**Fig. 3**) are important factors in the targeted adjustment of the composition and sequence of the iron materials and additives to be melted.



Enthalpy of cast iron	385 kWh/t
Plant efficiency	75–70 %
Energy requirement for melting	515–550 kWh/t
Energy requirement including preparing until pouring	570–700 kWh/t

Fig. 1: Energy requirement for inductive melting of cast iron [1]

Fig. 2: Loading of a charging vehicle by magnet on crane [1]

Fig. 3: Tapping a 19-t induction crucible furnace [1]

ENTHALPY OF METAL ALLOYS AS A HEAT BALANCE

The enthalpy of alloy melts is made up of the specific heats of each of the materials in solid and liquid states, their heats of transformation and of melting and also of exothermic or endothermic dissolving reactions. There have been tabular compilations listing thermochemical data since the 1970s, firstly for the pure materials, then also for alloys, which have enabled a quantitative description of technically relevant processes [2]. This applies just as much to stoichiometric reactions as to heat balances. The energy required to melt alloys can thus also be calculated from the tabular enthalpy values, in that a heat balance is created in order to produce the alloy as a product made of different components, as K. Hack has shown using a chromium-alloyed steel as an example [3]. The heat balance is derived by reading off the enthalpy value of the respective substance at the relevant temperature from the tables, multiplied by the associated amount of the substance in weight ratios and entered into the balance sum with the correct algebraic sign, as is done below to determine the enthalpy of cast iron.

SPECIFIC ENTHALPY OF CAST IRON

In order to calculate the specific enthalpy ΔH for cast iron, an idealized three substance system Fe-C-Si is assumed. The enthalpies H required for the three components Fe, C and Si, the two alloying materials FeSi and SiC and of a ductile cast iron NCI are stated in the tables of Hack [3] in dependence on temperature. Starting with the values of 25 °C at room temperature and of 1,500 °C melt temperature, the heat balance for melting cast iron NCI with 3.7 % C and 1.8 % Si is as follows:

$$0.945 \cdot H_{(Fe,\,25)} + 0.037 \cdot H_{(C,25)} + 0.018 \cdot H_{(Si,\,25)} = 1 \cdot H_{(NCI,1500)}$$

By definition, the pure substances have an enthalpy value of 0 at room temperature, whilst the tabular value $H_{(NCI,\,1500)}$ contains not only the specific heat, but also all heats of transformation and of reaction. Thus for melting NCI with the pure substances, the energy requirement ΔH is:

$\Delta H = -\ 0.037 \cdot 0 - 0.945 \cdot 0 - 0.08 \cdot 0 + 132.68 = 132.68$ kJ/100 g,
or with 1 kJ/100 g = 2.78 kWh/t
ΔH = 369 kWh/t.

It is assumed for the technical melting process that NCI is melted from scrap steel, idealized as pure iron, graphite as pure carbon and ferrosilicon FeSi (75). The heat balance / energy requirement is then:

$0.939 \cdot H_{(Fe,\,25)} + 0.024 \cdot H_{(FeSi,\,25)} + 0.037 \cdot H_{(C,\,25)} = 1 \cdot H_{(NCI,\,1500)}$,
$\Delta H = -\ 0.024 \cdot (-32.68) + 132.68 = 133.5$ kJ/100 g = 371 kWh/t.

If silicon carbide (SiC) is used for siliconizing instead of FeSi, the heat balance / energy requirement is as follows:

$0.945 \cdot H_{(Fe,\,25)} + 0.036 \cdot H_{(SiC,\,25)} + 0.019 \cdot H_{(C,\,25)} = 1 \cdot H_{(NCI,\,1500)}$,
$\Delta H = -\ 0.036 \cdot (-182.61) + 132.68 = 139.3$ kJ/100 g = 387 kWh/t.

Lastly, the energy required to melt recycling materials needs to be determined:
$1\ H_{(NCI,\,25)} = 1\ H_{(NCI,\,1500)}$,
$\Delta H = -1 \cdot (-8.33) + 1 \cdot 132.68 = 141$ kJ/100 g = 392 kWh/t.

The results of these calculations are summarized in **Table 1**. These make clear that the heat content of cast iron melts

Table 1: Specific enthalpy of cast iron with 3.7 % C and 1.8 % Si at 1,500 °C for different compositions of input materials

Enthalpies of NCL with 3.7 % C and 1.8 % Si produced from:	
Pure substances	369 kWh/t
Steel scrap, FeSi, Graphite	371 kWh/t
Steel scrap, SiC, Graphite	387 kWh/t
Returns	392 kWh/t
Max difference	21 kWh/t
With 70 % efficiency	30 kWh/t

greatly depends on the composition of the input materials. One of the main influencing factors is the energy required to dissolve silicon and carbon in the iron melt: silicon releases energy, whilst energy is required for carbon. This is apparent in the diagramme in **Fig. 4**, in which the specific enthalpies of cast iron melts using the three pure components at a melting temperature of 1,500 °C are shown for different Si-contents in dependence on the C-content [4]. It can be recognized that the energy requirement rises with a higher C-content due to the heat required to dissolve carbon, whereas it drops as the Si-content increases due to the positive heat of mixing. The higher heat content of the cast iron in the selected example with 3.7 % C and 1.8 % Si of 392 kWh/t using the finished alloy compared to 369 kWh/t using the three pure components shows that the positive effect gained from the released Si-heat of mixing more than compensates for the heat required to dissolve carbon.

This effect is nullified if SiC is used for siliconizing instead of FeSi, as is shown by the enthalpy values in Table 1. This is because silicon is not an almost pure substance as is the case with FeSi, but is rather a compound which requires additional energy to dissolve it during melting.

MEASURED ENTHALPY VALUES

In order to check the results of the calculations shown in Table 1, the heat contents of cast iron melts with 3.4 % C, 1.9 % Si and 0.7 % Mn were determined at 1,500 °C in a 6-t, 3,550 kW, 250 Hz induction furnace [5]. **Table 2** shows the

Table 2: Data from melting trials in a 6-t, 3,550 kW, 250 Hz crucible furnace [5]

Charge material	Testrun X	Testrun Y
Returns 250	6,000 kg	
St 30		5,634 kg
C - Type 0230		208 kg
Mn		11 kg
FeSi 75 %		147 kg

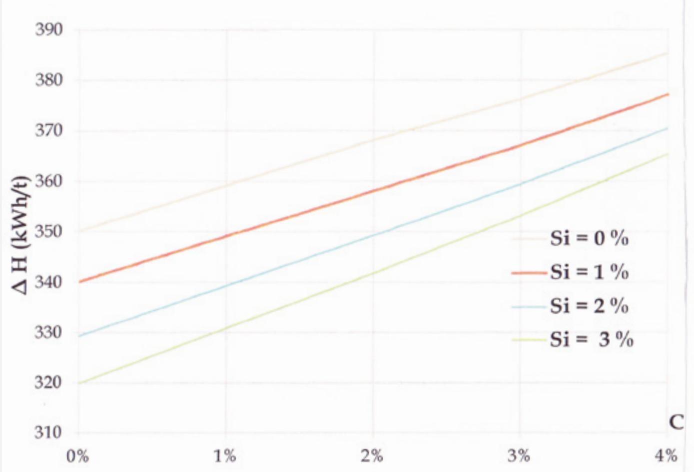


Fig. 4: Specific enthalpy ΔH of cast iron at 1,500 °C for different Si-contents in dependence on the C-content [4]

input materials, which were made up of 100 % recycling material in the stated composition on the one hand, and of scrap steel, manganese, FeSi and carbon on the other. The energy required for melting recycled material was measured at 532 kWh/t, that for melting steel plus alloying materials at 494 kWh/t. If one takes a degree of efficiency of 75 %, the resulting enthalpy values at 399 kWh/t for the recycled material and 370 kWh/t for the compound melt agree very well with the values calculated in Table 1.

The higher energy requirement during siliconizing with SiC instead of FeSi is proved by the results of measurements published in a paper by Smith and Bullard [6]. The specific energy requirement when melting in a 1-t, 750 kW, 500 Hz induction furnace whilst alloying with SiC is 651 kWh/t compared to 552 and 554 kWh/t when FeSi is used.

CONSEQUENCES FOR PRACTICE

As stated above, a value of 385 kWh/t is assumed in practice for the heat content of cast iron melts at 1,480 °C; this appears plausible in the context of the foregoing calculations, if one remembers that the percentage of recycled material used in iron foundries is generally up to 50 % and siliconizing is usually done with SiC instead of with FeSi. The reason for the latter is the positive influence that SiC-alloying has on the nuclear state of the melt [7]. Given appropriate experience in the particular application, such quality benefits are decisive because they outweigh the benefit of lower energy consumption. On the other hand, taking a degree of furnace efficiency of 70 % with (392 – 371) / 0.7 = 30 kWh/t, the maximum difference in the energy requirement for siliconizing with FeSi is so high that this effect needs to be taken into account as far as possible when putting together the charge and in selecting the silicon carrier. Using cast iron scrap purchased on

Table 3: Enthalpies referred to the respective melting temperatures of different alloys, melted from recycled material and from the single components [1]

Alloy	Melt temperature °C	Enthalpy (return scrap) kWh/t	Enthalpy (components) kWh/t	Superheating enthalpy kWh/(t · K)
G - X 20 Cr 14 (Fe 78,26 C 0,2 FeCr 21,54)	1,600	373	373	0.23
NCI (Fe 94,5 C 3,7 Si 1,8)	1,400	368	345	0.23
Alloyed cast iron (Fe 73 C 3 Si 2 Ni 22)	1,400	367	334	0.23
Ferrosilicon (Fe 25 Si 75)	1,400	621	530	0.26
Ferromanganese (Fe 25 Mn 75)	1,400	341	345	0.24
Brass (Cu 63 Zn 37)	1,000	149	128	0.14
Al alloys				
(Al 90 Si 6 Cu 4)	700	320	311	0.31
(Al 92 Cu 5 Mg 2)	700	306	292	0.32
(Al 94 Zn 5 Mg 1)	700	305	302	0.32
(Al 95 Mg 5)	700	307	306	0.33
(Al 88 Si 12)	650	323	323	0.32

the market as the iron carrier instead of steel scrap is also worth thinking about when seen from this aspect.

ENTHALPY VALUES OF DIFFERENT ALLOYS

The potential presented by enthalpy optimization can also be exploited when melting aluminium and copper alloys. **Table 3** lists the specific enthalpies of some significant alloys, referred to the respective melt temperature and the associated overheating enthalpies, which were melted from recycled material on the one hand and from the single components on the other [1]. The comparatively large difference in the enthalpies for melting brass from recycled/scrap brass and for the mixture of copper and zinc amounting to 21 kWh/t is particularly noticeable. If one remembers that the degree of furnace efficiency is around 55 % for this material, this results in a remarkable benefit in energy consumption of over 40 kWh/t when producing brass melts from the individual components. Such an advantage is often not considered in practice.

CONCLUSION

In the attempts to minimize energy consumption during inductive melting of metal alloys, account also needs to be taken of the potential offered by the specific enthalpy of the alloy melts. Tabular thermochemical data demonstrate that the composition of the input materials exercises a considerable influence on the energy requirement. The main factors here are primarily endothermic and exothermic processes of transformation and dissolution in the alloying components, as is shown by the enthalpy values determined for cast iron melts. Siliconizing with FeSi instead of with SiC produces an energy benefit of u p to 25 kWh/t here. It is also recommendable to make use of the available thermochemical data in melting practice for aluminium and copper alloys. For example, the energy requirement when melting brass from the components Cu and Zn is up to 40 kWh/t lower than if brass materials are fed in.

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