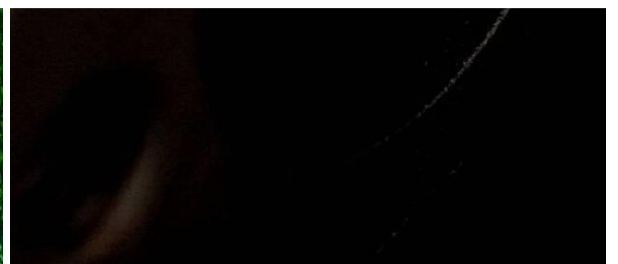


2014-001

# Casting of precipitation-hardening steel

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## Summary

17-4 PH and its cast equivalent Cb7Cu-1 are stainless precipitation-hardening steels with high strength and good corrosion resistance. Literature shows that the material properties can be tailored in detail by fine-tuning alloy composition and heat treatment. However, the result is also very sensitive to small changes in production environment. The goal of this literature survey has been to define which parameters are essential to make it possible to cast material involving extremely thin sections with  $d \leq 1$  mm. It has also taken into account the precipitation and hardening mechanisms of the material throughout the different process steps as well as possible means to analyze the resulting material. Additional theoretical calculations have been performed in order to suggest an optimized alloy for subsequent casting trials. The work has been performed within the *CLEAN SKY* project *LEAN: Development of light-weight steel castings for efficient aircraft engines*.

## Sammanfattning

17-4 PH och dess gjutna motsvarighet Cb7Cu-1 är rostfria utskiljningshärdade stål med goda egenskaper med avseende på hållfasthet och korrosion. En litteraturgenomgång visar hur materialegenskaperna kan skraddarsys i detalj genom väldefinierad legeringssammansättning och värmebehandling. Resultatet påverkas dock även i hög grad av små variationer i tillverkningsprocessen. Målet med denna litteraturstudie har varit att beskriva vilka parametrar som är avgörande för att kunna gjuta material med mycket tunna detaljer ned till  $d \leq 1$  mm. Även utskiljnings- och härdnings-mekanismer för materialet beskrivs under de olika tillverkningsstegen liksom metoder för att analysera det framställda materialets egenskaper. Slutligen har teoretiska beräkningar gjorts för att optimera en legering för kommande försöksgjutningar. Arbetet har utförts inom *CLEAN SKY*-projektet *LEAN: Development of light-weight steel castings for efficient aircraft engines*.



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# 1 Casting of precipitation-hardening steel

17-4 PH is a stainless precipitation-hardening steel with high strength and good corrosion resistance, widely used in military and commercial applications. Originally developed for wrought material, 17-4 PH steel is also used for casting, although the casting process and the resulting material is not yet fully described. The possibility to use 17-4 PH for extremely thin investment castings is being studied within the *CLEAN SKY* project *LEAN: Development of light-weight steel castings for efficient aircraft engines*.

A previous report within the project, “Thin Walled Investment castings”, describes the investment casting process and the influence of parameters related to the shell system, casting process, and thermo-physical properties [1]. The scope of this report is to define the effects of alloy composition on castability but also to investigate the influence of process parameters and alloying elements on the final material properties of the cast alloy. It will also take into account the precipitation and hardening mechanisms of the material throughout the different process steps as well as possible means to analyze the resulting material. The report consists of two parts: a complementary literature survey and calculations in order to define an optimum alloy composition for casting trials.

## 2 Precipitation-hardening stainless steel

The use of precipitation-hardening steel started with the Stainless W, developed in 1945 by U S Steel, using Al and Ti precipitations. This was followed by the copper precipitation systems 17-4 PH and 15-5 PH which are today the most common precipitation-hardening steels for investment casting, since they provide a tough and strong martensitic base matrix. The cast versions of these steel grades are Cb7Cu-1 and Cb7Cu-2, respectively. Some other martensitic grades are PH 13-8 Mo, Custom 450, and Custom 455; these are essentially free of  $\delta$ -ferrite and have thus better through-thickness properties. There are also semi-austenitic grades such as 17-7 PH, PH 15-7 Mo, and PH 14-8 Mo, having an austenitic matrix with up to 20 %  $\delta$ -ferrite in the solution-annealed condition. A heat treatment in several steps finally produces a complex structure also containing martensite. [2-3]

For further reading about precipitation-hardening steel, a recent literature survey performed by Abrahams and Voigt [4] is recommended. The study includes historical development of wrought and cast material, general physical metallurgy, precipitate systems, and considerations about future development.

### 2.1 Hardening mechanism

The addition of large amounts of chromium and nickel in stainless steel to create corrosion resistance means that traditional hardening and tempering methods are less efficient. However, addition of small amounts of other alloying elements such as aluminium, copper, titanium, molybdenum, or niobium, might create precipitations that strengthen the material. The precipitations are allowed to form by ageing a supersaturated solid solution, introducing strains in the lattice and thus strengthening the material.

The material properties can be tailored in detail by fine-tuning the heat treatment of the steel. The standard procedure for each steel grade is defined by the supplier. Solution treatment at high temperature is followed by an ageing treatment for a few hours at a lower temperature, typically between 400 and 800 °C, depending

on the required material properties. An initial homogenization might also be required due to copper segregation within the as-cast material. Two examples of standard heat treatment are shown in Figure 1.

The principles of precipitation hardening are thoroughly described in Refs. [2-5].

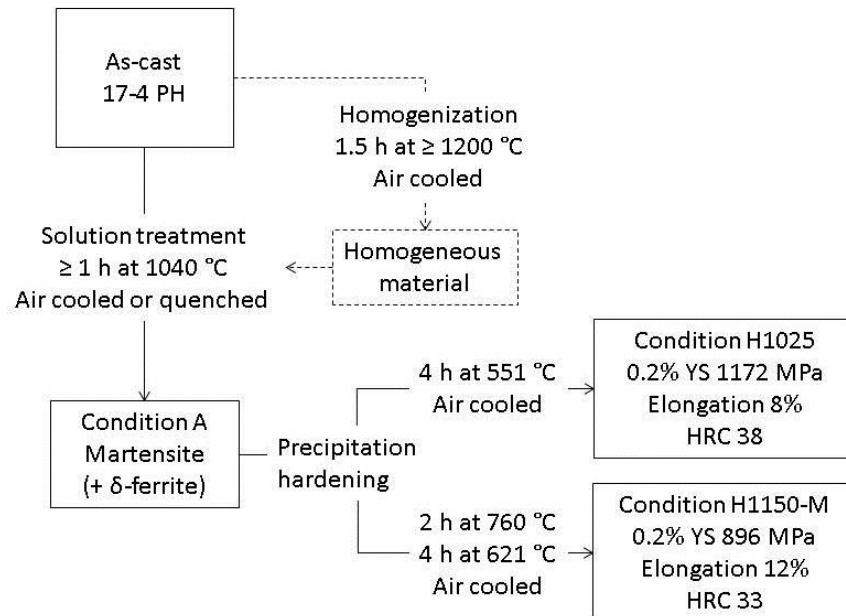


Figure 1. Example of heat treatment of cast 17-4 PH in order to achieve desired material properties. Reworked from Ref. [3].

## 2.2 Methods for material analysis

*Surface tension and density* of liquid ferritic stainless steel have been determined using the sessile drop technique, as described in Ref. [6]. The temperature range was above 1800 °C and a substrate of Al<sub>2</sub>O<sub>3</sub> was used in argon atmosphere.

*Microstructure* is usually investigated with light microscope. Suggestions for etchants are found in Ref. [2]. To selectively reveal δ-ferrite stringers in the martensitic matrix, electrolytic or magnetic etching might be used. The very fine particles involved in the precipitation hardening process, however, are generally not visible in the light microscope but can be detected by scanning transmission electron microscope, STEM [7-9].

*Phase transitions* of PH 13-8 Mo stainless steel have been studied in detail using differential thermal analysis (DTA), defining the cooling-rate dependence for different diffusion mechanisms. In contrast to 17-4 PH, however, this alloy is normally free from δ-ferrite, and therefore these results are not entirely applicable in the present study. [10]

*Kinetics of precipitation* of copper-rich phase in 17-4 PH have been studied with dilatometric experiments. The results were comparable with those calculated from hardness values during heat treatment. [11]

The general *corrosion resistance* of the material is typically evaluated in boiling acidic or caustic solution or in long-term corrosive environment such as marine atmosphere. Stress-corrosion resistance is typically evaluated in MgCl<sub>2</sub> solution with an applied bending stress. [12-13]



## 2.3 Material properties of 17-4 PH steel

The chemical compositions of 17-4 PH steel and its cast equivalent Cb7Cu-1 are displayed in Table 1. In the present project, a material according to the AMS 5343 specification was initially chosen, which is also included.

Table 1. Chemical composition of 17-4 PH and Cb7Cu-1 stainless steel [3]

Alloying element	17-4 PH (wrought)		Cb7Cu-1 (cast)		AMS 5343 [%]
	min [%]	max [%]	min [%]	max [%]	
C		0.07		0.07	0.07
Si		1.00		1.00	1.00
Mn		1.00		0.7	1.00
P		0.040		0.035	0.04
S		0.030		0.030	0.03
Cr	15.00	17.50	15.50	17.70	16
Ni	3.00	5.00	3.60	4.60	4.1
Cu	3.00	5.00	2.50	3.20	3.2
Nb	0.15	0.45	0.15	0.35	0.28
N				0.05	
Fe		Balance		Balance	Balance

Extensive summaries of process parameters and material properties of 17-4 PH and related alloys are found in Refs. [3], [4], and [14].

### 2.3.1 Physical properties and corrosion resistance

The thermo-physical and mechanical properties for 17-4 PH steel can be found in commercial data sheets as well as in the previous literature survey [1]. The corrosion resistance of 17-4 PH is better than any of the standard hardenable stainless steels and is comparable to austenitic 18-8 steel in most media, in both laboratory and external environment, such as marine atmosphere [6, 12, 15].

Only a few references were found for solidus and liquidus temperature for 17-4 PH steel in literature based on DTA measurements or theoretical calculations. They differ considerably, as shown in Table 2. Maguire *et al.* comment on their DTA measurements that the resulting temperatures were clearly above what could be seen during subsequent casting experiments [17].

Table 2. Solidus and liquidus temperatures for 17-4 PH steel

Author	Reference	Method	T <sub>solidus</sub> [°C]	T <sub>liquidus</sub> [°C]
SC Handbook	[3]	Undefined measurement	-	1510
Lorenz <i>et al.</i>	[16]	ThermoCalc calculations	1237	1406
Maguire <i>et al.</i>	[17]	DTA measurement	1449	1518
Sabau <i>et al.</i>	[18]	CompuTherm calculations	1430	1487

### 2.3.2 Microstructure

The microstructure of precipitation-hardening steels is influenced not only by composition, but also by processing. An example of heat treatment for two different final conditions was shown in Figure 1. Typical for cast 17-4 PH steel is a *homogenization treatment* at 1200 °C to reduce alloy segregation followed by a *solution treatment* at 1040 °C to gain a fully austenitic structure. A subsequent water quench ensures adequate martensitic transformation. For thin sections, air cooling might be sufficient. The resulting martensite is suggested to have a lath morphology with a dislocated substructure [19] or micro-twins [9]. The martensitic matrix usually contains a small percentage of isolated  $\delta$ -ferrite stringers [2]. Because of relatively slow solidification, cast 17-4 PH generally contains a little more  $\delta$ -ferrite than wrought material [4]. Reported values in the annealed state range from <2% [20] to 12% [21].

As the material is solution treated, all copper is placed into solid solution in the austenite. Upon quenching, copper is maintained within the martensitic structure. The material is then subsequently *aged* to promote precipitation of very fine second-phase copper-rich particles within the martensite matrix. In most cases, these precipitates are difficult to observe, except in severely over-aged condition. Studies of 17-4 PH as well as 15-5 PH material using STEM (scanning transmission electron microscope), however, show Cu-rich precipitates following solution treatment and ageing, and different authors have found copper-rich precipitates 150 Å in size [9], spheroid-shape copper, and fiber-shape secondary carbide  $\text{Cu}_{23}\text{C}_6$  [8]. In addition,  $\text{Cr}_{23}\text{C}_6$  particles are also precipitated within the material which is reported to reduce ductility [20].

Typical ageing treatment of 17-4 PH lasts for 1-4 hours in a temperature between 480 and 760 °C, depending on the required material properties. The rate of copper phase precipitation shows an exponential dependence on ageing temperature. For example, precipitation rate at the ageing temperature for the H900 condition, 482 °C, is 100 times greater than that at 400 °C, while the rate at the H1150 condition at 621 °C is 100 000 times greater [22]. Higher ageing temperatures will produce retained austenite, which transforms to untempered martensite upon cooling [2]. During long-term ageing at 400 °C, the martensite matrix decomposes into chromium-enriched and iron-enriched domains, although this process is reversible by an appropriate heat treatment of the aged alloy [23].

### 3 Parameters affecting castability

The influence of process parameters on castability has been covered earlier within this project [1]. Two additional aspect will be mentioned here: alloy composition and the effect of changing the surrounding atmosphere.

#### 3.1 Alloy composition

Both viscosity and surface tension of the molten metal are largely influenced by the actual alloy composition in the melt, which thereby affects the castability.

*Copper.* Increasing the copper content in Type 410 stainless steel from 3% to 4-6% increases the fluidity, but a further addition to 7% has a negative effect, partly due to alloy segregation. In the cast equivalent to 17-4PH, Cb7Cu, the copper content is generally somewhat lower than in the wrought version, only 2.5-3.2%, in order to ensure proper precipitation control. [3, 24]

*Silicon* improves the fluidity of the steel melt and protects chromium and columbium from oxidation during melting; it is generally kept somewhat higher in the cast Cb7Cu alloy than in 17-4 PH. Increasing the silicon content in 17-4 PH steel from 1% to 2% improves the fluidity, but the casting shrinkage also increases slightly. [4, 13-14]

*Sulphur and nitrogen.* Even small amounts of surface-active elements can have a marked effect on the surface tension of liquid stainless steel. Li *et al.* observed that the surface tension of ferritic chromium steel decreased with increasing sulphur content up to at least 0.05%, while no effect was detected when changing the nitrogen content. [6]

### 3.2 Process parameters

The effect of a protective atmosphere during melting was evaluated by Anderson *et al.* using SPAL technique, *i.e.* surrounding the metal with liquified argon or nitrogen during melting in an induction furnace. Different degrees of superheating were also used. The effect on fluidity by exchanging air for argon is summarized in Figure 2 (nitrogen not included in this particular part of their work). [25]

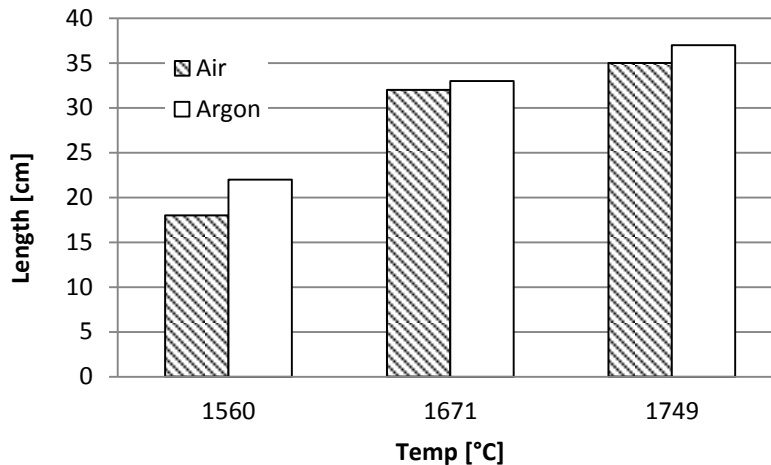


Figure 2. Effect of atmosphere and pour temperature on fluidity of 17-4 PH steel melt. Adapted from Ref. [25].

- An argon atmosphere gave approx. 20% better fluidity than air at 1560 °C, although the effect was less pronounced at higher temperatures.
- The amount of surface cracks as measured with liquid penetrant inspection was considerably lower when argon atmosphere was used; nitrogen atmosphere made no effect. Both argon and nitrogen reduced the size and density of micro-inclusions.
- Increased pouring temperature resulted in significantly higher oxygen and nitrogen pick-up in the material. As nitrogen atmosphere was used, the nitrogen pick-up was additional 1000 ppm, five times higher than in air. Nitrogen should therefore not be used as atmosphere for casting this alloy.
- The elemental alloy fade of manganese and silicon due to slag formation was apparent in air atmosphere, but was reduced by 50% and 75%, respectively, when argon was used.

## 4 Parameters affecting final material properties

The final material properties of 17-4 PH steel is highly dependent on the exact alloy composition, since even small changes may have a large impact on the structure. The process parameters during melting and casting will also affect the result. The effects of variation in heat treatment and additional process steps are also reviewed in this section.

### 4.1 Alloy composition

*Nickel and chromium.* 15-5 PH stainless steel was developed to improve 17-4 PH by increasing the nickel content and lowering the chromium content to suppress the formation of  $\delta$ -ferrite, especially in thick sections. The chemical compositions are displayed in Table 3. The mechanical properties and corrosion resistance are

essentially the same for both grades, although 15-5 PH retains ductility somewhat better as thickness increases. [28]

*Table 3. Chemical composition of precipitation hardening steel grades*

<b>Alloy</b>	<b>Cr min [%]</b>	<b>Cr max [%]</b>	<b>Ni min [%]</b>	<b>Ni max [%]</b>
17-4 PH	15.50	17.70	3.60	4.60
15-5 PH	14.00	15.50	4.50	5.50

*Copper.* The solubility of copper in austenite is about 6%, considerably higher than in ferrite or martensite. An excess amount of copper does not contribute to precipitation hardening but amounts above 5% can adversely decrease both toughness and strength considerably due to segregation of copper at the grain boundaries. This might also cause low ductility and cracking during welding. Therefore, if welding is anticipated, the copper content should be kept to the low side of the specification, preferably below 3.0%. [3-4, 14]

*Silicon and manganese* act as deoxidants but are preferably kept to low levels because of their deleterious effects on toughness, corrosion resistance, and the austenite-martensite balance in the material. At least 0.2% silicon or manganese, on the other hand, is desired when oxides are inclined to be present in the material, to assure cleanliness. Increasing the amount of silicon in 17-4 PH steel from 1% to 3% promotes the formation of  $\delta$ -ferrite, although some is dissolved during heat treatment if subzero-cooling is applied. Up to 2% silicon improves the toughness of the material without losing strength; it also improves the corrosion resistance. [13, 26, 31-32]

*Phosphorous and sulphur* levels are kept low because these elements tend to segregate towards grain boundaries and reduce grain cohesion, resulting in negative effects on toughness, workability, and corrosion resistance. [32]

*Molybdenum* is known as an impurity in 17-4 PH steel, promoting ferrite formation. It is found to have a positive effect on stress corrosion resistance. When present in larger amounts, molybdenum might form a  $Fe_2Mo$  phase, thus increasing the relative nickel content in the matrix and thereby stabilizing austenite formation. [31-34]

*Niobium, tantalum, and vanadium.* Niobium and tantalum are often added to high strength steels to form fine Nb/Ta carbides that are more favourable than the often coarse chromium carbides. The corrosion resistance is also enhanced since chromium carbides generally promote intergranular corrosion due to chromium depletion in the adjacent material. In many cases, niobium and tantalum are added at a ratio of 4:1-8:1 of the carbon content. However, niobium and tantalum are often not specified for 17-4 PH steel because of the toughness reduction from these additions [4, 29-31]. 17-4 PH steel modified by addition of niobium and vanadium together with nitrogen exhibits increased tensile strength, although niobium- and vanadium-rich carbonitrides might initiate micro-void formation [20].

*Nitrogen* additions up to 500 ppm to martensitic stainless steel have been suggested to improve impact properties due to finer  $Cr_2N$  precipitates compared to coarse chromium carbides at grain boundaries [4]. Large amounts of nitrogen ( $\leq 0.10\%$ ) have also been added in order to study additional hardening of vanadium carbonitrides [20]. However, nitrogen acts as an extremely potent austenite stabilizer and can be difficult to control in a production environment [4].

## 4.2 Process parameters

The effect of section thickness on the tensile properties of cast and heat treated 17-4 PH was studied by Ekey and Black as shown in Figure 3. As the section size was decreased from 100 mm to 25 mm, the ductility increased, while the strength remained essentially constant. [36]

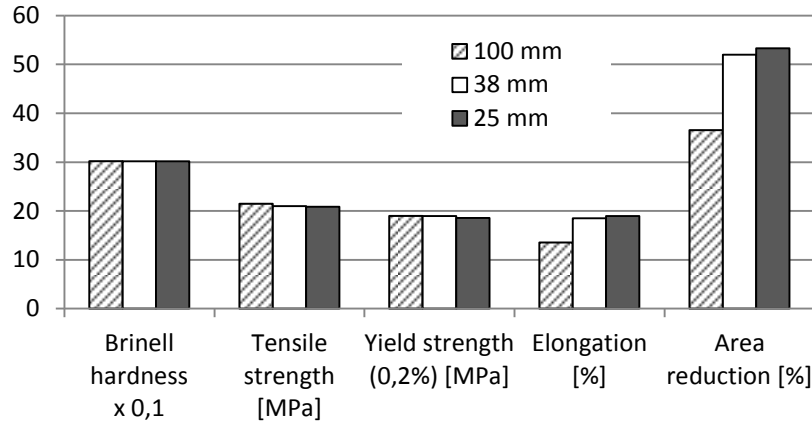


Figure 3. Effect of section thickness on tensile properties of cast 17-4 PH. Reworked from Ref. [36].

Hall *et al.* studied the effect on final composition of repeated meltdown in an induction furnace [26]. The results are summarized in Figure 4. Nitrogen shows a continuous increase due to uptake from the atmosphere, although below the allowed level (0.05% for cast material). Silicon and manganese decrease for each cycle but the slope gradually levels out. The chromium content, on the other hand, is initially constant but starts to decrease as silicon and manganese are consumed, demonstrating the deoxidating ability of these elements. The copper and nickel contents, however, are unaffected by the remelting process.

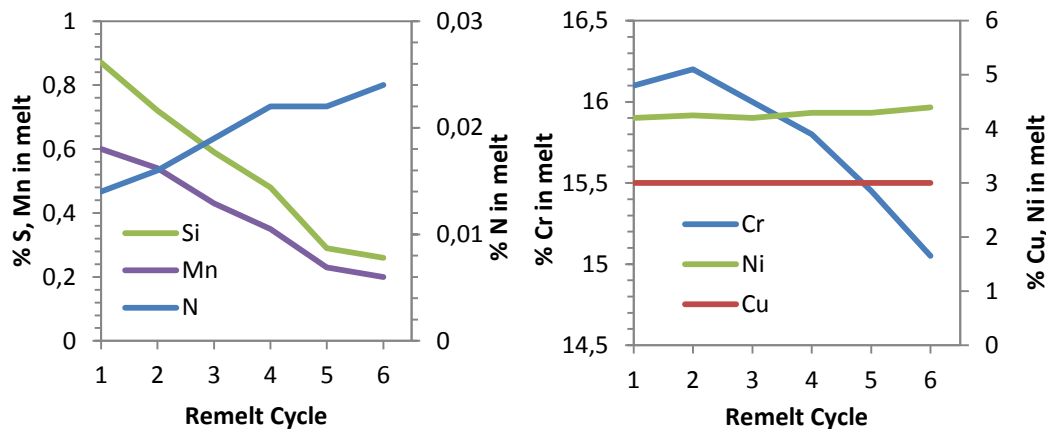


Figure 4. Variation in alloy composition during repeated meltdown of 17-4 PH stainless steel. Reworked from Ref. [26].

High pouring temperatures and/or slow cooling rates might promote a *coarse-grain structure* which affects ductility adversely [35]. Slow cooling might also promote the formation of  $\delta$ -ferrite *stringers*; a comparison between air-cooled and water-cooled 17-4 PH shows a  $\delta$ -ferrite content of 7% and 3%, respectively [20]. High amounts of  $\delta$ -ferrite can be reduced by extended solution treatment at 1050 °C [13]. *Retained austenite* can also remain in the matrix after solution treatment if the treatment time is too short, the quenching temperature is not low enough, or if the time in the quenching bath is too short. This will also lead to a

decrease of the yield and tensile strength of the material [4]. A comparison between air-cooled and water-cooled 17-4 PH shows an austenite content of 26% and 2%, respectively [20].

A number of possible means to improve material properties through heat treatment control are also reviewed by Abrahams and Voigt [4], such as HIP (hot isostatic pressing), solution treatment, quench treatment, and multistage ageing. Some of these techniques were evaluated by the same authors as reported in Ref. [27]:

- The response of mechanical properties to heat treatment for the Cb7Cu-1 alloy differed slightly from that of 17-4 PH.
- HIP prior to solutionizing resulted in better tensile properties, less micropores, and less  $\delta$ -ferrite. The  $\delta$ -ferrite also tended to change from stringers to the more favourable globular shape.
- Cryoquenching after solutionizing gave a fully martensitic transformation with no retained austenite.
- Longer ageing time at a lower temperature resulted in improved ductility.

## 5 Computational optimization of alloy composition

Fluidity is an empirical concept defined as the ability of molten metal to flow and fill a mould and is often divided into two different aspects, flowability and fillability. Flowability is a function of properties related to the shell system and the molten alloy, such as *viscosity* and *solidus and liquidus temperatures*. Fillability, on the other hand, is related to the ability of filling small cross sections and is therefore related to *surface tension*. Fillability becomes an important factor as section thickness decreases and a limit of  $d \leq 2.5$  mm has been reported. [1]

The influence of alloy composition on these properties has been evaluated theoretically using the computational program JMatPro with a Design of Experiments approach in order to suggest an optimized chemical composition for the casting trials in the project.

The relative amount of different alloying elements was varied within the limits of the specification for cast Cb7Cu-1 but also within the wider limits for 17-4 PH, allowing a copper content of up to 5.0%. Additional care was taken to consider effects on castability and material properties as described in the literature survey in the previous chapters of this report. As a reference point, the alloy described by Matsuno and Ohama in Ref. [37] was used, since the authors claim that they have successfully produced extremely thin ( $d \leq 1$  mm) investment castings using vacuum moulding [1, 37].

*Copper.* The copper content was found to have a dominating influence on surface tension. Figure 5 shows the calculated values for surface tension at the solidus temperature for different amounts of copper, chromium, and nickel. Only the copper content has a substantial effect on the surface tension with considerably lower values for the highest amount, 5%, which is consequently suggested to be the most favourable for casting. It should be noted, however, that this is well above the upper limit for the cast alloy Cb7Cu-1 as well as the upper limit for welding purposes, 3.0% [14].

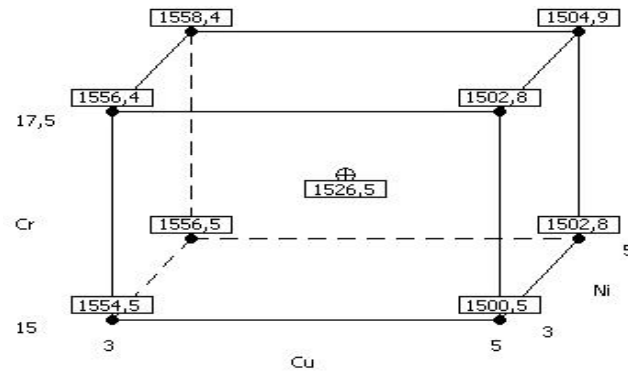


Figure 5. Calculated surface tension [mN/m] at 1650 °C for varied copper, chromium, and nickel content [%].

*Nickel and chromium.* For the purpose of very thin investment castings, a small  $\Delta T$  ( $T_{\text{liquidus}} - T_{\text{solidus}}$ ) is preferred. The influence of copper and nickel content of the alloy on  $\Delta T$  is shown in Figure 6. The lowest  $\Delta T$  is found for the highest nickel and copper content, respectively. The liquid viscosity, on the other hand, is minimized for low nickel and high copper content, although the effect is less pronounced (Figure 6). Therefore, an intermediate nickel content of 4.3% is suggested. The chromium content turned out to have only a minor effect on the calculated parameters. Nevertheless, it was chosen to be kept on the lower side to suppress the formation of  $\delta$ -ferrite [28].

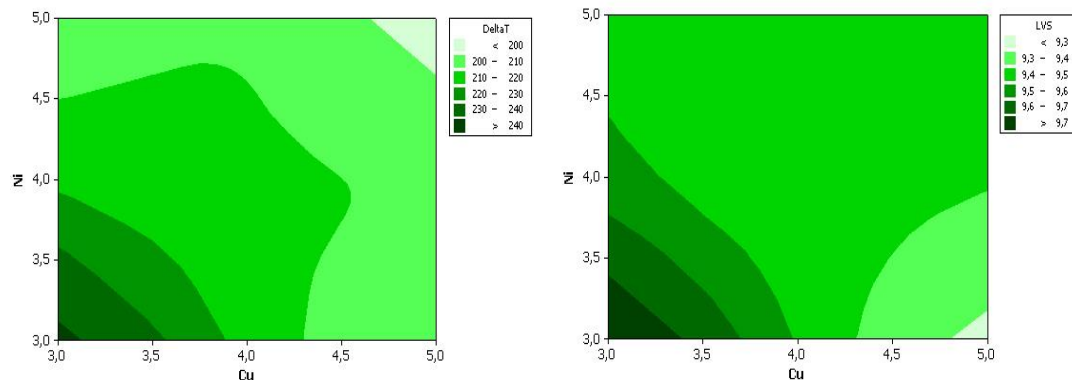


Figure 6. Calculated  $\Delta T$  [°C] and liquid viscosity [mPa s] at the solidus temperature for varied copper and nickel content [%].

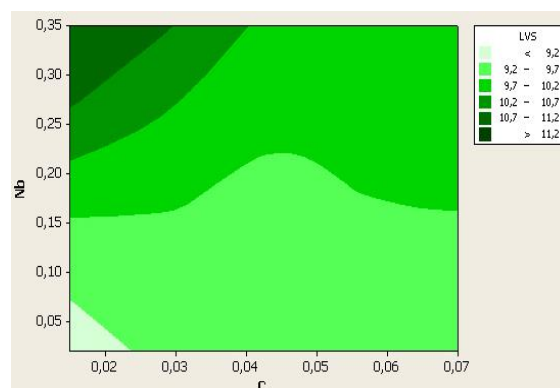


Figure 7. Calculated liquid viscosity [mPa s] at the solidus temperature for varied carbon and niobium content [%].

*Carbon* and *niobium* were also found to have a pronounced influence on calculated  $\Delta T$  and liquid viscosity (Figure 7). A niobium content below 0.2% and a carbon content below 0.03% are suggested.

*Phosphorous* and *sulphur* were found to have only little influence on the calculated parameters, although contents below 0.02% were slightly beneficial with respect to liquid viscosity. Low contents are also beneficial for material properties [4][32]. The same was found for *manganese and silicon*, partly in contrast to what is stated in Ref. [14], although an intermediate content of 0.6% turned out to be optimal for both elements. *Nitrogen* was also found to have a very small effect in the calculations which is consistent with Ref. [6]. Due to expected process conditions, the nitrogen content was set to 0.03%.

To summarize, the positive effect of copper on fluidity of the molten alloy as reported in Ref. [24] was confirmed by the JMatPro calculations with a pronounced minimum in viscosity and surface tension for a copper content of 5%. Furthermore, the optimization includes slightly lower contents of other elements as compared to the AMS5343E alloy. The final composition of “17-4 PH optimized” is displayed in Table 4.

The optimized composition turned out to be close to that used for thin investment castings by Matsuno and Ohama [37] as shown in Table 4, “M-O”. This composition includes a copper content of 3.3% which is within the specification for cast Cb7Cu-1 but still above the upper limit recommended for welding purposes. Therefore, a new composition was optimized for 3.0% copper, “M-O weldable”, with slightly adjusted amounts of nickel and chromium (Table 4).

Table 4. Alloy compositions suggested for casting trials together with AMS5343 and Matsuno-Ohama.

Comp. [%]	C	Si	Mn	P	S	Cr	Ni	Cu	N	Nb+Ta
AMS5343E	0.07	1.00	1.00	0.04	0.03	16.0	4.1	3.2	0.03*	0.28
M-O [28]	0.03	0.6	0.6	0.023	0.018	15.75	4.3	3.3	0.03*	0.3
M-O weldable	0.03	0.6	0.6	0.023	0.018	15.5	4.0	3.0	0.03	0.3
17-4 PH opt.	0.03	0.6	0.6	0.015	0.01	15.0	4.3	5.0	0.03	0.3

\*Nitrogen content not defined in references

The *solidus and liquidus temperatures* calculated for each of the suggested alloys are shown in Table 5. There are interesting differences between these data and those reported in literature (Table 2). A deviation from DTA measurements as well as from casting experience was expected since no overheating effects are taken into account for in the calculations. Deviations between calculated values can be attributed to differences in data sets and definitions. It is necessary to define  $f_{sol}$  for the calculations, *i. e.* the fraction of solid phase still present at the solidus temperature. Here,  $f_{sol}=0.05$  was used, resulting in a lower solidus temperature in correspondence with Lorenz *et al.* [16]. A considerably higher value of  $f_{sol}=0.30$  might be motivated by casting simulation practice [38] as well as by a comparison with related alloys [39], resulting in higher solidus temperatures in accordance with Sabau *et al.* [18]. The calculated liquidus temperature, however, is not affected by  $f_{sol}$  but is always approximately 60 degrees lower than the measured values in Table 2. The resulting solidus and liquidus for the different approaches are compared in Table 5. The trends are the same for both series and can very well be used for internal comparison between the different alloys. In the previous and following discussion, however, data corresponding to  $f_{sol}=0.05$  are used throughout.



Table 5. Calculated solidus and liquidus temperatures for the optimized alloys and reference compositions

Alloy	$T_{\text{solidus}} [^{\circ}\text{C}]$		$T_{\text{liquidus}} [^{\circ}\text{C}]$	$\Delta T = T_{\text{liq}} - T_{\text{sol}}$	
	$f_{\text{sol}}=0.05$	$f_{\text{sol}}=0.30$		$f_{\text{sol}}=0.05$	$f_{\text{sol}}=0.30$
AMS5343E	1230	1380	1438	208	58
M-O [28]	1275	1405	1448	173	45
M-O weldable	1285	1405	1452	167	47
17-4 PH optimized	1245	1385	1443	198	51

The changes in composition do not have any marked effect on the liquidus temperature, but the solidus temperature varies in a range from 1230 °C for the AMS5343 alloy to 1285 °C for the Matsuno-Ohama alloy. Consequently, the solidification interval is the smallest for the latter, with or without modified copper content. The optimized 17-4 PH with 5% copper has a solidification interval slightly smaller than that of AMS5343.

The resulting *liquid viscosity* data for the four alloys are shown in Figure 8. There is no difference between the two Matsuno-Ohama compositions. Below the liquidus temperature, AMS5343E has the lowest viscosity except for very close to the solidus temperature where the optimized 17-4 PH has an equal or even lower viscosity.

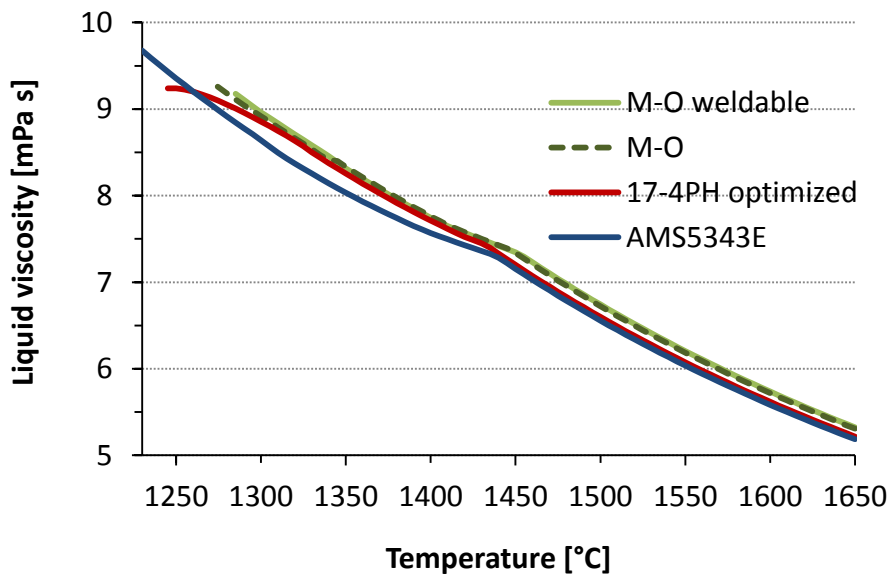


Figure 8. Calculated liquid viscosity for the optimized alloys and reference compositions.

The resulting calculated *surface tension* data for the four alloys are shown in Figure 9. Above the liquidus temperature, the effect of composition on surface tension is large. The modified Matsuno-Ohama shows a higher surface tension than the original alloy in this region, but below  $T_{\text{liq}}$  they are again equal to that of AMS5343E. The surface tension of the optimized 17-4PH, however, remains substantially lower within the whole temperature range.

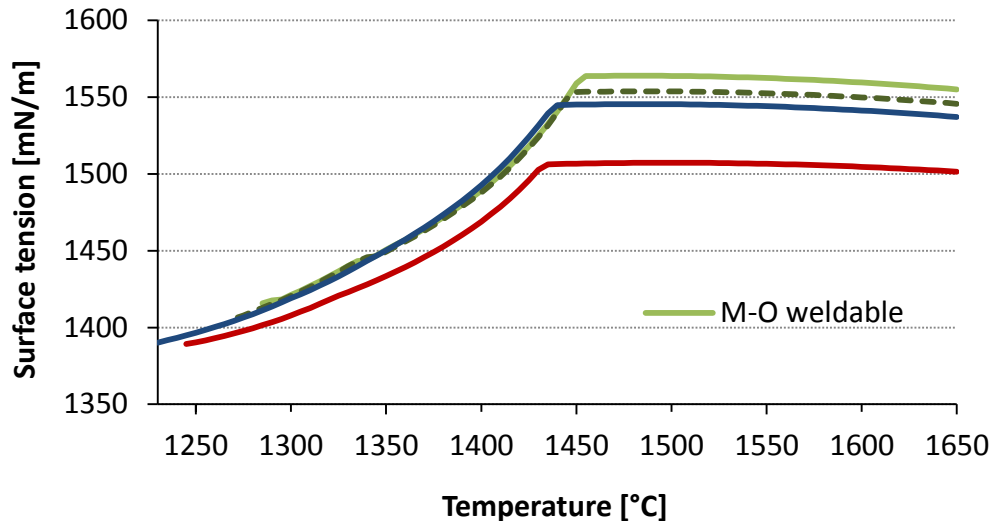


Figure 9. Calculated surface tension for the optimized alloys and reference compositions.

## 6 General considerations

17-4 PH and its cast equivalent Cb7Cu-1 are stainless precipitation-hardening steels with high strength and good corrosion resistance. Literature shows that the material properties can be tailored in detail by fine-tuning alloy composition and heat treatment. However, the result is also very sensitive to small changes in production environment. The goal of this study has been to define which parameters are essential to make it possible to cast material involving extremely thin sections, with  $d \leq 1$  mm.

Based on literature and theoretical calculations, two revised compositions of 17-4 PH are suggested for casting trials on thin investment castings. Copper is the single alloying element that has the most pronounced effect on fluidity in terms of  $\Delta T$ , viscosity, and surface tension, as shown by Ref. [24] and supported by the present JMatPro calculations. A copper content of 5.0% is consequently suggested in the first composition. This is, however, above the upper limit for cast Cb7Cu-1, and might cause problems with precipitation control, mechanical properties, and welding [3-4, 14]. Therefore, a second composition is suggested based on the work by Matsuno-Ohama but adjusted to a copper content of 3.0%.

The resulting calculated  $\Delta T$ , viscosity, and surface tension for the suggested alloys have been compared to those of AMS5354E and Matsuno-Ohama in Table 5 and Figures 8 and 9.

- Comparing  $\Delta T$  for the four alloys in Table 5, it is evident that the Matsuno-Ohama compositions show the smallest solidification interval. This is an indication that the alloy is closer to a eutecticum which might be the goal for optimization for these authors in order to achieve very thin castings. [37]
- The liquid viscosity is related to flowability and is expected to be the predominant factor for fluidity when casting cross-sections above 2.5 mm [1]. Figure 8 shows that the AMS5343E composition has the lowest calculated viscosity throughout the whole temperature range. Still, as Matsuno-Ohama chose a composition with higher viscosity for their successful thin-walled investment casting [37], this property is probably not the predominant factor for fluidity in this case.

- The largest effect of the high copper content in the Optimized 17-4 PH alloy is found for surface tension (Fig. 9). This alloy has a substantially lower surface tension than the other alloys over the entire temperature range. Since surface tension is closely connected to fillability, it grows increasingly important for the resulting fluidity as the thickness of the casting decreases below 2.5 mm [1]. Therefore, this parameter might be the predominant factor for success. Still, the high amount of copper present might induce difficulties and great care must be taken to investigate possible negative effects on the cast material.

In short, the two chosen modified alloys as presented in Table 4 represent two different approaches to the defined goal of achieving thin investment castings.

1. “17-4 PH Optimized”: an alloy optimized with reference to surface tension, the single parameter that appears to be of the largest importance for the fluidity of the melt under these circumstances.
2. “Matsuno-Ohama weldable”: an alloy with slightly inferior properties, but known to fulfill the demands for the desired dimensions, although slightly adjusted to requirements for welding.

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## 8 Acknowledgement

The JMatPro and DoE calculations were performed under supervision by Henrik Borgström, which is hereby most gratefully acknowledged.