

行政院國家科學委員會專題研究計畫 成果報告

低熱膨脹鑄鐵之鑄造性及加工性研究 研究成果報告(精簡版)

計畫類別：個別型
計畫編號：NSC 95-2221-E-002-114-
執行期間：95年08月01日至96年07月31日
執行單位：國立臺灣大學機械工程學系暨研究所

計畫主持人：潘永寧

計畫參與人員：博士班研究生-兼任助理：林明山
碩士班研究生-兼任助理：洪文琦

報告附件：出席國際會議研究心得報告及發表論文

處理方式：本計畫可公開查詢

中 華 民 國 96 年 12 月 07 日

On The Riser Design of Cast Irons With Low Thermal Expansion Coefficient

E. N. PAN, M. S. LIN

Department of Mechanical Engineering, National Taiwan University, Taipei, Taiwan

發表期刊: *E. N. Pan and M. S. Lin, "On the Riser Design of Cast Iron With Low Thermal Expansion Coefficient," Transactions of American Foundry Society (AFS Trans.), Vol.113, 2006.*

ABSTRACT

The objective of this study is to evaluate the castability, alloy solidification shrinkage and the riser design in particular, of low thermal expansion (LTE) cast irons with relatively low C and Si content ($< 2.0\%$). The solidification temperatures as well as the solidification shrinkage and solid contraction were analyzed, and also the riser design was performed in this work. Thermal analyses results indicate that the alloy liquidus temperatures are closely related with the CE value. In addition, the amounts of solidification shrinkage were measured to be around 5% for 1%C-1%Si-35%Ni FG irons, and around 6.5% for SG irons of similar compositions, with a difference of some 1.5%. Furthermore, the percent solidification shrinkage decreases as the Co content increases from nil to 6% at a constant NiE, with a 0.35% reduction for each 1% Co substitution for an equivalent amount of Ni. Increasing C and Si contents reduces the amount of solidification shrinkage, but no noticeable effect of substitution of Co for Ni on solidification shrinkage was obtained as C and Si were increased. Finally, the optimal riser designs for LTE cast irons with various compositions were attained.

INTRODUCTION

In high-precision machining, semi-conductor manufacturing processes and pairs of conjugated rotating components, all of which generate heat, the demand for a high dimensional accuracy under the influence of thermal heat continuously increases. Alloys with low thermal expansion coefficients (α) are suitable for such applications.

Guillaume developed Invar (Fe-Ni alloys) in 1896. The α values of Invar are quite low, typically at $(1 \sim 3) \times 10^{-6}/^{\circ}\text{C}$ (or $(0.56 \sim 1.67) \times 10^{-6}/^{\circ}\text{F}$) (ASM Metals Handbook, 10th ed., Vol. 2, 1990). However, the low C and Si contents ($\text{C} < 0.2\%$, $\text{Si} < 0.4\%$) and the austenitic phase in the microstructure cause Invar to exhibit relatively poor machinability and castability. In 1927, the International Nickel Company developed a series of high-Ni austenitic cast irons (later specified as ASTM "Ni-resist") for various special applications. Of the ASTM Ni-resist alloys, Alloy D-5, which contains 34 ~ 36% Ni was designated for use in applications that require low thermal expansion. This high-Ni austenitic cast iron has α value of about $(5 \sim 6) \times 10^{-6}/^{\circ}\text{C}$ (or $(2.8 \sim 3.3) \times 10^{-6}/^{\circ}\text{F}$), which is around one-third to one-half that of the ordinary cast irons (INCO, 1970, ASM Metals Handbook, 10th ed., Vol. 1, 1990). The relatively high C and Si contents and the presence of the graphite phase in the microstructure allow Alloy D-5 to have much better machinability and castability than Invar. However, the coefficients of Alloy D-5 are still too high for specific applications.

In the authors' earlier work (Pan et. al., 2003), issues such as developing cast irons with low thermal expansion coefficient with the α value approaching that of Invar, the recovery of alloying elements on melting and the solidification characteristics of the developed alloys, were investigated. The results show that α decreases as C and/or Si contents (or CE) decreases. Cast irons with a nominal composition of 1.0%C-1.0%Si-36%Ni have α values obtained in the temperature range 50 ~ 150°C of $(2.3 \sim 3.3) \times 10^{-6}/^{\circ}\text{C}$ for FG iron and $(3.5 \sim 3.8) \times 10^{-6}/^{\circ}\text{C}$ for SG iron, respectively. Coefficients can be further reduced by replacing some Ni with Co at a constant NiE of 36%. For instance, α values in the range of $(1.2 \sim 2.5) \times 10^{-6}/^{\circ}\text{C}$ have been achieved for alloys with a nominal composition of 1.0%C-1.0%Si-30%Ni-6%Co.

The development of low thermal expansion (LTE) graphite cast irons has led to the conclusions that relatively low α values can be obtained mainly by reducing C and/or Si contents. However, both machinability and castability are expected to fall as the C and Si contents decline. In the authors' another work (Pan et. al. 2005), the machinability of LTE cast irons had been studied. The objective of this study is to evaluate the castability, alloy solidification shrinkage and the riser design in particular, of LTE graphite cast irons with relatively low C and Si contents (both are less than 2.0%).

EXPERIMENTAL

ALLOY DESIGN

Table 1 presents the alloy design for this study. Two nominal levels of C and Si were considered — 1.0%C-1.0%Si and 2.0%C-2.0%Si, and two nominal combinations of Ni and Co were evaluated — 35%Ni and 29%Ni+6%Co, for both gray and ductile irons. The chemical analyses of all heats are presented in Table 2.

Table 1. Summary of Alloy Design

Heat No.	Chemical composition, %				Graphite type
	C	Si	Ni	Co	
A1	1.0	1.0	35	0	Flaky
A2	1.0	1.0	29	6	
A3	2.0	2.0	35	0	
A4	2.0	2.0	29	6	
B1	1.0	1.0	35	0	Spheroidal
B2	1.0	1.0	29	6	
B3	2.0	2.0	35	0	
B4	2.0	2.0	29	6	

Table 2. Chemical Analyses of All Heats

Heat No.	C, %	Si, %	Ni, %	Co, %	Mg, %
A1	0.95	0.93	33.6	-	-
A2	0.96	1.02	29.4	6.1	-
A3	2.06	2.11	35.4	-	-
A4	1.82	2.13	29.4	6.1	-
B1	0.97	1.11	35.5	-	0.026
B2	1.14	1.05	27.6	5.9	0.019
B3	1.83	2.19	34.3	-	0.021
B4	2.20	2.23	28.5	6.3	0.026

ANALYSES OF SOLIDIFICATION TEMPERATURES

The analyses of the solidification cooling curves were conducted by equipping S-type thermocouples at the center of shell molds, $\phi 40\text{mm} \times 60\text{ mm L}$. A typical solidification cooling curve is illustrated in Fig. 1, where the liquidus temperature (the primary arrest, T_L) and the eutectic temperatures (the eutectic arrest) are indicated. Regarding the eutectic arrest temperature, for the apparatus employed in the present study, one can see that the eutectic reaction occurred at continuing decreasing temperatures. For the sake of discussion, the beginning and the end of the eutectic reaction are respectively denoted as T_{E1} and T_{E2} .

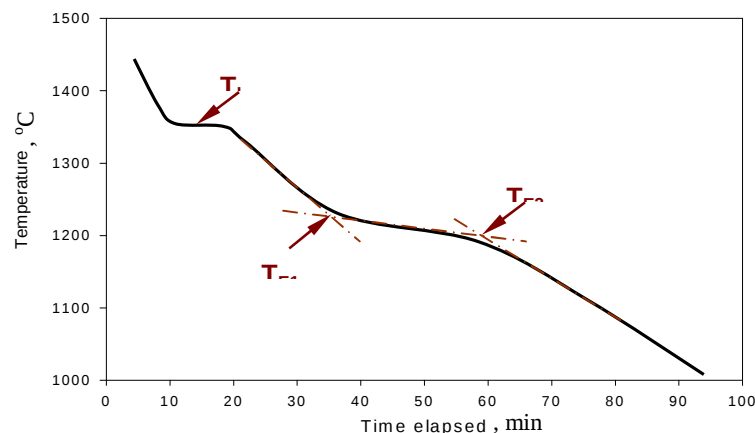


Fig. 1. An example of the solidification cooling curve.

MEASUREMENTS OF SOLIDIFICATION AND SOLID SHRINKAGES

In order to study the mode and amounts of solidification shrinkage and solid contraction, the mold design as illustrated in Fig. 2 was employed (Harinath et al., 1979). The dimensions of a block-shaped pattern (casting) are shown in Fig. 3. The molds were made by CO2 process. When castings were poured and cooled, and then sectioned, various shrinkages can be observed. A schematic illustration of various solidification and solid shrinkages is depicted in Fig. 4. For detailed analysis, both the internal shrinkages (the pipe and the internal dispersed porosity) and the external shrinkages (the surface sink and the contour contraction) were considered and determined by volume and density measurements of the poured castings. In this study, both the internal shrinkages (the pipe (V_{pipe}) and the internal dispersed porosity (V_{internal})) and the external shrinkages (the contour contraction and the surface sink), V_{external} , as illustrated in Fig. 4 (Patterson et al., 1962), were considered and determined by volume and density measurements (Archimedes' principle). The determinations of various types of shrinkages are stated below:

V_{c1} = The volume of the solidified casting measured by Archimedes' principle without sealing the pipe opening.

V_{c2} = The volume of the solidified casting measured by Archimedes' principle by sealing the pipe opening.

V_p = The volume of the original pattern.

D_i = The density of the specimens taken from a Keel-block mold which was concurrently cast from the same melt, where a sound casting without the presence of porosity is assumed.

W_c = The casting weight.

From the measurements of V_{c1} , V_{c2} , V_p , D_i and W_c , the amount of various types of shrinkages, V_{pipe} , V_{internal} and V_{external} , can be calculated as follows:

$$V_{\text{pipe}} = V_{c2} - V_{c1}$$

$$V_{\text{internal}} = V_{c1} - W_c / D_i$$

$$V_{\text{external}} = V_p - V_{c2}$$

The gross shrinkage which includes solidification shrinkage and solid contraction is equal to $V_{\text{pipe}} + V_{\text{internal}} + V_{\text{external}}$. The solid contraction is defined as the contraction of the casting from the solidified temperature to the ambient temperature, which is calculated by the temperature change and the thermal expansion coefficient. Then, the solidification shrinkage can be determined by contracting the solid contraction from the gross shrinkage.

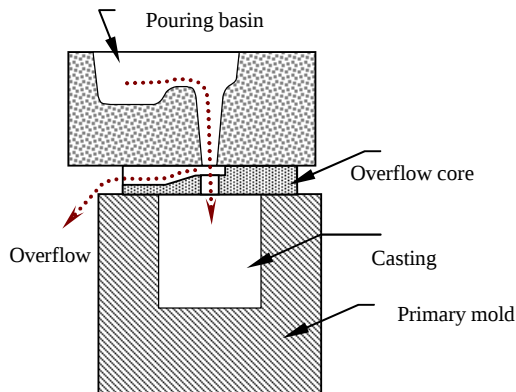


Fig. 2. Mold design for solidification and solid shrinkage test.

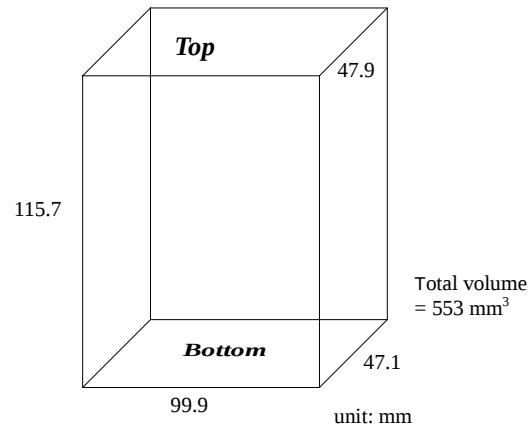


Fig. 3. Pattern (casting) for solidification and solid shrinkage test.

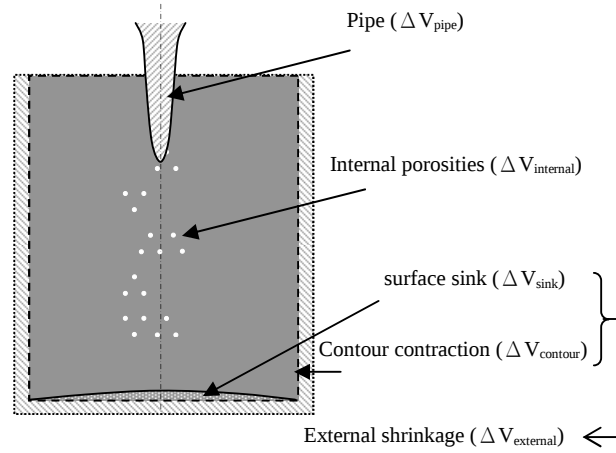


Fig. 4. A schematic illustration of various shrinkages.

RISER DESIGN

In this study, the riser design for the alloys studied, owing to their relatively low C and Si contents, was performed based upon the concept of cast steel (Chvorinov, 1940, Woldawer, 1966). The Geometric method developed by Heine (Heine, 1963) was adopted here for the riser design. Following is a brief review of the Geometric method. A complete riser system includes three sections: (1) the feeding section, (2) the pressure section, and (3) the riser base, as illustrated in Fig. 5. The feeding section serves as a reservoir that provides liquid metal to compensate for the solidification shrinkage of the casting. The pressure section is optionally added to ensure the feeding section being above the casting to achieve efficient feeding. While, the riser base serves as a channel between the feeding section and the casting. For a side-riser, all the three sections are usually required, whereas, only the feeding section is required for a top-riser.

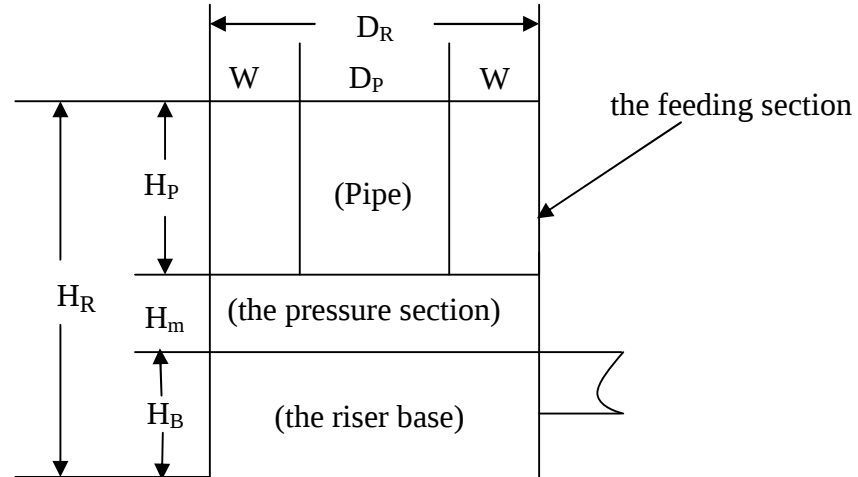


Fig. 5. A complete riser system for the Geometric method.

Regarding the feeding section, it is further divided to two sub-sections, namely, the outer ring with a shell thickness of w and the central pipe section with a diameter D_p and a height H_p . The diameter and the height of the feeding section are D_R and H_p , respectively, where $D_R = 2w + D_p$. On the other hand, the shell thickness w is equal to $2M_c$, where M_c is the casting modulus. Furthermore, the volume of the pipe, $(\pi D_p^2 H_p) / 4$, is equal to the amount of the solidification shrinkage of the casting alloy, namely, $(\pi D_p^2 H_p) / 4 = b \times V_c$, where b is the percent solidification shrinkage and V_c is the casting volume. Based upon the data of casting volume (V_c), percent solidification shrinkage (b), and casting modulus (M_c), together with the assumption of $H_p = n D_p$ (n is normally 1 ~ 3), the dimensions of the feeding section, D_R and H_p , can be readily obtained.

The experimental setup for evaluating the feeding efficient of various riser sizes is illustrated in Fig. 6, which includes a pouring basin, an overflow, a riser mold and a primary mold. The molds were made by the CO_2 process, and the treatment

temperatures were set at $(T_L + 200^\circ\text{C})$ for FG irons and at $(T_L + 250^\circ\text{C})$ for SG irons. After treatments, the melt was poured immediately into the molds.

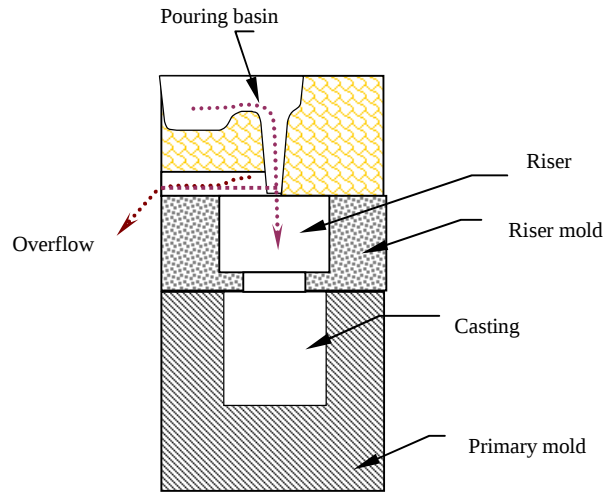


Fig. 6. An assembly mold design for the feeding test of risers.

RESULTS AND DISCUSSION

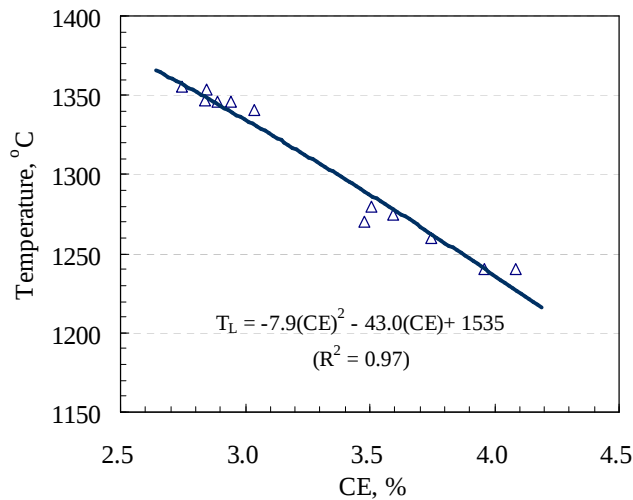
The solidification temperatures for the low C and Si LTE graphite cast irons had been investigated in authors' previous work (Pan, et.al. 2003), and a brief summary of the results is presented here. The relationship between the liquidus temperatures and the CE value for both FG and SG cast irons are shown in Figs. 7(a) and 7(b), respectively. The CE is defined as: $\text{CE} = \%C + 0.33 \%Si + 0.047 \%Ni - 0.0055 (\%Ni \times \%Si)$ (Schelleng, 1960). Note in Fig. 7 that the liquidus temperature decreases with increasing CE value. Here, non-linear regression equations were derived for both FG and SG irons as follows:

$$\text{For FG irons: } T_L, (^\circ\text{C}) = -7.9 (\text{CE})^2 - 43 (\text{CE}) + 1535 \quad (R^2 = 0.97)$$

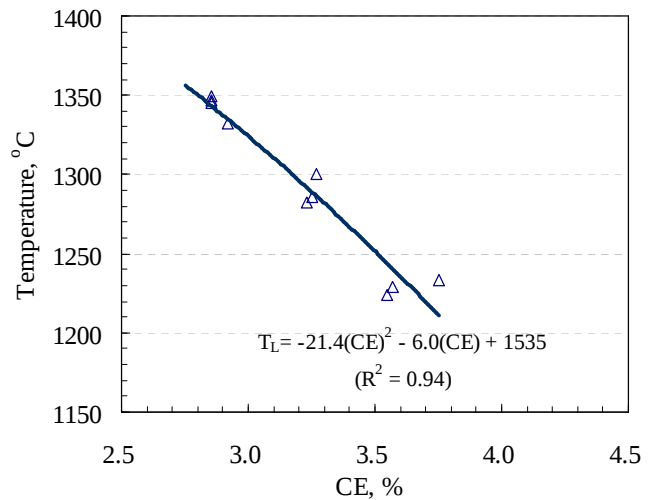
Equation 1

$$\text{For SG irons: } T_L, (^\circ\text{C}) = -21.4 (\text{CE})^2 - 6 (\text{CE}) + 1535 \quad (R^2 = 0.94)$$

Equation 2



7(a) FG irons



7(b) SG irons

Fig. 7. The liquidus temperature with respect to CE value.

It has been well realized that in the Fe-C-Si system the eutectic temperatures of both the stable and metastable reactions are influenced mainly by the Si content. Therefore, change in eutectic temperatures (T_{E1} and T_{E2}) as affected by the Si content was first plotted, with the results being depicted in Fig. 8(a) and Fig. 8(b) for flake and spheroidal graphite irons, respectively.

The regression analyses were also performed with the prediction equations being denoted in the figures.

It can be noticed that all the above four coefficients of determination are relatively low, implying that the Si alone as the dependent variable may not be sufficient enough to attain good correlation with the eutectic temperatures. It should be recognized that the alloys studied herein contain not only Si but also a substantial amount of Ni, and in some cases some amounts of Co. The role of Ni should not be ignored due to its similarity in metallurgical effect as Si though with different (less) degree. Therefore, both the effects of Si and Ni are considered and combined into a single parameter, i.e., silicon equivalent (Si.E.), where $\text{Si.E.} = \% \text{Si} + 0.141\% \text{Ni} + 0.0165(\% \text{Si} \times \% \text{Ni})$. Again, when the relationships between the eutectic temperature and Si.E. were plotted, the results are shown in Fig. 9(a) and Fig. 9(b) for FG irons and SG irons, respectively. However, the coefficients of determination of the regression equations derived are still relatively low.

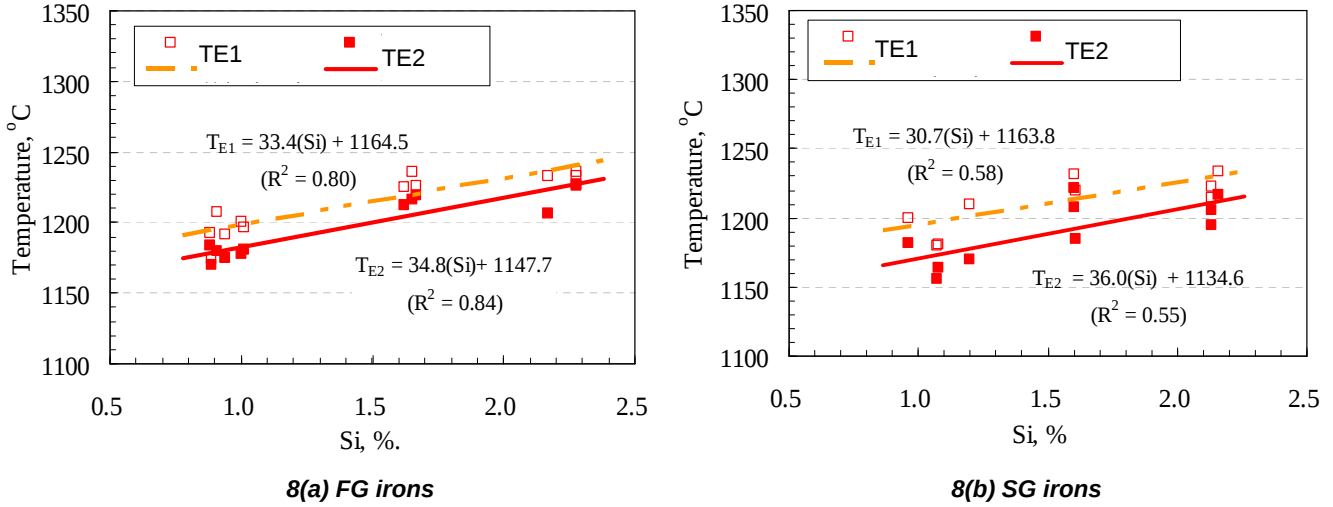


Fig. 8. The eutectic temperature with respect to Si value.

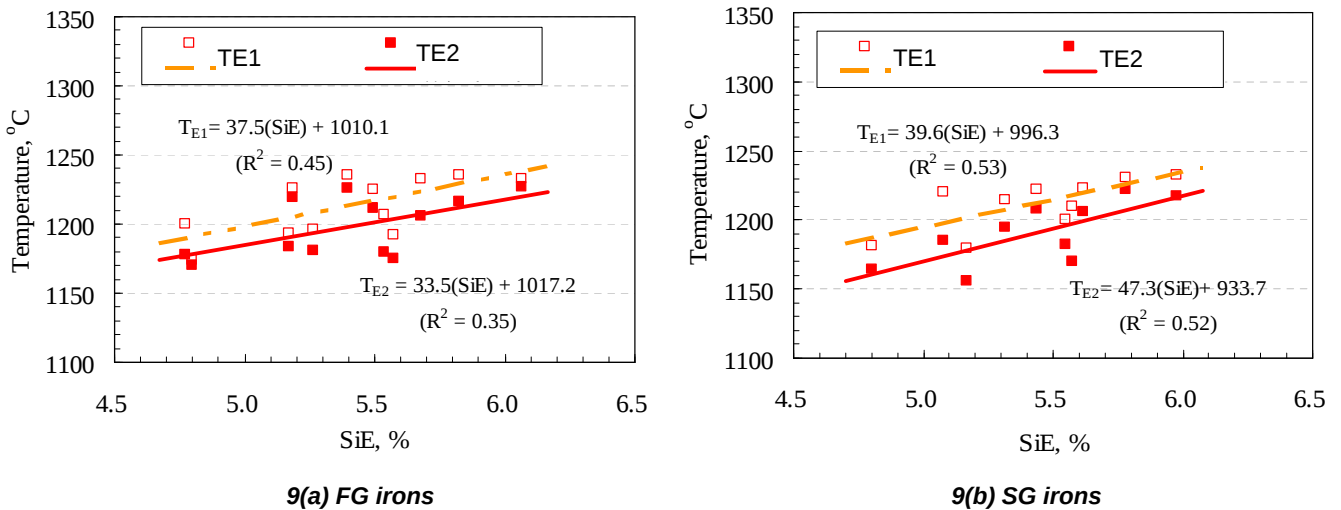


Fig. 9. The eutectic temperature with respect to SiE value.

ANALYSES OF SOLIDIFICATION AND SOLID SHRINKAGES

A typical example depicting the contour and the sectioned view of a casting is shown in Fig. 10, where the presence of a pipe, internal porosities and surface sinks are evident. The data for the gross shrinkage (includes both solidification shrinkage and solid contraction) and solid contraction for all the alloys studied are listed in Table 3 and Table 4, respectively. The gross shrinkage for the 1.0%C-1.0%Si alloys with different Ni and Co combinations are shown in Fig. 11(a) for FG irons and Fig. 11(b) for SG irons. The gross shrinkage is lower for FG irons (7.35% ~ 9.73%) than for SG irons (9.07% ~ 11.17%), with a difference of some 1.5%. Further, if the solid contraction was excluded and only the solidification shrinkage was considered, a similar trend was obtained, namely, (2.91% ~ 5.2%) for FG irons and (4.51% ~ 6.48%) for SG irons, and again with a

difference of some 1.5%, Fig. 12. Further analysis indicated that the gross shrinkage decreases as the Co content increases from 0 to 6% at a constant NiE, with a 0.35% reduction in solidification shrinkage for each 1% Co substitution for an equivalent amount of Ni. Based upon the results obtained herein, the amount of the solidification shrinkage of 3 ~ 5% can be adopted for FG irons that contain 1.0%C and 1.0%Si, while an additional 1.5% should be added for ductile irons of similar compositions.



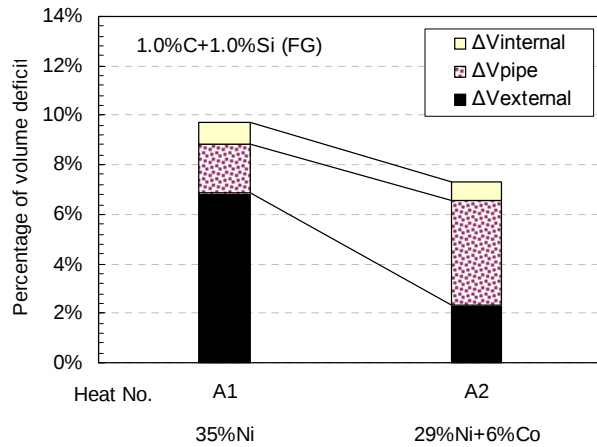
Fig. 10. A sectional view of a typical solidification shrinkage test casting.

Table 3. Results of Gross Shrinkage ($V_{\text{external}} + V_{\text{pipe}} + V_{\text{internal}}$) of All Alloys Studied

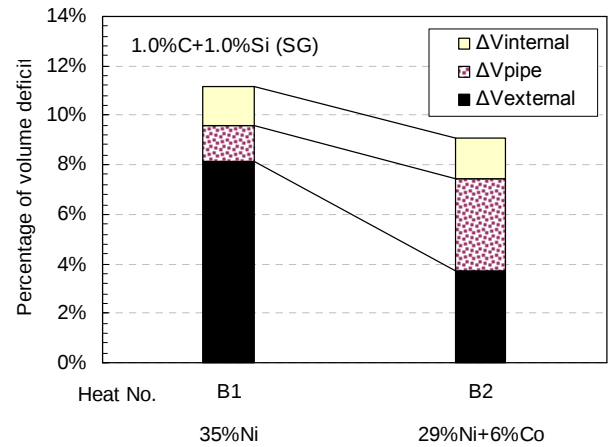
Heat No.	Pattern measurements			Casting measurements			Calculated results							
	W_i	V_i	D_i	W_c	V_{c1}	V_{c2}	$\Delta V_{\text{external}}$		ΔV_{pipe}		$\Delta V_{\text{internal}}$		ΔV_{gross}	
	g	cm ³	g/cm ³	g	cm ³	cm ³	cm ³	%	cm ³	%	cm ³	%	cm ³	%
A1	4378	564	7.77	3953	525	514	38.7	6.9	11.0	2.0	5.1	0.9	54.8	9.7
A2	4390	564	7.78	4068	551	527	13.0	2.3	24.0	4.3	4.4	0.8	41.5	7.4
A3	4241	564	7.52	3948	543	528	21.0	3.7	15.0	2.7	3.0	0.5	39.0	6.9
A4	4303	546	7.63	3992	543	527	21.0	3.7	16.0	2.8	4.0	0.7	41.0	7.3
B1	4372	564	7.77	3878	517	508	45.2	8.1	8.4	1.5	8.8	1.6	62.9	11.2
B2	4416	564	7.83	4016	543	522	21.0	3.7	21.0	3.7	9.1	1.6	51.1	9.1
B3	4235	564	7.51	3861	542	518	23.7	4.2	16.2	2.9	3.8	0.7	40.7	7.8
B4	4224	564	7.49	3890	544	523	21.5	3.8	18.3	3.3	3.6	0.6	40.1	7.7

Table 4. Estimations of Solid Contraction

Original volume: 553 cm ³			Height	Top end		Bottom end		Contour volume	Solid contraction	
Heat No.	T_{E2}	Expan. Coeff.	H	L_{top}	W_{top}	L_{bottom}	W_{bottom}	V_{contour}	$\Delta V_{\text{contour}}$	
	°C	cm/cm							cm ³	%
A1	1180	0.01533	11.39	9.98	4.72	9.84	4.64	527.9	25.1	4.53
A2	1170	0.01501	11.40	9.98	4.72	9.84	4.64	528.4	24.6	4.44
A3	1227	0.01797	11.36	9.95	4.70	9.81	4.63	523.6	29.4	5.30
A4	1226	0.01666	11.38	9.96	4.71	9.82	4.63	525.7	27.3	4.91
B1	1182	0.01589	11.39	9.97	4.71	9.83	4.64	527.0	26.0	4.69
B2	1170	0.01543	11.39	9.97	4.72	9.84	4.64	527.7	25.3	4.56
B3	1217	0.01669	11.38	9.96	4.71	9.82	4.63	525.7	27.3	4.91
B4	1195	0.01787	11.36	9.95	4.70	9.81	4.63	523.9	29.1	5.27

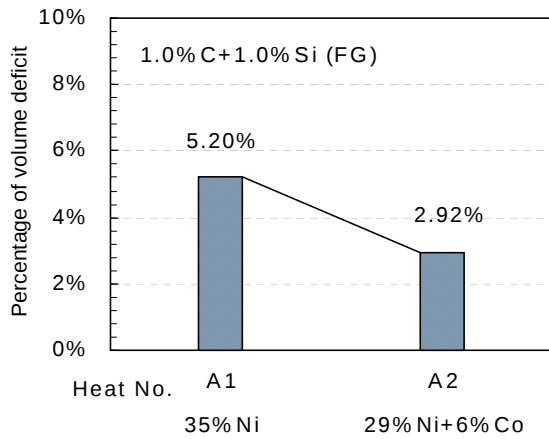


11(a) FG irons

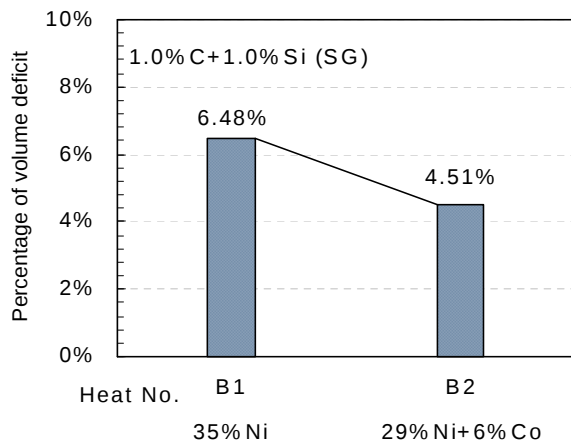


11(b) SG irons

Fig. 11. A comparison of the gross shrinkage of irons (1%C+1%Si) with different combinations of Ni and Co.



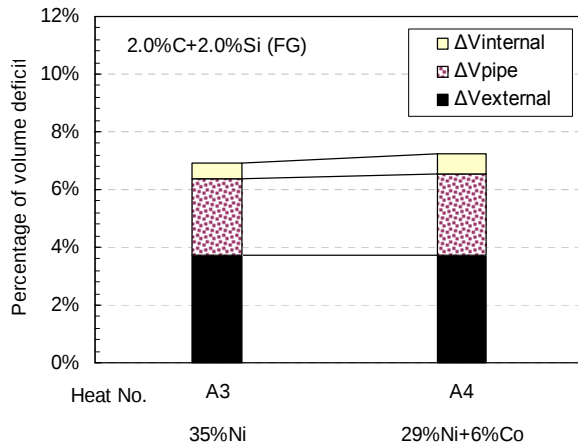
12(a) FG irons



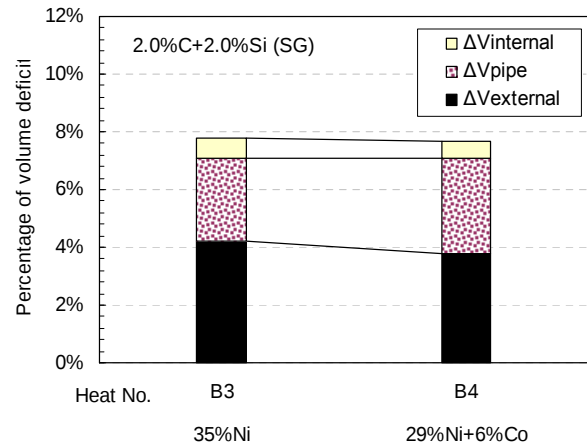
12(b) SG irons

Fig. 12. A comparison of the solidification shrinkage of irons (1%C+1%Si) with different combinations of Ni and Co.

The gross shrinkage (both solidification shrinkage and solid contraction) for the 2.0%C-2.0%Si alloys with different Ni and Co combinations are shown in Fig. 13(a) for FG irons and Fig. 13(b) for SG irons. Noting that the differences in gross shrinkage between FG irons and SG irons are around 0.5% ~ 0.8%. However, the gross shrinkages remain more or less unchanged for both FG irons (6.9% ~ 7.3%) and SG irons (7.7% ~ 7.8%) as the Co content increases from 0 to 6% at a constant NiE. Furthermore, if the solid contraction was excluded and only the solidification shrinkage was considered, a similar trend was obtained, (1.6% ~ 2.4%) for FG irons and (2.4% ~ 2.9%) for SG irons, with again a difference of 0.5% ~ 0.8 %, Fig. 14. It is apparent that less shrinkage for 2.0%C-2.0%Si alloys was obtained when compared with 1.0%C-1.0%Si alloys.

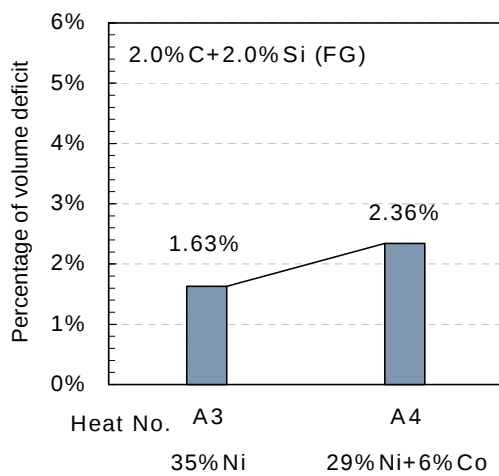


13(a) FG irons

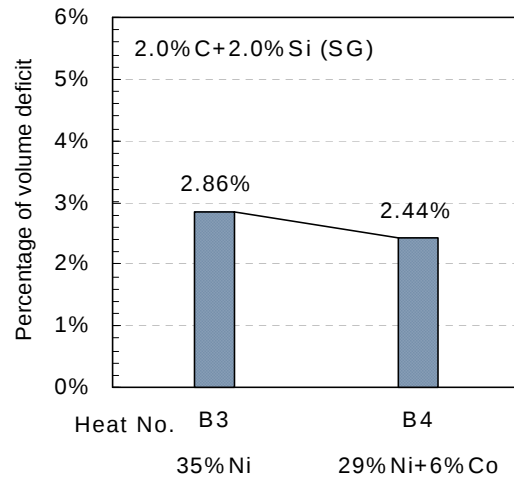


13(b) SG irons

Fig. 13. A comparison of the gross shrinkage of irons (2%C+2%Si) with different combinations of Ni and Co.



14(a) FG irons



14(b) SG irons

Fig. 14. A comparison of the solidification shrinkage of irons (2%C+2% Si) with different combinations of Ni and Co.

RISER DESIGN

The data needed for the riser design include percent solidification shrinkage of the alloys, casting volume, casting modulus and the ratio between diameter and height of the pipe section in the riser, which are listed in Table 5 for the alloys studied. Based upon the data in Table 5, the theoretical optimal riser sizes for each alloy were calculated and are presented also in Table 5. Based on the calculated optimal riser sizes, a series of various riser sizes, including both smaller and larger than the calculated optimal values, were selected for further experimental verification in order to attain the actual optimal riser sizes. The experimental designs are presented in Table 6 for alloys containing 1%C-1%Si-Ni-Co, and Table 7 for alloys containing 2%C-2%Si-Ni-Co.

Table 5. Data for Riser Design and the Optimal Riser Dimensions for Various Alloys by Calculation

Alloy	Casting Volume, V _c	Solidification Shrinkage, b	Casting modulus, M _C	Optimal Riser Size(Calculated)	
				D _R	H _R
1%C-1%Si-35%Ni FG iron	553cm ³	5.2%	1.26cm	7.3cm	6.9cm
1%C-1%Si-29%Ni-6%Co FG iron	553cm ³	2.9%	1.26cm	6.9cm	5.7cm
1%C-1%Si-35%Ni SG iron	553cm ³	6.5%	1.26cm	7.5cm	7.4cm
1%C-1%Si-29%Ni-6%Co SG iron	553cm ³	4.5%	1.26cm	7.2cm	6.6cm
2%C-2%Si-35%Ni FG iron	553cm ³	1.6%	1.26cm	6.1cm	4.7cm
2%C-2%Si-29%Ni-6%Co FG iron	553cm ³	2.4%	1.26cm	6.8cm	5.3cm
2%C-2%Si-35%Ni SG iron	553cm ³	2.9%	1.26cm	6.9cm	5.7cm
2%C-2%Si-29%Ni-6%Co SG iron	553cm ³	2.4%	1.26cm	6.8cm	5.3cm

Note : Assume H_p = 3D_p

Table 6. Experimental Design of Risers for Alloys Containing 1%C-1%Si-Ni-Co

Heat No.	Casting	Riser (mm)	Riser neck (mm)	M _R (mm)	M _R / M _C
A1	A11	D=55 , H=55	D=33 , H=10	11	0.87
	A12	D=60 , H=60	D=36 , H=10	12	0.95
	A13	D=65 , H=65	D=39 , H=10	13	1.03
	A14	D=70 , H=70	D=42 , H=10	14	1.11
	A15	D=80 , H=80	D=40 , H=10	16	1.27
	A16	D=90 , H=90	D=45 , H=10	18	1.43
A2	A21	D=55 , H=55	D=33 , H=10	11	0.87
	A22	D=60 , H=60	D=36 , H=10	12	0.95
	A23	D=65 , H=65	D=39 , H=10	13	1.03
	A24	D=70 , H=70	D=42 , H=10	14	1.11
	A25	D=80 , H=80	D=40 , H=10	16	1.27
	A26	D=90 , H=90	D=45 , H=10	18	1.43
B1	B11	D=55 , H=55	D=33 , H=10	11	0.87
	B12	D=60 , H=60	D=36 , H=10	12	0.95
	B13	D=65 , H=65	D=39 , H=10	13	1.03
	B14	D=70 , H=70	D=42 , H=10	14	1.11
	B15	D=80 , H=80	D=40 , H=10	16	1.27
	B16	D=90 , H=90	D=45 , H=10	18	1.43
B2	B21	D=55 , H=55	D=33 , H=10	11	0.87
	B22	D=60 , H=60	D=36 , H=10	12	0.95
	B23	D=65 , H=65	D=39 , H=10	13	1.03
	B24	D=70 , H=70	D=42 , H=10	14	1.11
	B25	D=80 , H=80	D=40 , H=10	16	1.27
	B26	D=90 , H=90	D=45 , H=10	18	1.43

Table 7. Experimental Design of Risers for Alloys Containing 2%C-2%Si-Ni-Co

Heat No.	Casting.	Riser (mm)	Riser neck(mm)	M _R (mm)	M _R / M _C
A3	A31	D=30 , H=30	D=20 , H=10	6	0.48
	A32	D=50 , H=50	D=20 , H=10	10	0.79
	A33	D=60 , H=60	D=36 , H=10	12	0.95
	A34	D=70 , H=70	D=42 , H=10	14	1.11
	A35	D=80 , H=80	D=40 , H=10	16	1.27
A4	A41	D=30 , H=30	D=20 , H=10	6	0.48
	A42	D=50 , H=50	D=20 , H=10	10	0.79
	A43	D=60 , H=60	D=36 , H=10	12	0.95
	A44	D=70 , H=70	D=42 , H=10	14	1.11
	A45	D=80 , H=80	D=40 , H=10	16	1.27
B3	B31	D=30 , H=30	D=20 , H=10	6	0.48
	B32	D=50 , H=50	D=20 , H=10	10	0.79
	B33	D=60 , H=60	D=36 , H=10	12	0.95
	B34	D=70 , H=70	D=42 , H=10	14	1.11
	B35	D=80 , H=80	D=40 , H=10	16	1.27
	B36	D=90 , H=90	D=45 , H=10	18	1.43
B4	B41	D=30 , H=30	D=20 , H=10	6	0.48
	B42	D=50 , H=50	D=20 , H=10	10	0.79
	B43	D=60 , H=60	D=36 , H=10	12	0.95
	B44	D=70 , H=70	D=42 , H=10	14	1.11
	B45	D=80 , H=80	D=40 , H=10	16	1.27

1.0%C-1.0%Si-Ni-Co LTE Cast Irons

For 1.0%C-1.0%Si-35%Ni FG irons, for the range of the riser diameter (also the riser height) studied, 55mm ~ 90mm, the experimental results that are shown in Fig. 15 indicate that when a 55mm-diameter riser (A11) was employed, obvious macro-shrinkage porosity in the casting just under the riser neck and also a clear pipe inside the riser which extended to the riser neck can be observed, indicating an inadequate riser design. When the riser diameter was increased to 70mm (A14), shrinkage porosity can still be observed in the casting. However, when the riser diameter was further increased to 80mm (A15) and above, sound castings without any trace of porosity were obtained.

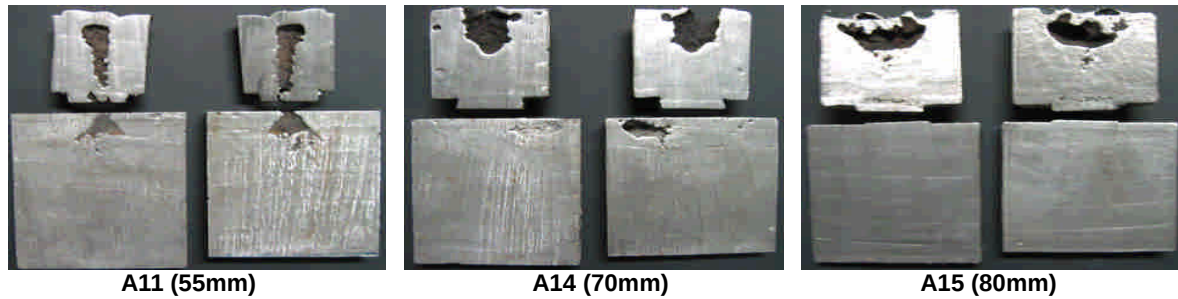


Fig. 15. Sectional views of risers and castings for alloy A1 (1.0%C+1.0%Si+35%Ni FG irons).

For 1.0%C-1.0%Si-29%Ni-6%Co FG irons, a similar trend of reducing casting porosity with a gradual increase of riser diameter with that of 1.0%C-1.0%Si-35%Ni FG irons was obtained (Fig. 16). However, a sound casting can be achieved with a riser diameter of only 65mm (A23), implying that somewhat less risering is required for LTE FG irons when part of Ni is replaced with Co. The results are in total agreement with the measurements of solidification shrinkage presented in the previous section where less shrinkage was obtained for Co-containing (1%C-1%Si-29%Ni-6%Co) irons.

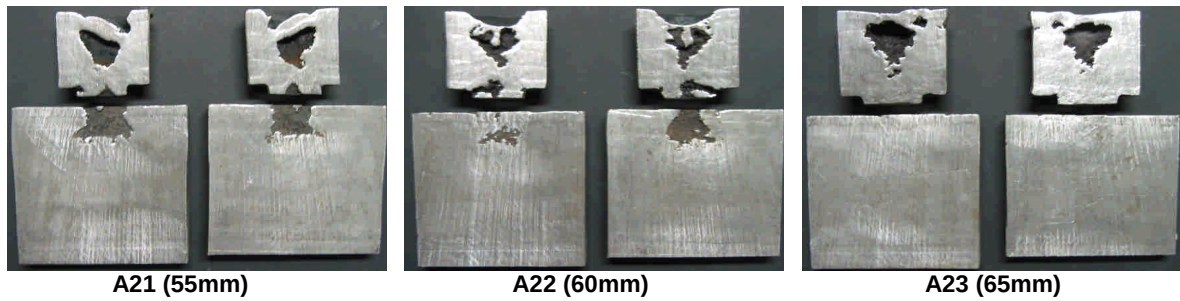


Fig. 16. Sectional views of risers and castings for alloy A2 (1.0%C+1.0%Si+29%Ni+6%Co FG irons).

For 1.0%C-1.0%Si-35%Ni SG irons, the results that are shown in Fig. 17 indicate that the shrinkage porosity can be totally eliminated only when the riser diameter was raised to 90mm (B16). Fig. 18 illustrates the experimental results for 1.0%C-1.0%Si-29%Ni-6%Co SG irons, where sound castings can be obtained when a riser diameter of 80mm (B25) was employed. As in LTE FG irons, less risering is required for 1.0%C-1.0%Si-29%Ni-6%Co SG irons than for 1.0%C-1.0%Si-35%Ni SG irons when both results of Fig. 17 and Fig. 18 are compared.

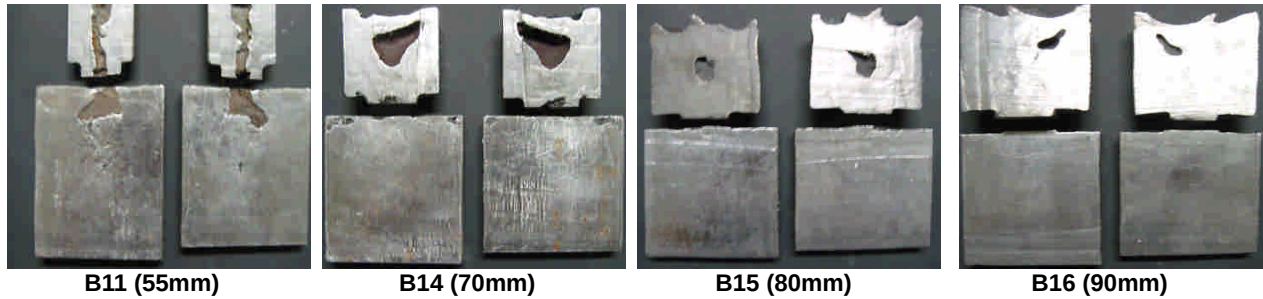


Fig. 17 Sectional views of risers and castings for alloy B1 (1.0%C+1.0%Si+35%Ni SG irons).

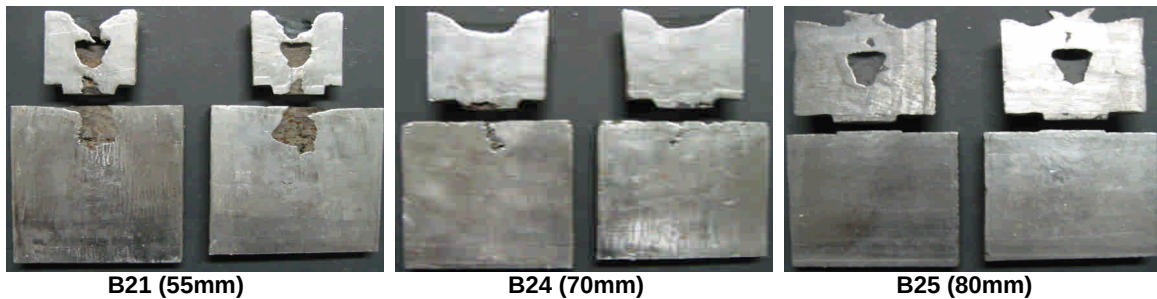


Fig. 18. Sectional views of risers and castings for alloy B2 (1.0%C+1.0%Si+29%Ni+6.0%Co SG irons).

2.0%C-2.0%Si-Ni-Co LTE Cast Irons

Fig. 19 shows the sectional views of castings with various riser sizes for 2.0%C-2.0%Si-35%Ni FG irons. When a 30mm-diameter riser (A31) was used, not only the whole riser was almost consumed, but also the casting exhibited serious shrinkage porosity at the upper central region of the casting, indicating a substantial under-design of the riser. When the riser diameter was increased to 60mm (A33), a significant pipe in the riser was observed, which extended into the riser neck and also the upper central portion of the casting, indicating still an insufficient riser design. Nevertheless, a sound casting was obtained when the riser diameter was increased to 80mm (A35). For 2.0%C-2.0%Si-29%Ni-6%Co FG irons, similar results were obtained as in 2.0%C-2.0%Si-35%Ni FG irons, with the optimum riser diameter of being 80mm (Fig. 20).

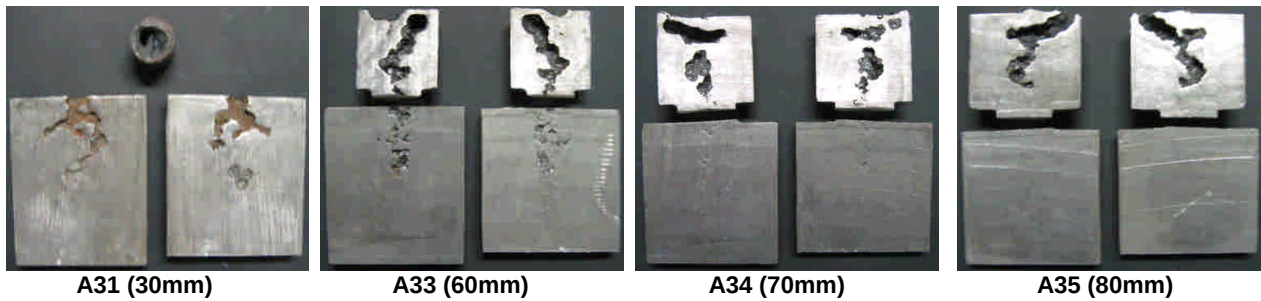


Fig. 19. Sectional views of risers and castings for alloy A3 (2.0%C+2.0%Si+35%Ni FG irons).

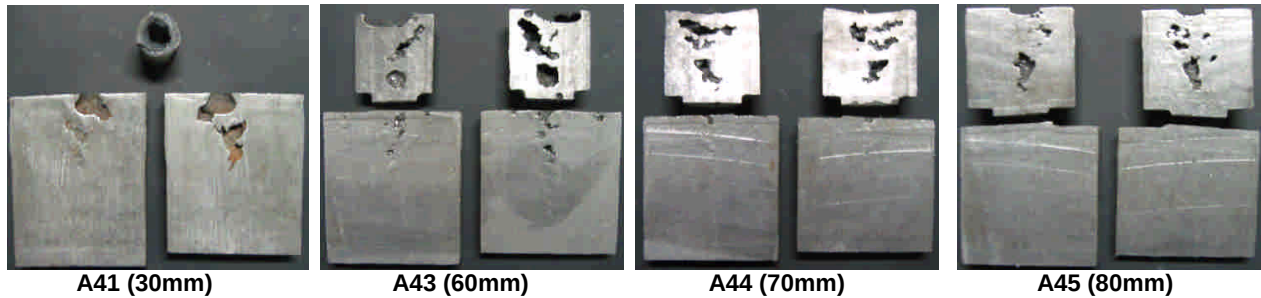


Fig. 20. Sectional views of risers and castings for alloy A4 (2.0%C+2.0%Si+29%Ni+6%Co FG irons).

The results for both 2.0%C-2.0%Si-35%Ni and 2.0%C-2.0%Si-29%Ni-6%Co SG irons that are shown in Fig. 21 and Fig. 22, respectively, exhibit similar pattern, where scattered shrinkage porosity can still be detected when the riser diameter was increased to 80mm (A45). It is then reasonable to expect that a riser diameter of around 90mm should be sufficient to achieve sound castings. For 2.0%C-2.0%Si alloys, the substitution of part of Co for Ni did not exhibit any benefit in risering when compared with alloys having lower C and Si contents. Furthermore, within the ranges of C and Si studied, increasing both elements also did not show any expected benefit in risering.

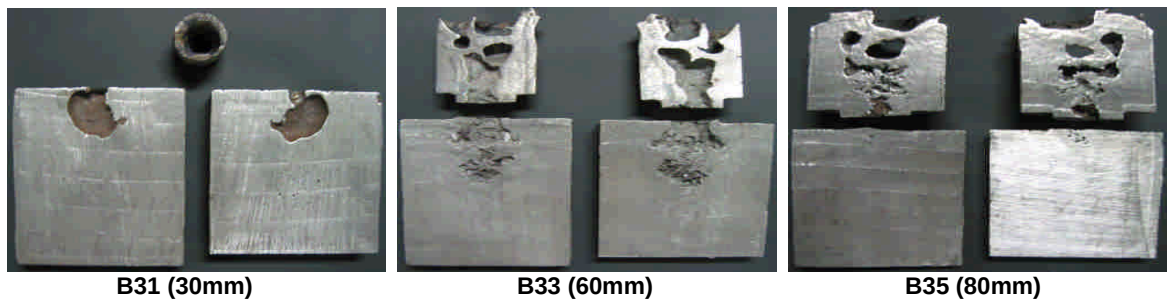


Fig. 21. Sectional views of risers and castings for alloy B3 (2.0%C+2.0%Si+35%Ni SG irons).

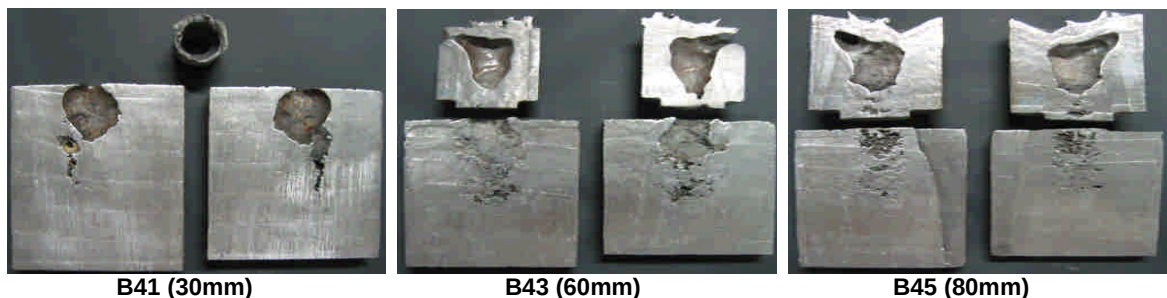


Fig. 22. Sectional views of risers and castings for alloy B4 (1.0%C+1.0%Si+29%Ni+6.0%Co SG irons).

Table 8 summarizes the optimal ratios of the rise modulus (M_R) to the casting modulus (M_C) for achieving sound castings for various alloys, together with the data of percent solidification shrinkage and the optimal riser diameter.

Table 8. Optimal Ratios of Riser Modulus to Casting Modulus for Achieving Sound Casting for Various Alloys Together With the Data of Percent Solidification Shrinkage and Optimal Riser Diameter

Alloy	Solidification Shrinkage, b	Optimal riser Diameter	Optimal M_R/M_C
1%C-1%Si-35%Ni FG iron	5.2%	80mm	1.27
1%C-1%Si-29%Ni-6%Co FG iron	2.9%	65mm	1.03
1%C-1%Si-35%Ni SG iron	6.5%	90mm	1.43
1%C-1%Si-29%Ni-6%Co SG Iron	4.5%	80mm	1.27
2%C-2%Si-35%Ni FG iron	1.6%	80mm	1.27
2%C-2%Si-29%Ni-6%Co FG iron	2.4%	80mm	1.27
2%C-2%Si-35%Ni SG iron	2.9%	~ 90mm	~ 1.43
2%C-2%Si-29%Ni-6%Co SG iron	2.4%	~ 90mm	~ 1.43

Effects of Insulating Sleeve and/or Exothermic Compounds on Riser

In order to realize the effectiveness of employing insulating sleeves and/or exothermic compounds on risering, Alloys A1, A3, B1 and B3 were selected for investigation. However, it has to be noted that, due to the size standardization of the commercially supplied insulating sleeves, only limited variation in sleeve diameter are available. The experimental design is shown in Table 9.

Table 9. Experimental Design of Risers Incorporating With Insulating Sleeve and/or Exothermic Compounds

Riser condition	Heat No.	Casting	Riser size(mm)
Riser with insulating sleeve	A1	A1-I	D=50 , H=50
		A1-II	D=60 , H=60
		A1-III	D=70 , H=70
	A3	A3-I	D=50 , H=50
		A3-II	D=60 , H=60
		A3-III	D=70 , H=70
	B1	B1-I	D=50 , H=50
		B1-II	D=60 , H=60
		B1-III	D=70 , H=70
	B3	B3-I	D=60 , H=60
		B3-II	D=70 , H=70
		B3-III	D=80 , H=80
Riser with insulating sleeve & exothermic compounds	A1	A1-IV	D=50 , H=30
	A3	A3-IV	D=50 , H=30

For Alloy A1 (1.0%C-1.0%Si-35%Ni FG irons), when an insulating sleeve was used, a riser with a 50mm diameter (A1-I) has been found sufficient for attaining a sound casting (Fig. 23), a reduction of some 76% in riser volume was obtained when compared with the case without employing insulating sleeve, where a riser diameter of 80mm is required. Furthermore, the required riser size can be further reduced to D=50mm & H=30mm (A1-IV) when both an insulating sleeve and exothermic compounds were employed, with a reduction of riser volume of over 85%. For Alloy A3 (2.0%C-2.0%Si-35%Ni FG irons), sound castings can be achieved with a riser diameter of 60mm (A3-II) when employing an insulating sleeve alone, and with a riser of D=50mm & H=30mm (A3-IV) when employing both an insulating sleeve and exothermic compounds (Fig. 24), corresponding to 58% and over 85% reduction in riser volume, respectively, when compared with the case without employing insulating sleeve and exothermic compounds (80mm diameter). Similar results were obtained for Alloys B1 and B3. Table 10 and Fig. 25 summarize the percent reduction in riser volume by employing insulating sleeve and/or exothermic compounds.

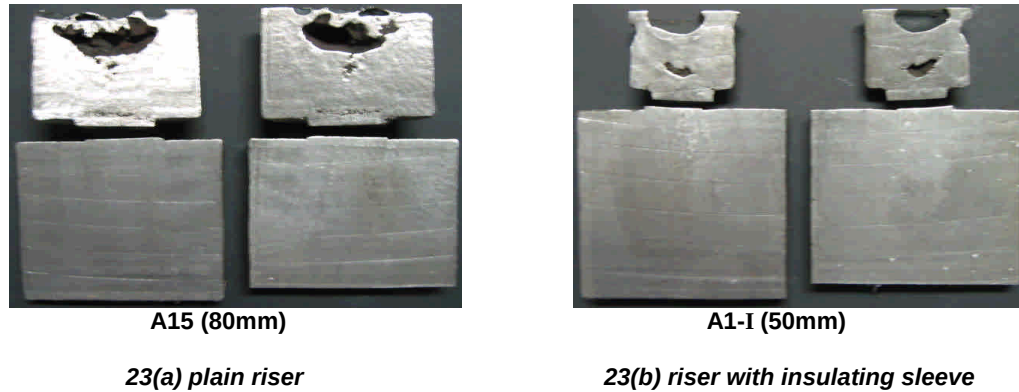


Fig.23. Sectional views of risers and castings for alloy A1 (1%C+1%Si+35%Ni FG irons).

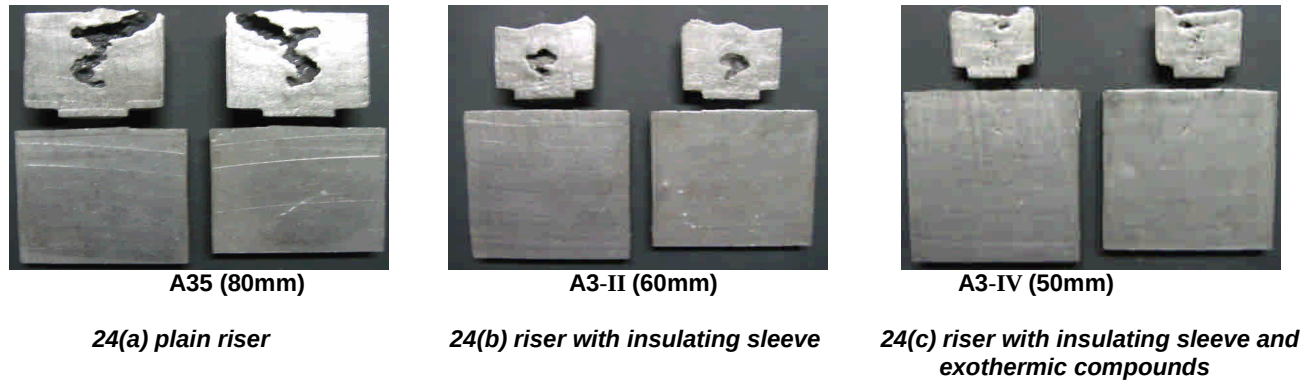


Fig. 24. Sectional views of risers and castings for alloy A3 (1%C+1%Si+35%Ni FG irons).

Table 10. Required Riser Volume and Percent Reduction in Riser Volume by Employing Insulating Sleeve and/or Exothermic Compounds

Heat No.	Plain riser	Riser with insulating sleeve	Reduction of riser volume	Riser with sleeve & exothermic compounds	Reduction of riser volume
A1	402.1 cm ³	98.6 cm ³	76 %	59 cm ³	85%
A3	402.1 cm ³	169.6 cm ³	58 %	59 cm ³	85%

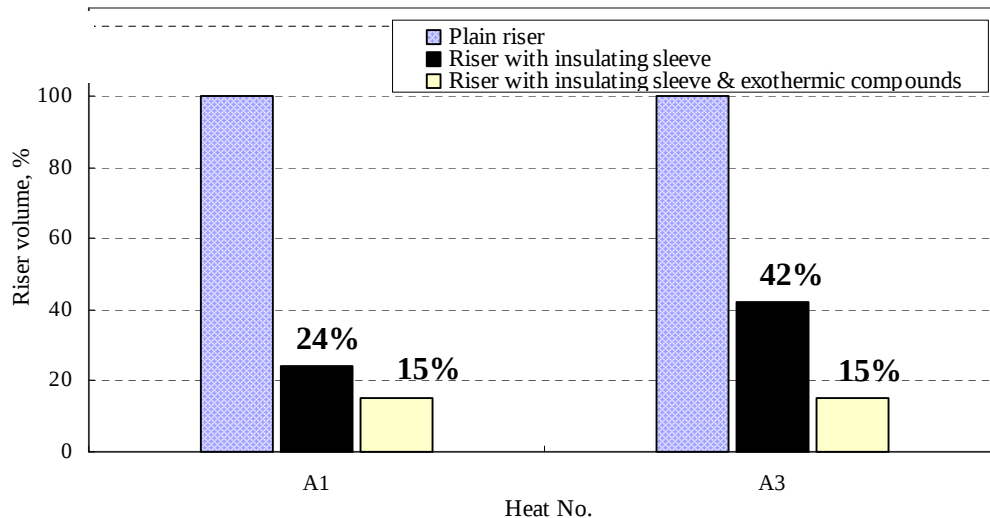


Fig. 25. Percent reduction in riser volume by employing insulating sleeve and/or exothermic compounds.

CONCLUSIONS

- (1) The liquidus temperature of the low thermal expansion cast irons is closely correlated with the CE, where $CE = \%C + 0.33x\%Si + 0.047x\%Ni - 0.0055x(\%Ni x \%Si)$. However, the eutectic temperatures are fairly correlated with the Si content or SiE value.
- (2) The measurements of alloy solidification shrinkage and solid contraction indicate that the percent solidification shrinkage for FG irons that contain 1.0%C, 1.0%Si and 36%Ni is about 5.2%, while an additional 1.5% should be added for SG irons of similar compositions. In addition, a 0.35% reduction in solidification shrinkage for each 1% Co replacement was obtained. Increasing C and Si contents reduces the amount of solidification shrinkage somewhat, and (1.6% ~ 2.4%) for FG irons and (2.4% ~ 2.9%) for SG irons, with a difference of 0.5% ~ 0.8 %, were obtained. While, no noticeable change in solidification shrinkage was obtained with substitution of Co for Ni in 2.0%C/2.0%Si irons of both FG and SG type.
- (3) The optimal riser designs for LTE cast irons with various compositions were attained. The experimental results indicate that the optimal ratios of the riser modulus (M_R) to the casting modulus (M_C) for achieving sound castings are around 1.27 and 1.43 for FG irons and SG irons, respectively. In addition, the riser requirement is substantially reduced when insulating sleeves and/or exothermic compounds were employed.

REFERENCES

- ASM Metals Handbook, 10th ed., Vol. 2., pp. 889-896 (1990).
 ASM Metals Handbook, 10th ed., Vol. 1., pp. 85-104 (1990).
 Chvorinov, N., "Theory of the Solidification of Castings," Giesserei, Vol. 27, pp. 177-225 (1940).
 Harinath, U., Narayana, K. L., Roshan, H. Md., "Studies on Volume Deficit of LM6 Alloy in Shell Molds," AFS Trans., Vol. 87, pp. 231-236 (1979).
 Heine, R. W., "Piping Riser for White Iron Castings," Malleable Founders' Society, Tech. Bull. 63-3 (1963).
 INCO, Engineering Properties of Ni-Resist Ductile Irons, International Nickel Co., Inc. (1970).
 Pan, E. N., Lin, M. S., Hong, W. C., "Machinability of Cast Irons with Low Thermal Expansion Coefficient," AFS Trans., Vol. 113 (2005).
 Pan, E. N., Lin, M. S., Lao, J. H., Liao, K. Y., "Development of Low Thermal Expansion Cast Iron," AFS Trans., Vol. 111, pp. 961-977 (2003).
 Patterson, W., Engler, S., Aluminum, Vol. 38, p. 507 (1962).
 Schelleng, R. D., "Influence of Nickel Up to 37 Per Cent and Silicon Up to 3 per Cent Eutectic Carbon Content of Cast Iron," AFS Trans., Vol. 68, pp. 301-303 (1960).
 Woldawer, R., Directional Solidification of Steel Castings, Oxford: Pergamon Press (1966).

美國鑄造學會第 111 屆鑄造會議

潘永寧

國立台灣大學機械系教授

一、 參加會議經過

美國鑄造學會所主辦之第 111 屆鑄造會議於 2007 年 5 月 15 日至 18 日在美國德州休士頓市舉行。此次會議是美國鑄造學會(American Foundry Society, AFS)與北美壓鑄協會(North American Die Casting Association, NADCA)共同主辦。整個會議議程包含：(1) 研究論文發表、(2) 小組研討會、(3) 主題演講、(4) 鑄造廠商展覽、(5) 各專業領域之餐會及正式晚宴等，整個會議內容頗為多樣化，而與會人士則來自世界各國，包含學術界、研究機構、工業界、設備材料廠商等，是一極為熱烈的會議。

在研究論文發表方面，會議議程涵蓋 14 個領域，在每一時段同時有 4 或 5 個研究領域同步進行。以下就此 14 個研究領域之內容以及所安排的場次數目（以括弧內之數字表示）作一敘述：

1. 鋁合金（6 個場次）
2. 造模方法及材料（6 個場次）
3. 鑄鐵（7 個場次）
4. 鑄造相關工程（5 個場次）
5. 鑄鋼（2 個場次）
6. 熔解及材料（3 個場次）
7. 消失模型鑄造法（3 個場次）
8. 模型及加工（1 個場次）
9. 銅合金（3 個場次）
10. 鎂合金（4 個場次）
11. 環保及安全（3 個場次）
12. 市場及管理（1 個場次）
13. 人力資源（1 個場次）
14. 壓鑄（11 個場次）

近幾年來，美國鑄造學會不僅非常重視基礎學術研究，且積極推動學術研究機構與工業界的技術交流及合作，並整合雙方面之特長及優勢以進行鑄造新技術之研發及應用，並有效解決鑄造工業界所面臨的問題。這可由會議之議程和內容明顯看出；除了個人之研究論文外，大量增加小組研討會、主題演講及美國鑄造學會所規劃、贊助之研究成果發表之場次。整個鑄造會議的進行，頗能兼顧學術研究和應用研究，且提供許多實務工程問題的探討及解決的場合，使得來自不同背景之與會人士皆能實際的參與，並提出個人的經驗及意見，而得到實質的收穫。

在研究論文方面，除壓鑄外，在研究領域逐漸呈多元化，主要包含有鑄鐵、鋁合金、鎂合金、消失模、造模方法及材料等，研究內容均針對現階段鑄造之關鍵技術進行研發探討，以期能突破及創新。

在小組研討會方面，本次大會共安排 18 個場次，所佔比例極高。此小組研討會係由美國鑄造學會所屬之 13 個技術委員會分別擬定研討主題並邀請專家學者參加。基本上每一小組研討會由主辦單位邀請 3、4 位專家學者，以來自工業界為主，針對研討主題，由各種不同技術層面各發表約 15 分鐘，隨後由所有與會者與專家學者進行討論。此類型之研討會大多以實務技術為主，大家充分溝通，經驗交流，場面非常熱烈，實是一獲益良多的研討方式。

在主題演講方面，此次大會安排有二個場次，演講題目及主講者如下：

1. 鑄鐵領域

C.Bates (AlchemCast LLC): Near Term Technical Developments for Casting Production

2. 造模方法和材料領域

D.Hoyt (Foundry Sand Technology): Identifying and Eliminating the Variables that Affect the Performance of No-bake and Cold Box Binder Systems

美國鑄造會議的一重要議程是「Hoyt Memorial Lecture」，這是美國鑄造會議的傳統，自一九三八年開始至今已近七十年，是紀念 Charles Edgar Hoyt，第一位由美國鑄造學會服務退休的傑出鑄造工程師及主管。每年被邀

請的演講者均是在鑄造領域有傑出成就，且對鑄造工程有特殊貢獻者。基本上，這個邀請也是美國鑄造學會對被邀請者終身成就的肯定，因此特頒一演講獎章，並贈與終身榮譽會員。今年的 Hoyt Memorial Lecture 是邀請 Mr.D.Apedian，其演講題目是：「The Engineering Profession in 21st Century – Educational Needs and Societal Challenges Facing the Profession」

Mr.Apedian 的演講內容主要是強調為因應國際經濟全球化之趨勢以及網際網路和電腦資訊快速發展之 21 世紀，如何提升創新能力、資訊分析及判斷能力以及國家競爭力，在工程專業教育上，提出了幾個思考方向及策略，茲扼要列出其重點：

1. 在基礎工程科學教育上，應考量現階段及未來之跨領域及多層面之科技發展。
2. 加強訓練學生之溝通能力(言語及文字)，以因應國際合作及跨領域合作之計畫。
3. 除了專業技術之外，應加強培育學生之想像力、創新能力、新思維、專注及堅忍，並加強實踐的能力。
4. 加強學生之實驗及專題實作能力，並積極建立學校與工業界之橋樑，以提供學生赴工業界實習之機會，而使得學校所學與實務技術能夠結合。

最後，大會亦安排有鑄造展覽，但因今年並非主要的展覽年（美國鑄造年會每三年舉辦一次大型展覽），因此規模稍小，但仍舊有近百家廠商參展，且展覽內容亦極為豐富。

二、 與會心得

鑄造工業界，無論是在國內或國外，以往在設備投資、生產模式及經營理念等方面，一直是比較保守的。但是最近幾年深切感受到美國鑄造工業界的明顯轉變，除了製程自動化外，電腦科技、新技術及科技整合技術等在鑄造上的應用愈來愈普遍，也逐漸形成了鑄造工業的一個新氣象。美國鑄造學會近幾年來也非常重視實務技術，使得學術研究與工業應用得到充分的結合，此不僅促使研發成果發揮其最大的功效，且大大提昇了鑄造工業的技術水準，進而提高競爭力。