Development of H13 ESR Hot Work Tool Steels Produced Using Continuous Casting Electrodes

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The characteristics of AISI H13 Electro-Slag Remelted (ESR) tool steels produced using continuous casting electrodes (H13 ESR_CC) were investigated. The internal quality, such as segregation and cleanliness, and the application features, such as high temperature wear resistance, heat checking resistance, and thermal conductivity of the H13 ESR_CC tool steels were compared with the H13 ESR steels using conventional mold casting electrodes (H13 ESR_MC). It was found that the H13 ESR_CC steels exhibited superior segregation and cleanliness to that of the H13 ESR_MC. The hardness, high temperature wear resistance, heat checking resistance, and thermal conductivity of H13 ESR _CC tool steels showed the same level of the often applied tool steels for hot stamp tooling. Such H13 ESR_CC steels have been successfully implemented to the hot stamping mold for a B pillar with patchwork blank design.

Keywords: Hot work tool steel, Electro-Slag Remelting (ESR), Continuous Casting (CC) electrode, Hot stamping, Wear resistance, Heat checking

1. INTRODUCTION

AISI H13 (American Iron and Steel Institute, AISI) hot work tool steel is one of the widely-applied hot work tool steels used in the molding industry, such as hot forging, hot extruding and die casting. For severe hot working environments, the H13 hot work tool steel often requires a further refining process before hot forging to increase its performance. The Electro-Slag Remelting (ESR) process is one of the most accepted refining processes. To carry out the ESR process, a tool steel electrode is the prerequisite and the key property determining factor for hot work tool steel. Conventionally, the H13 ESR steel electrode is prepared by bottom-pouring mold-casting ingots melted by Electric Arc Furnace (EAF). Before ESR processing, the top and bottom segments of each Mold-Casting (MC) ingot has to be trimmed to avoid any resulting defects, thus causing a lowering of the yield. In order to increase the yield and keep a more stable electrode condition, a Continuous Casting (CC) electrode is proposed in this study. The segregation and cleanliness of the H13 ESR steel using a CC electrode (hereinafter termed as H13 ESR_CC) was compared with the H13 ESR steel melted by conventional mold casting electrode (hereinafter termed as H13 ESR_MC). Recently, the hot stamping process has attracted a lot of interest from the automobile industries due to the weight-saving issue(1). To meet the requirement of hot stamping molding, the mechanical properties, and application features, such as high temperature wear resistance, heat checking resistance, and thermal conductivity, of such H13 ESR _CC steel were also evaluated and compared with the often suggested hot work tool steels for hot stamping.

2. EXPERIMENTAL METHOD

2.1 Materials

The CC bloom is melted using an EAF and a vertical and bending-type caster with a cross section of 200mm x 480mm. To prevent the occurrence of thermal and transformation cracking and distortion, a slow cooling and special lay-down process was proposed after on-line cutting. Two pieces of CC blooms were assembly welded together to become an electrode for a 5t IG-ESR furnace, as illustrated in Fig.1. For comparison, a conventional mold casting electrode with an average diameter of 520mm was used. Both the CC and MC electrodes were refined using a similar ESR process. Subsequently the ESR ingots were subject to hot forging and a spheroidization-annealing process. The chemical compositions of the H13 ESR_CC steel and H13 ESR _MC steel were listed in Table 1. The compositions of two AISI H13 steels made by two European tool steel makers (denoted as F H13) were also listed in Table 1 for comparison.

2.2 Internal qualities and microstructure observation

The segregation and cleanliness were evaluated according to the requirement of NADCA #207-2003(2). A JEOL JXA-8200 Electro Probe Micro Analyzer (EPMA) was used to measure the central element segregation. The microstructure was observed and evaluated followed the NADCA #207 specification.

Fig.1. The production of H13 ESR_CC tool steels: (a) CC bloom (200×480mm), (b)Auto slag feeding, (c)Electrode assembling and (d)3t ingot.

Table 1 Chemical compositions of H13 ESR steels used

(wt%)

ID	C	Si	Mn	Cr	Mo	V	P	S
H13 ESR_CC1	0.39	1.05	0.39	5.22	1.35	0.95	0.011	0.002
H13 ESR_CC1e*	0.40	1.07	0.4	5.12	1.36	0.98	0.011	0.001
H13 ESR_CC2	0.42	1.06	0.35	5.16	1.41	1.02	0.012	0.002
H13 ESR_CC2e*	0.42	1.14	0.37	5.19	1.42	1.05	0.013	0.001
H13 ESR_MC1	0.38	1.07	0.40	5.11	1.28	0.95	0.013	0.001
H13 ESR_CC2	0.38	1.03	0.38	5.09	1.27	0.97	0.014	0.001
F H13_1	0.40	1.06	0.39	5.12	1.25	0.96	0.021	0.001
F H13_2	0.40	1.16	0.35	5.08	1.42	0.96	0.009	0.001
ASTM A681 H13	0.32 ~0.45	0.80 ~1.25	0.20 ~0.60	4.75 ~5.50	1.10 ~1.75	0.80 ~1.20	≤0.030	≤0.030
NADCA #207 _premium	0.37 ~0.42	0.80 ~1.20	0.20 ~0.50	5.00 ~5.50	1.20 ~1.75	0.80 ~1.20	≤0.025	≤0.005
NADCA #207 _superior	0.37 ~0.42	0.80 ~1.20	0.20 ~0.50	5.00 ~5.50	1.20 ~1.75	0.80 ~1.20	≤0.015	≤0.003

*: The composition of CC electrodes

2.3 Heat treatment, surface treatment and hardness

All the specimens were subjected to a vacuum hardening of 1020^{o}Cx for 30min and double tempering at 560^{o}C for 1 hr to achieve a hardness higher than 52 HRC to meet the customer's hot stamping requirement. Some as-heat treated steels were further gas nitrided at 530^{o}C to obtain a white-layer free nitriding hardening layer for evaluating its effect on high temperature wear resistance.

2.4 Application properties

The high temperature wear resistance of both as-heat treated and nitrided tool steels were evaluated by a pin-on-disk type wear tester with the condition of 150N-16d-300rpm-100min at 200, and 600^{o}C, respectively. A self-designed thermal fatigue tester was applied to evaluate the heat checking resistance (heating to 690~720^{o}C within 2.5s and cooling to lower than 50^{o}C within 2.5s for 2000cycles). The thermal conductivity was measured by using a hot disc method.

3. RESULTS AND DISCUSSION

3.1 Suitability

3.1.1 Chemical compositions

As listed in Table 1, the compositions of ESR H13 steel made using CC electrodes can meet both ASTM A681 and NADCA #207_superior specifications, the same as that made using MC electrodes, showing the same level as the H13 steels made by other tool steel makers. This suggests that the idea to use the CC electrode is practicable. Since the product yield ratio of the ESR H13 made using CC electrodes (around 93%) is significantly higher than that of the ESR H13 made using MC electrodes (around 88%), such a production route exhibits an economical benefit .

3.1.2 Segregation and cleanliness

Figure 2 shows the micro segregation extent of H13 ESR_CC, H13 ESR_MC and F H13 steels, respectively. It was found that the segregation extent of H13 ESR_CC was significantly smaller than that of H13 ESR_MC, and is similar to that of H13 steels made by other tool steel makers (F H13). This is further known from the Cr segregation index measured using EPMA in Fig.3. The cleanliness of H13 ESR_CC, H13 ESR_MC and F H13 steels were listed in Table 2. It was found that the inclusion content of H13 ESR_CC steel is much better than that of H13 ESR_MC steel, and was slightly worse than that of F H13 steels.

3.1.3 Short summary

The adaption of continuous casting electrode for the H13 ESR refining process is a promising process in terms of composition, micro segregation, cleanliness, and product yield ratio.

3.2 Applicability to hot stamping

Hot stamping is an attractive technology to the automobile industries due to the weight-saving consideration. During the hot stamping process, the steel sheet with anti-oxidation coating or naked steel sheet is heated to around 900 ^{o}C, then subjected to a hot pressing to form it into various shapes with in-die cooling to obtain high strength. That is to say that hot stamping is

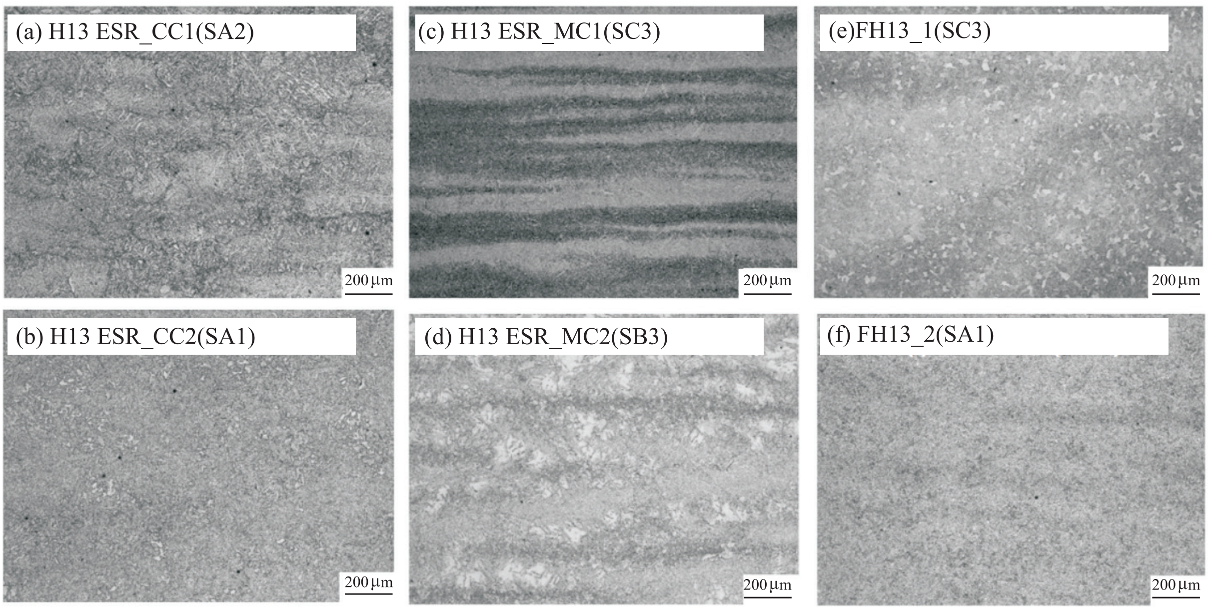

Fig.2. The micro segregation of H13 tool steels used. (NADCA #207 standard)

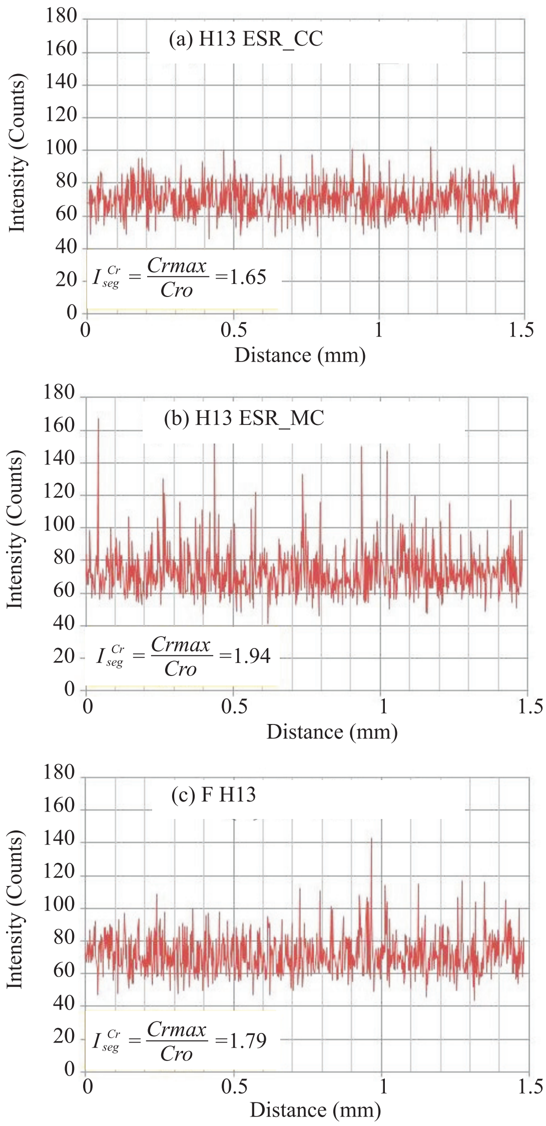

Fig.3. The Cr line scan segregation of H13 tool steels used.

a non-isothermal forming process for sheet metals, where forming and quenching takes place in the same forming step[1]. To secure the strength of the sheet steel and sustain the life of the mold, the hot stamping tool steel requires the combined properties of good wear resistance at elevated temperatures, excellent thermal conductivity, and high anti heat checking resistance, etc.[3,4]. To evaluate the applicability of the ESR H13_CC steel, the room temperature hardness and various high temperature properties were measured and compared with the often suggested H13 modified hot work tool steels obtained from the market place. The main compositions were listed in Table 3. The room temperature hardness of the evaluated tool steels were also listed in Table 3. It can be found that the room temperature hardness of all the hot work steels used after quenching and double tempering can meet the customer's required minimum value of 52 HRC.

3.2.1 High temperature wear resistance

Figure 4 shows the wear loss of as-heat treated and gas nitrided tool steels. It can be found that the as-heat treated and nitrided H13 ESR_CC steels exhibited the best high temperature wear resistance, even the room temperature hardness is not the highest one. It is well-accepted that the wear resistance of as-heat treated tool steels is related to the characteristics of carbides (type, volume and size) rather than directly linked to its hardness[5]. The hardness of various carbides is listed in Table 4. It can be found that the sequentially decreasing order of carbides is VC> Cr_7C_3> Mo_6C> $Cr_{23}C_6$> Fe_3C [6]. By using SEM-EDS, the carbide types of the tool steels investigated are listed in Table 4 too. Since the H13 ESR_CC steel contains the highest V content, the best wear resistance might be related to its higher volume of VC carbides. It is also well-known that the nitriding surface heat treatment can significantly increase the

Table 2 Cleanliness of H13 tool steels used (ASTM E45 Method A)

ID	Type A (Sulfide)		Type B (Alumina)		Type C (Silicate)		Type D (Globular Oxide)	
	Thin	Heavy	Thin	Heavy	Thin	Heavy	Thin	Heavy
H13 ESR_CC1	0.0	0.0	0.0	0.0	0.0	0.0	1.5	1.0
H13 ESR_CC2	0.0	0.0	0.0	0.0	0.0	0.0	1.5	1.0
H13 ESR_MC1	0.0	0.0	1.5	1.5	0.0	0.0	1.5	1.5
H13 ESR_MC2	0.0	0.0	0.0	0.0	0.0	0.0	0.5	0.5
F H13_1	0.0	0.0	0.0	0.0	0.0	0.0	1.0	0.5
F H13_2	0.0	0.0	0.0	0.0	0.0	0.0	1.0	1.0
NADCA #207 _premium	1.0	0.5	1.5	1.0	1.0	1.0	2.0	1.0
NADCA #207 _superior	0.5	0.5	1.5	1.0	0.5	0.5	1.5	1.0

Table 3 Chemical compositions of various mold steels for hot stamping

(wt%)

Mold Steel for hot stamping	C	Si	Mn	Cr	Mo	V	P	S	Q&T hard (HRC)*
H13 ESR_CC	0.39	1.05	0.39	5.22	1.35	0.97	0.011	0.002	53.8
H13 Mod._1	0.34	0.21	0.44	5.01	2.26	0.53	0.007	0.001	52.8
H13 Mod._2	0.38	0.31	0.70	2.41	2.21	0.86	0.006	0.001	53.2
H13 Mod._3	0.49	0.16	0.47	5.00	2.24	0.53	0.007	0.001	57.0

*: austenitizing at 1020°C for 30 min and double tempering at 560°C for 1 hr

Table 4 The hardness of various carbides and the carbide types of the hot work tool steels evaluated

Wear Resistance	VC 〉	Cr_7C_3 〉	Mo_6C 〉	$Cr_{23}C_6$ 〉	Fe_3C
Carbide hardness(HV)	2800	1800	1400	1200	1000

ID	Main alloying contents					Carbide type	Hardness (HRC)	Wear loss @600C (g)
	C	Cr	Mo	V	Si			
H13 ESR_CC	0.39	5.30	1.35	0.97	1.05	M C (V rich) M_6C (Fe, Mo rich) M_7C_3 (Cr rich) $M_{23}C_6$ (Cr rich)	53.8	0.0140
Mod. H13_1	0.34	5.01	2.26	0.53	0.21		52.8	0.0150
Mod. H13_2	0.38	2.41	2.21	0.86	0.30	MC (V rich) M_6C (Fe, Mo rich)	53.2	0.0177
Mod. H13_3	0.49	5.00	2.24	0.53	0.16	MC (V rich) M_6C (Fe, Mo rich) M_7C_3 (Cr rich) $M_{23}C_6$ (Cr rich)	57.0	0.0173

wear resistance of steel once the nitride-forming elements are added. The wear resistance enhanced tendency of the nitride-forming elements is Cr>> Mo> Mn~ Si(7). The higher wear resistance of nitrided H13 ESR_CC steel is thought to be attributed to its highest Cr and Mn+Si contents.

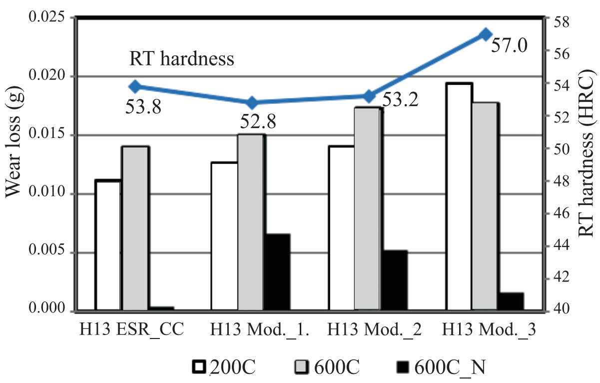

Fig.4. The wear loss of as-heat treated and gas nitrided tool steels.

3.2.2 Heat checking resistance and thermal conductivity

Figure 5 shows the surface heat checking crack pattern and cross section of cracks of various tool steels subject to 2000 thermal cycles (the surface crack area ratio and the average depth of the top 5 deepest cracks are denoted in the parentheses). It can be found that H13 ESR_CC steel exhibited a good heat checking resistance in terms of crack area and crack depth.

Figure 6 shows the thermal conductivity of various tool steels. It can be found that the H13 ESR_CC steels exhibited a lower thermal conductivity. Another study on the detrimental effect of the addition of alloying on thermal conductivity showed that the decreasing tendency is Si>Mn>Mo>Cr. The high Si content of H13 ESR_CC steel thus contributed to its lowest thermal conductivity.

3.2.3 Overall rating and practical application to hot stamping

The intrinsic properties of various tool steels for the hot stamping application are listed in Table 5. The H13 ESR

_CC steels overally rated to be a promising tool steel for hot stamping applications. Based on the above evaluation, the H13 ESR _CC steel has been used to make a hot stamping mold for a B pillar with patchwork blank design in Fig.7 for both naked and anti-oxidation coated Boron steel. To practically evaluate the applicability of H13 ESR _CC steels for hot stamping, a two cavity mold made by using H13 ESR _CC and a typical H13 ESR tool steel (ASSAB 8407), respectively, was used. After a thousand hits, both tool steels exhibit similar performance in terms of wear and heat checking of the mold and the resulting strength of the hot stamped parts.

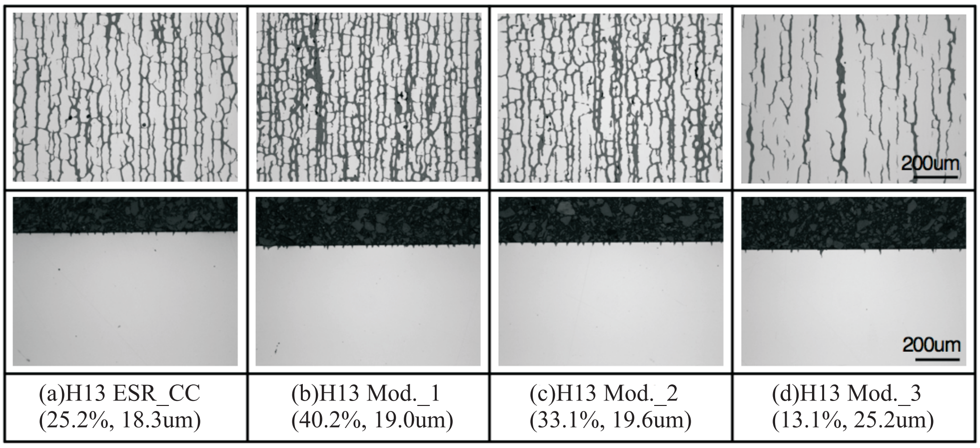

Fig.5. The surface heat checking crack pattern and cross section crack of various tool steels subject to 2000 thermal cycles. (The surface crack area ratio and the average depth of top 5 deep cracks are denoted in the parentheses)

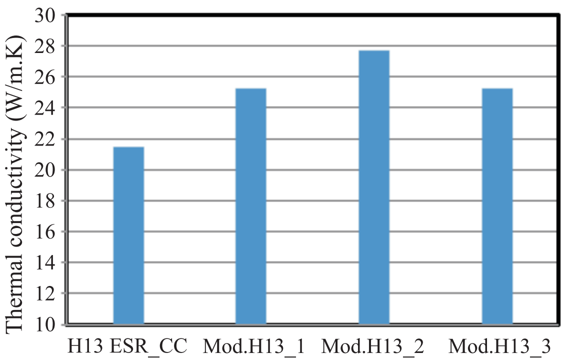

Fig.6. The thermal conductivities of various tool steels.

Fig.7. The photo of hot stamped B pillar with patchwork blank design.

Table 5 The intrinsic properties of various tool steels for the hot stamping application

ID	Q&T Hardness	High temp. wear resistance	High temp. wear resistance (nitride)	Heat checking resistance	Thermal conductivity	Overall rating
H13 ESR _CC	○	○	◎	○	Δ	○
Mod. H13_1	○	Δ	Δ	○	○	Δ
Mod. H13_2	○	X	Δ	○	◎	Δ
Mod. H13_3	◎	○	◎	Δ	○	◎

Note: ◎: best, ○: good, Δ: fair, X: poor

4. CONCLUSIONS

The microstructure, mechanical properties and application features of H13 ESR tool steels produced using CC electrodes were investigated in this study. The main findings are as follows:

(1)The compositions, micro segregation, and cleanliness of H13 ESR steels made using CC electrodes can meet NADCA #207_superior specifications, suggesting that the idea to use the CC electrodes to produce high quality H13 tool steels is practicable.

(2)The fact that the H13 ESR_CC steels exhibited better central segregation and a higher production yield than the H13 ESR steel made using a mold casting electrode demonstrates the benefits of the process of using a CC electrode.

(3)The H13 ESR_CC steel featuring excellent high temperature wear resistance, good heat checking resistance and sufficient thermal conductivity, suggests that it is suitable for hot stamping tooling. Practically, such H13 ESR _CC steel has been successfully implemented to a hot stamping mold for a B pillar with patchwork blank design.

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