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# 越窑秘色瓷匣钵装烧工艺的实验考古学研究

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**摘要:**上林湖越窑在晚唐、五代时期烧制出了釉色青灰、色泽莹润的秘色瓷,迎来了越窑瓷业的巅峰。以上林湖后司岙越窑遗址出土唐、五代秘色瓷和普通青瓷科技分析数据为基础,采用当地沉积黏土、草木灰等为主要原料开展了秘色瓷的工艺模拟实验研究,重点对比了不同类型匣钵和装烧方式对模拟烧制青瓷釉的影响。此外,通过色度分析仪及光电子能谱仪等对模拟烧制青瓷釉色度和着色物质铁的价态进行测试,探讨了瓷质匣钵口沿封釉装烧秘色青瓷的作用和机理。越窑青瓷实验考古中,对七件青瓷样品进行了光电子能谱分析,结果显示,采用瓷质匣钵口沿封釉装烧青瓷釉的 $Fe^{2+}/Fe^{3+}$ 比值为2.8,远大于普通匣钵内青瓷釉的0.57。结合考古实地调查研究,可以推断这是越窑秘色瓷呈色不同于普通青瓷的主要原因。

**关键词:**越窑;秘色瓷;模拟实验;价态

**中图分类号:** K876.3 **文献标识码:** A

## 0 引言

青釉是以铁为着色元素的传统瓷釉,越窑自东汉烧制出成熟瓷器开始,一直到宋代均以烧制的青瓷为主要产品。后司岙窑址位于浙江省慈溪市桥头镇上林湖中部的西岸边,是上林湖越窑遗址中最核心的窑址。2015年10月至2017年1月,浙江省文物考古研究所、国家文物局水下文化遗产保护中心、宁波市文物考古研究所、慈溪市文物管理委员会办公室,对后司岙窑址及包括该窑址在内的上林湖水下遗存进行了考古发掘与勘探工作,出土了包括秘色瓷在内的大量晚唐、五代时期越窑青瓷精品。此次发掘基本理清了以后司岙窑址为代表的晚唐、五代时期秘色瓷的基本面貌与生产工艺、秘色瓷窑场基本格局、唐代法门寺地宫与五代吴越国钱氏家族墓出土秘色瓷的产地问题<sup>[1]</sup>。其中对于出土秘色瓷与普通青瓷呈色差异的原因这一得到长期关注的问题,学界结合科技分析和考古发掘资料也开展了大量的研究工作,结果认为越窑秘色瓷与普通青瓷瓷釉化学组成并无明显区别,但秘色瓷釉色较普通青瓷更偏

绿<sup>[2-5]</sup>,主要原因应是秘色瓷采用了瓷质匣钵加口沿封釉的独特装烧工艺烧制<sup>[6-8]</sup>,但尚缺乏实验验证。可见,从实验考古的角度,以秘色瓷和普通青瓷科技测试分析数据为基础,采用工艺模拟实验验证瓷质匣钵口沿封釉装烧工艺是否是秘色瓷烧制的关键原因以及具体会产生什么样的影响等是十分必要的。

## 1 样品与方法

吴军明等<sup>[2]</sup>对相关瓷片进行了测试,结果显示两者瓷釉化学组成无明显区别,主要是因为秘色瓷采用瓷质匣钵口沿封釉装烧,工艺的不同导致其釉面呈色优于用普通匣钵装烧的。鉴于此,为验证瓷质匣钵口沿封釉装烧工艺是否是秘色瓷烧制的关键原因及具体会产生什么样的影响,进行了相应的工艺模拟实验。

### 1.1 釉的制备

实验采用上林湖越窑窑址周边的沉积黏土、釉果、松木灰、石灰石为原料制备一种青釉。相关原料的化学组成见表1,拟采用的青釉配方见表2,唐、五代青瓷釉化学组成见表3。使用 DECO-PBV-V-

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L-A型行星式轻型球磨机将原料混合后球磨成釉浆。球磨制度为:料:球:水=1:2.5:1.2~1.3(质量比),转速500 r/min,球磨15 min,釉浆过250目筛后储存备用。

表1 原料化学组成

Table 1 Chemical compositions of raw materials (%)

原料	质量分数									
	Na <sub>2</sub> O	MgO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	K <sub>2</sub> O	CaO	TiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	P <sub>2</sub> O <sub>5</sub>
沉积黏土	1.02	0.38	16.80	75.38	2.71	0.62	0.72	2.37	—	—
松木	0.04	5.35	7.63	34.90	7.81	38.93	0.13	1.05	2.12	2.04
釉果	1.93	0.28	68.62	20.31	4.40	3.80	0.06	0.60	—	—
石灰石	—	1.87	0.53	1.75	0.07	95.64	—	0.15	—	—

表2 釉料配方组成

Table 2 Compositions of glaze formulas (%)

编号	质量分数			
	釉果	沉积黏土	松木	石灰石
A	40	30	20	10
B	30	40	20	10

表3 唐、五代青瓷釉化学组成

Table 3 Chemical compositions of celadon glazes of the Tang and Five Dynasties (%)

编号		质量分数									
		Na <sub>2</sub> O	MgO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	K <sub>2</sub> O	CaO	TiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	MnO	P <sub>2</sub> O <sub>5</sub>
TMS	均值	0.64	3.90	12.14	64.81	1.60	13.81	0.34	1.77	0.33	0.50
	标准差	0.13	0.33	0.71	0.91	0.07	1.05	0.02	0.17	0.04	0.02
WMS	均值	0.62	3.71	11.58	64.64	1.78	14.88	0.31	1.47	0.28	0.53
	标准差	0.25	0.42	0.22	1.99	0.21	1.62	0.04	0.28	0.06	0.05
TPT	均值	1.19	3.45	11.12	65.31	1.69	14.07	0.31	1.55	0.73	0.41
	标准差	0.58	0.66	0.22	1.17	0.12	0.44	0.01	0.24	0.6	0.08
WPT	均值	0.34	3.21	11.95	65.74	1.97	13.89	0.37	1.52	0.26	0.56
	标准差	0.44	0.49	0.68	1.89	0.31	1.65	0.01	0.17	0.07	0.08

注: TMS为唐代秘色瓷; WMS为五代秘色瓷; TPT为唐代普通青瓷; WPT为五代普通青瓷。

## 1.2 胎的制备

研究表明,在釉层薄且透明的情况下,胎体颜色对釉面呈色具有一定的影响<sup>[9]</sup>。晚唐、五代时期越窑秘色瓷、普通青瓷胎体中都含有一定量的Fe<sub>2</sub>O<sub>3</sub>、TiO<sub>2</sub>,在还原气氛下使得胎体颜色呈现青灰色<sup>[10-11]</sup>。为了尽量减少胎体对釉面呈色的影响,使

釉色更接近越窑青瓷,实验使用瓷泥(台达609)、铁胎泥(含铁量高的泥料)配制一种颜色接近越窑青瓷的灰色胎体,两种泥料化学组成见表4。将瓷泥和铁泥按不同质量比配制并观察相应颜色效果(表5)后,选用灰胎(3号)作为胎体。该灰胎和秘色瓷胎的化学组成同样见表4。

表4 泥料/胎的化学组成

Table 4 Chemical compositions of mud/body materials (%)

样品	质量分数								
	Na <sub>2</sub> O	MgO	Al <sub>2</sub> O <sub>3</sub>	SiO <sub>2</sub>	K <sub>2</sub> O	CaO	TiO <sub>2</sub>	Fe <sub>2</sub> O <sub>3</sub>	
瓷泥	0.91	0.33	28.81	66.36	3.21	0.12	0.03	0.22	
铁泥	0.68	0.98	30.99	51.17	3.62	0.12	0.70	11.75	
灰胎	0.68	0.49	27.67	64.87	3.23	0.13	0.16	2.77	
唐秘色	1.02	0.55	15.87	76.43	2.97	0.63	0.80	1.75	

表 5 胎的配方组成和相应颜色效果

Table 5 Compositions of body formulas and corresponding color effects (%)

编号	质量分数		颜色效果
	瓷泥	铁泥	
1	90	10	浅白色
2	85	15	浅灰色
3(灰胎)	80	20	浅灰色
4	70	30	棕褐色

胎的制备工艺流程如图 1 所示:将瓷泥与铁泥按比例称量后放入行星式球磨机中球磨,将球磨后的泥浆烘干,粉碎后过 80 目筛,粉料造粒压制成圆饼,在电窑中经 800℃ 素烧后备用。

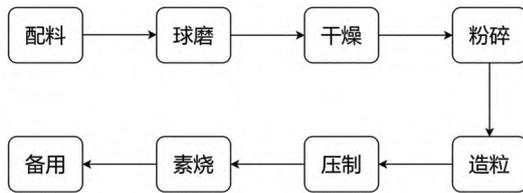


图 1 胎的制备流程

Fig. 1 Preparation process of the body

### 1.3 模拟烧制

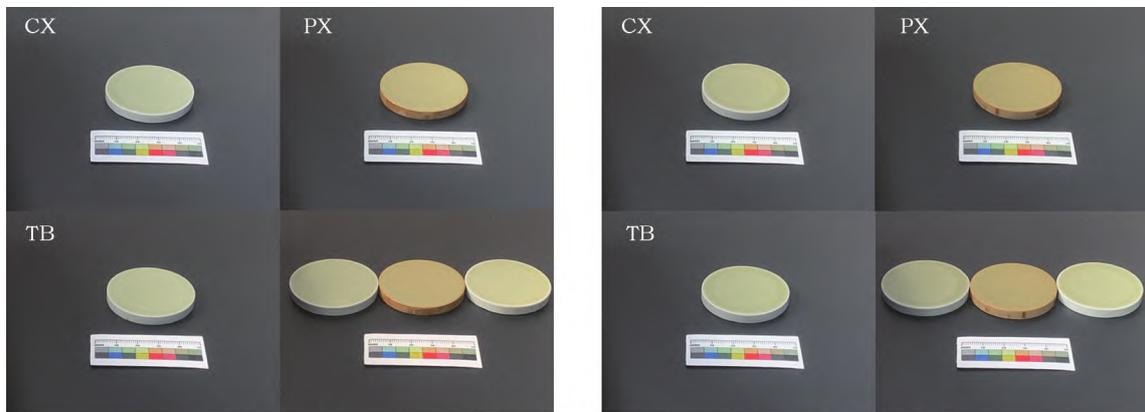
为探究不同材质匣钵及装烧方式对青瓷釉面呈色的影响,模拟实验选取表 2 中的 A、B 两组配方作为瓷釉,采用轻质耐火匣钵作为普通匣钵,使用瓷泥

制成瓷质匣钵,匣钵与匣钵盖接口处涂釉密封。在匣钵内外均放置测温环(范围 1 130 ~ 1 400℃),匣钵外还放置测温锥(锥号 102、8、9)。使用梭式燃气窑烧成,烧成阶段前期为氧化气氛,中后期为还原气氛,并进行多温度实验。实验分两次进行,由于现代气窑的烧成温度一般为 1 280℃,还原点多在 980℃ 左右,综合瓷质匣钵的烧结性能(高温下烧结,低温下未烧结),故此拟定第一次熄火温度为 1 280℃(I),第二次为 1 250℃(II)。使用瓷质匣钵(口沿封釉)、普通匣钵、普通匣钵内套烧瓷质匣钵(口沿封釉)等三种装烧方式进行模拟烧制。每种装烧方式在匣钵内放置 A、B 组配方试片各两件,烧制的青瓷试片编号字母对应如下: CX 为瓷质匣钵、PX 为普通匣钵、TB 为套钵。具体装烧形式及烧成后代表性青瓷样品如图 2 ~ 图 4 所示。



图 2 梭式燃气窑装烧

Fig. 2 Loading and firing in a shuttle gas kiln



(a) 釉料配方 A

(b) 釉料配方 B

图 3 不同装烧方式模拟烧制的青瓷样品(1 280℃)

Fig. 3 Celadon samples made by different loading and firing methods (1 280℃)

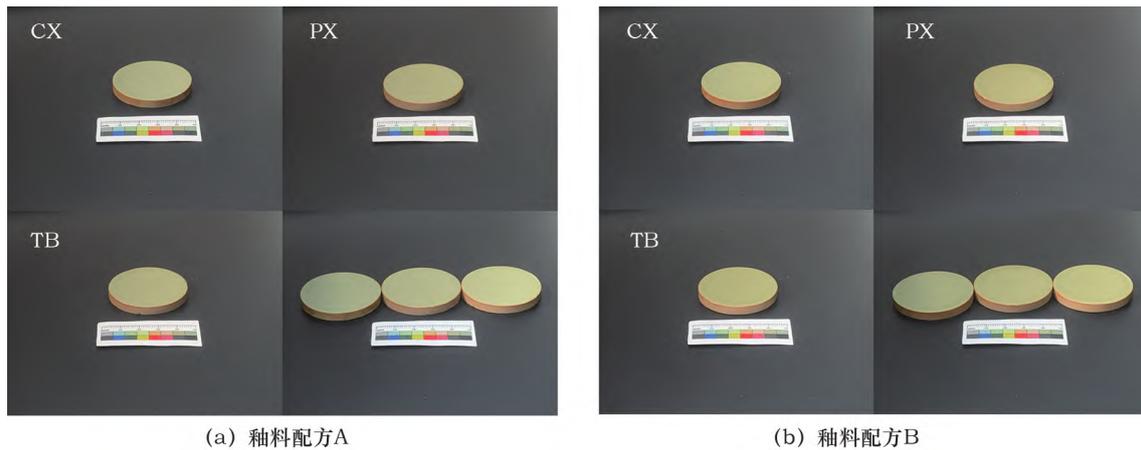


图4 不同装烧方式模拟烧制的青瓷样品(1 250℃)  
Fig. 4 Celadon samples made by different loading and firing methods (1 250℃)

#### 1.4 测试方法

釉色是青瓷釉面质量重要表现形式之一,为科学直观地对青瓷釉面的呈色进行表征,实验使用柯尼卡美能达公司型号为CM-5的分光测色计对上林湖后司岙窑址出土唐代秘色瓷(TMS)、普通青瓷(TPT)及工艺模拟实验所烧制的青瓷共14件进行了釉面色度测试。

为探究青瓷釉中铁元素价态对青瓷釉面的呈色的影响,选取上林湖后司岙窑址出土唐代秘色瓷、普通青瓷及模拟实验所得青瓷共7件,送至江西南昌指南针测试公司进行瓷釉光电子能谱测试。测试所用仪器型号为Thermo Scientific K-Alpha,参数设置:X射线源激发源为Al K $\alpha$ 射线( $h\nu = 1486.6 \text{ eV}$ ),

束斑直径 $400 \mu\text{m}$ ,分析室真空度优于 $5.0 \times 10^{-7} \text{ mBar}$ ,工作电压 $12 \text{ kV}$ ,灯丝电流 $6 \text{ mA}$ ;全谱扫描通能为 $100 \text{ eV}$ ,步长 $1 \text{ eV}$ ;窄谱扫描通能为 $50 \text{ eV}$ ,步长 $0.05 \text{ eV}$ 。测试了全谱加精细谱铁、钛、碳三个元素,窄谱默认测试其最强峰轨道。以 $C1s = 284.80 \text{ eV}$ 为结合能能量标准进行荷电校正。使用Avantage软件对测试数据中铁元素进行分峰拟合。

## 2 分析与讨论

### 2.1 釉面呈色特征分析

使用不同装烧方式模拟烧制的青瓷样品外观如图3和图4所示。14件青瓷样品的釉面色度测试结果见表6,并根据其 $a^*$ 、 $b^*$ 值绘制二维散点图(图5)。

表6 拟烧制青瓷与唐代秘色瓷、普通青瓷的釉面色度测试结果

Table 6 Glaze chromatic values of the simulation-fired celadon and Tang Dynasty *Mi'se* porcelain and ordinary celadon

编号	$L^*$	$a^*$	$b^*$	$x$	$y$
PX(A)(I)	54.16	-1.49	18.16	0.3603	0.3857
CX(A)(I)	58.09	-3.18	13.80	0.3431	0.3729
TB(A)(I)	56.76	-2.61	13.88	0.3451	0.3732
PX(B)(I)	51.04	-1.21	20.48	0.3695	0.3946
CX(B)(I)	51.51	-2.01	17.28	0.3584	0.3859
TB(B)(I)	52.98	-2.51	16.88	0.3552	0.3843
PX(A)(II)	53.91	-2.14	16.15	0.3535	0.3809
CX(A)(II)	54.61	-2.39	13.92	0.3466	0.3743
TB(A)(II)	55.87	-2.47	15.85	0.3510	0.3792
PX(B)(II)	52.37	-1.89	19.07	0.3630	0.3903
CX(B)(II)	56.09	-2.36	16.99	0.3541	0.3821
TB(B)(II)	51.21	-1.81	17.11	0.3586	0.3854
TMS	60.51	-3.79	11.09	0.3333	0.3633
TPT	53.64	0.65	15.05	0.3567	0.3733

注:(I)表示1 280℃,(II)表示1 250℃。

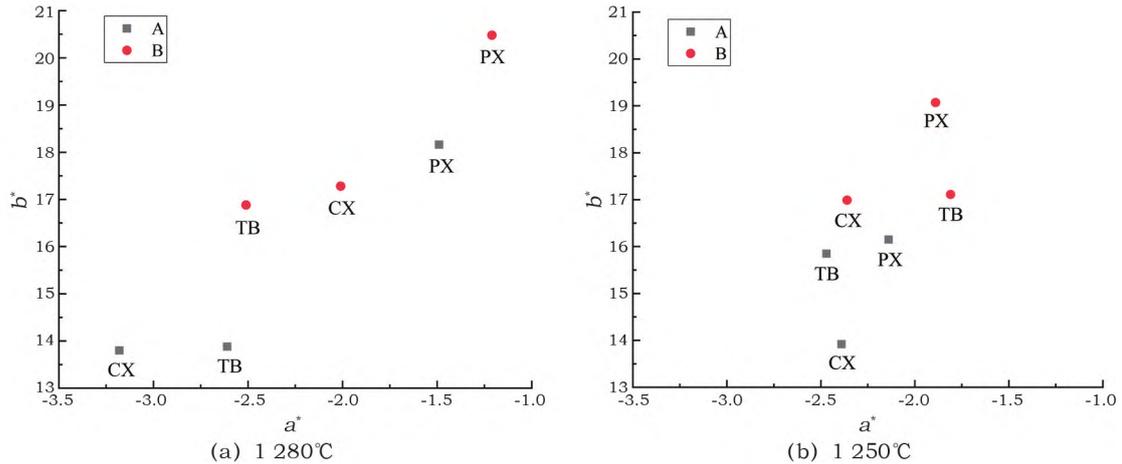


图 5 梭式燃气窑青瓷釉色度  $a^*$ 、 $b^*$  值二维散点图

Fig. 5 Two-dimensional scatter diagrams of  $a^*$  and  $b^*$  values of the glazes of celadon samples fired in the shuttle gas kiln

由图 3 可以看出,高温(1 280℃)时,采用普通匣钵装烧方式的青瓷(PX)釉面为青黄色。表 6 中色度分析数据显示,釉面色度  $b^*$  值在 18.16 ~ 20.48 之间,处在图 5a 的右上角,且胎体表面亦泛黄,这应是冷却阶段外界空气进入对青瓷釉面及胎体产生了二次氧化的结果。采用瓷质匣钵(CX)及套钵(TB)装烧的青瓷釉面为青灰色,釉面色度  $b^*$  值在 13.80 ~ 17.28 之间,处于色度散点图左下角,胎体表面为明亮的青色。

由图 4 可以看出,低温时(1 250℃)时,不同类型匣钵内装烧青瓷釉色应是基本为青黄色,但是从图 5b 与表 6 色度分析结果来看,还是采用瓷质匣钵口沿封釉装烧青瓷(CX)釉面呈色效果优于普通匣钵装烧的青瓷(PX)。采用普通匣钵装烧的青瓷(PX)釉面色度  $b^*$  值在 16.15 ~ 19.07 之间,高于采用瓷质匣钵(CX)及套钵(TB)装烧的  $b^*$  值(13.92 ~ 17.11),因此釉色也相对偏向青黄色。CX、TB 釉面呈色青黄应是由于匣钵尚未烧结,气孔率大,冷却阶段会有部分外界空气再次进入匣钵对装烧青瓷釉面产生二次氧化所导致。

将表 6 中唐代秘色瓷(TMS)、普通青瓷(TPT)、模拟瓷质匣钵装烧青瓷(CX)、套钵(TB)和普通匣钵装烧青瓷(PX)瓷釉的色度颜色坐标  $x$ 、 $y$  平均值计算后绘制成 CIE 坐标图(图 6),由该图可知: CX 与 TB 色度数据点基本重合,与唐代秘色瓷类似,处在相对更为偏蓝绿色的区域;而 PX 与唐代普通青瓷相似,处于相对更为偏红黄色的区域。这表明模拟烧制的 CX 与 PX 釉面呈色效果的比较与唐代秘色瓷之于普通青瓷相同,采用瓷质匣钵口沿封釉可以烧制出釉色青绿的青瓷。

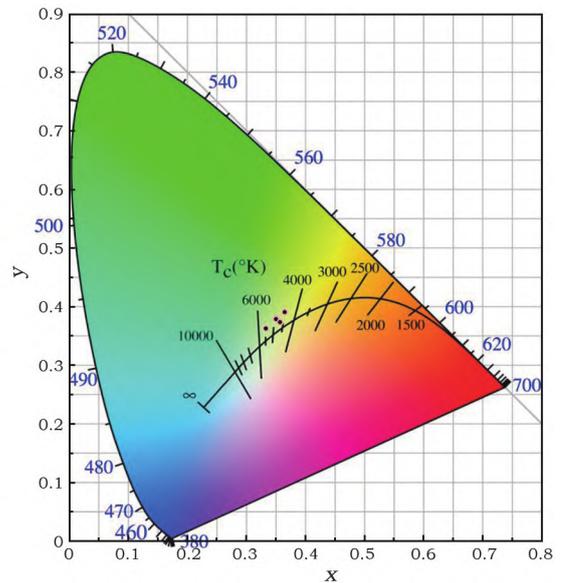


图 6 瓷釉色度结果的 CIE 色度空间分布图

Fig. 6 CIE chromaticity spatial distribution of the porcelain glazes

从表 6 中还可以明显看出, B 组的青瓷釉色度  $b^*$  值普遍高于 A 组的(A、B 为两组配方不同的青瓷釉),说明在此情况下,铁含量越高,釉面呈色更易由青绿色变为青黄色。

结合不同类型匣钵装烧青瓷釉面呈色及数据可以看出,无论是在高温还是低温下烧成,采用瓷质匣钵口沿封釉工艺装烧的青瓷(CX)釉面呈色均优于采用普通匣钵装烧的青瓷(PX)——前者工艺有利于烧制出釉色稳定且青绿的青瓷。

## 2.2 青瓷瓷釉价态分析

根据 7 件青瓷样品的瓷釉光电子能谱测试数据,使用 Avantage 软件对其中铁元素进行分峰拟

合,拟合后的峰位及峰面积数据见表7。唐代青瓷和使用梭式燃气窑烧制的青瓷的瓷釉光电子能谱拟合图分别如图7和图8所示。

由图7和图8可知,上林湖后司岙窑址唐代秘色瓷及普通青瓷样品瓷釉中的铁元素主要以FeO和Fe<sub>2</sub>O<sub>3</sub>两种形式存在。以唐代秘色瓷(TMS2)为例,分峰拟合后的铁元素有两组共四个峰位,其中FeO的峰位出现在709.89 eV(FeO 2p<sub>3/2</sub>)、723.32 eV(FeO 2p<sub>1/2</sub>),Fe<sub>2</sub>O<sub>3</sub>的峰位出现在712.16 eV(Fe<sub>2</sub>O<sub>3</sub> 2p<sub>3/2</sub>)、725.32 eV(Fe<sub>2</sub>O<sub>3</sub> 2p<sub>1/2</sub>)。图7和图8中灰色阴影部分为拟合后FeO的面积,蓝色阴影部分为拟合后Fe<sub>2</sub>O<sub>3</sub>的面积,其数值如表7所示。

表7 模拟烧制青瓷与唐代秘色瓷、普通青瓷的瓷釉光电子能谱测试结果

Table 7 Glaze photoelectron spectrometry results of the simulation-fired celadon and Tang *Mi'se* porcelain, ordinary celadon

编号	结合能/eV		峰面积	结合能/eV		峰面积	还原比值
	FeO 2p <sub>3/2</sub>	FeO 2p <sub>1/2</sub>		Fe <sub>2</sub> O <sub>3</sub> 2p <sub>3/2</sub>	Fe <sub>2</sub> O <sub>3</sub> 2p <sub>1/2</sub>		
TMS2	709.89	723.32	61.91	712.16	725.32	38.09	1.63
TMS5	709.71	723.27	68.54	710.98	724.56	31.46	2.18
TPT16	709.69	722.73	19.17	711.43	725.05	80.83	0.24
TPT19	710.14	723.59	36.13	711.74	725.54	63.87	0.57
CX	710.60	723.63	73.69	714.84	728.64	26.31	2.80
TB	710.51	723.31	69.50	715.59	728.89	30.50	2.28
PX	711.41	724.92	36.23	713.08	726.88	63.77	0.57

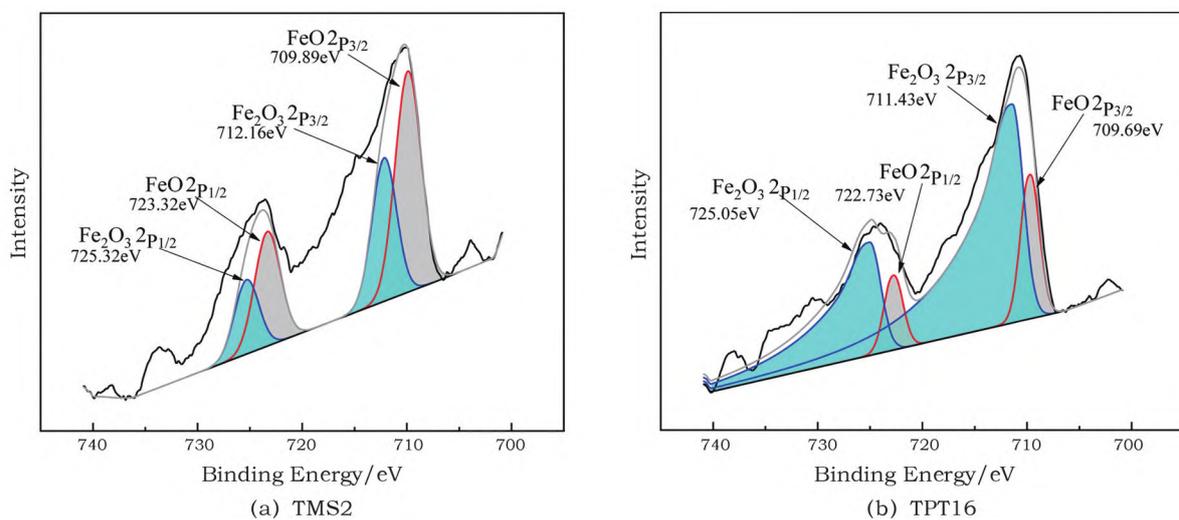


图7 唐代青瓷的瓷釉光电子能谱拟合

Fig. 7 Fitting of the photoelectron spectra of Tang Dynasty celadon glazes

综上所述,相对于普通匣钵装烧,采用瓷质匣钵口沿封釉装烧工艺装烧的青瓷(CX)釉中Fe<sup>2+</sup>/Fe<sup>3+</sup>比值更大,青瓷的釉面呈色也更佳。这主要是因为瓷质匣钵在高温下烧结程度高且气孔率小,口沿釉封后匣钵形成密闭的空间,在冷却过程中,有效避免

使用Aventage软件对数据处理后得出唐代瓷釉的Fe<sup>2+</sup>/Fe<sup>3+</sup>比值分别为1.63(TMS2)、2.18(TMS5)、0.24(TPT16)、0.57(TPT19),秘色瓷釉中Fe<sup>2+</sup>/Fe<sup>3+</sup>比值高于普通青瓷釉,说明秘色瓷在烧制过程时是处于还原气氛中的。

从表7结果可知,在梭式燃气窑中烧成时,采用瓷质匣钵(CX)、套钵(TB)、普通匣钵(PX)烧制的青瓷釉中Fe<sup>2+</sup>/Fe<sup>3+</sup>比值分别为2.80(CX)、2.28(TB)、0.57(PX),瓷质匣钵与套钵中青瓷釉的Fe<sup>2+</sup>/Fe<sup>3+</sup>比值明显高于普通匣钵中青瓷釉,表明瓷质匣钵内还原气氛相对普通匣钵更强更稳定,在烧成时较普通匣钵更易烧制出Fe<sup>2+</sup>含量高的青瓷。

外界空气进入匣钵内对装烧青瓷造成二次氧化,对钵内气氛有一定的保持作用,有利于促进青瓷釉中Fe<sup>3+</sup>向Fe<sup>2+</sup>的转换,提高了釉中Fe<sup>2+</sup>/Fe<sup>3+</sup>的含量比例,使得釉面更易呈现青绿色。

模拟实验及科技分析结果表明,采用瓷质匣钵

且口沿封釉工艺装烧的青瓷(CX)外观呈色更接近于唐、五代时期越窑后司岙遗址出土的秘色瓷釉,初步验证了秘色瓷釉呈色优于普通青瓷主要是由这种独特装烧工艺所促成。采用瓷质匣钵且口沿封釉工

艺对匣钵内还原气氛有一定的保持作用,较大程度地避免了冷却过程中外界空气重新进入匣钵内对装烧青瓷的瓷釉造成二次氧化,从而使得青瓷釉面的呈色更佳,并保证了成批次产品呈色的稳定性。

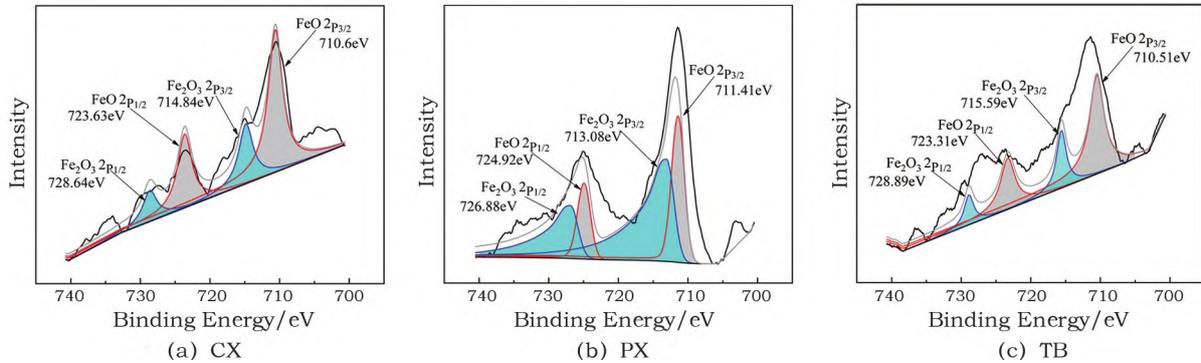


图8 梭式燃气窑青瓷的瓷釉光电子能谱拟合

Fig. 8 Fitting of the photoelectron spectra of the shuttle gas kiln-fired celadon glazes

### 3 结论

1) 在本次越窑青瓷实验考古中,对14件青瓷样品进行了色度分析。结果表明,不论是否外套普通匣钵,采用瓷质匣钵口沿封釉装烧的青瓷釉色都更为均匀且偏青绿。其色度 $a^*$ 值在 $-3.18 \sim -2.01$ , $b^*$ 值在 $13.80 \sim 17.28$ ,明显低于普通匣钵装烧青瓷釉的色度 $a^*$ 值( $-1.49 \sim -1.21$ )和 $b^*$ 值( $18.16 \sim 20.48$ )。这与唐代秘色瓷釉面之于普通青瓷釉面的呈色规律一致。

2) 对7件青瓷样品进行了光电子能谱分析。结果表明,采用瓷质匣钵口沿封釉装烧的青瓷釉 $Fe^{2+}/Fe^{3+}$ 比值为2.80,明显高于普通匣钵装烧青瓷釉的0.57。这与唐代秘色瓷釉之于普通青瓷釉的 $Fe^{2+}/Fe^{3+}$ 比值规律一致。

3) 综合模拟实验及科技分析可有效验证越窑秘色瓷外观有别于普通青瓷的主要原因是其采用一种独特的装烧工艺——瓷质匣钵口沿封釉工艺。尤其在冷却阶段,已经烧结且口沿密封的瓷质匣钵可对匣钵内的还原气氛起到良好的保持作用,较大程度避免了冷却过程中外界空气重新进入匣钵内对瓷釉表面造成二次氧化,有利于青瓷釉面呈色和批量产品的呈色稳定。

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## Experimental archaeological study on the firing technology for Yue kiln *Mi'se* porcelain with sagers

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**Abstract:** The Yue kiln began firing mature porcelain in the Eastern Han Dynasty, and fired celadon was its main product until the Song Dynasties. The Housi'ao kiln site, located on the west bank of the middle part of Shanglin Lake at Qiaotou Town, Cixi, Zhejiang Province, is the core kiln site among the Shanglin Lake Yue kiln sites. From October 2015 to January 2017, Zhejiang Provincial Institute of Cultural Relics and Archaeology, Underwater Cultural Heritage Conservation Center of the National Cultural Heritage Administration, Ningbo Municipal Institute of Cultural Relics and Archaeology, and Cixi Cultural Relics Management Committee Office carried out inspections of the Housi'ao kiln site. The archaeological excavation and exploration work was conducted on the underwater remains of Shanglin Lake, including the kiln site itself. A large number of exquisite Yue kiln celadon objects (including *Mi'se* porcelain) of the late Tang Dynasty and Five Dynasties were unearthed. This excavation clarified the basic appearance and production techniques used for *Mi'se* porcelain in the late Tang and the Five - Dynasty periods (represented by the Housi'ao kiln site), basic layout of the *Mi'se* porcelain kiln site, and provenance of the *Mi'se* porcelain unearthed from the underground palace of Famen Temple (Tang Dynasty) and the Qians' cemetery (Wuyue Kingdom in the Five Dynasties). Among these issues, the reasons for the color difference between unearthed *Mi'se* porcelain and ordinary celadon have been a matter of long-term concern. The academic community has also carried out a lot of research work based on scientific and technological analysis and archaeological excavation data. The results show that there is no obvious difference in the chemical composition of glaze between *Mi'se* porcelain and ordinary celadon, but the glaze color of *Mi'se* porcelain is greener than that of ordinary celadon. The main reason may be that *Mi'se* porcelain was fired through a unique firing process with porcelain sagers and rim sealing using glaze; however, there is still a lack of experimental verification. It can be seen that from the perspective of experimental archaeology, based on the scientific and technological testing and analytical data of *Mi'se* porcelain and ordinary celadon, a process simulation experiment is very necessary to verify whether this kind of firing process was the key reason for the firing of *Mi'se* porcelain and to determine what kind of impact it could have.

Based on scientific and technological analysis data of Tang and Five – Dynasty *Mi' se* porcelain and ordinary celadon unearthed from the Housi' ao Yue kiln site at Shanglin Lake, local sedimentary clay and plant ash, etc. were used as the main raw materials to carry out a process simulation study on *Mi' se* porcelain. The focus is on comparative analysis of the effects of different types of saggars (ordinary one vs. porcelain one) and firing methods (glazed sealing vs. unglazed sealing) on the color of celadon glaze. The chromaticity of the simulated fired celadon glaze and the valence state of the coloring element Fe were determined and analyzed using a variety of instruments, such as colorimeter and photoelectron spectrometer, and the function and mechanism of the method of sealing the rims of porcelain saggars with glaze to fire *Mi' se* porcelain were discussed. The study found that:

1) The chromaticity analysis results of 14 celadon samples analyzed in the experiment show that the glaze color of celadon fired using porcelain saggars sealed with glaze was more uniform and greenish, regardless of whether it was covered with ordinary saggars or not. Their values of  $a^*$  were from  $-3.18$  to  $-2.01$ , and their values of  $b^*$  were from  $13.80$  to  $17.28$ , which were significantly lower than the values of  $a^*$  (from  $-1.49$  to  $-1.21$ ) and  $b^*$  (from  $18.16$  to  $20.48$ ) of ordinary sagger – fired celadon glaze. This is consistent with the color pattern of *Mi' se* porcelain glazes in the Tang Dynasty compared to ordinary celadon glazes.

2) The results of photoelectron spectrometry of 7 celadon samples show that the  $Fe^{2+}/Fe^{3+}$  ratio of celadon glazes fired using porcelain saggars sealed with glaze was  $2.80$ , which was significantly higher than  $0.57$  of celadon glazes fired in ordinary saggars. This is consistent with the  $Fe^{2+}/Fe^{3+}$  ratio of *Mi' se* porcelain glazes in the Tang Dynasty compared to ordinary celadon glaze.

3) The comprehensive simulation experiment and scientific and technological analysis can effectively verify that the main reason why the appearance of Yue kiln *Mi' se* porcelain is different from ordinary celadon is that it adopted a unique firing process—sealing the rims of porcelain saggars with glaze. Especially during the cooling stage, the sintered porcelain sagger with its rims sealed can play a good role in maintaining the reducing atmosphere in the sagger, and to a large extent, it can avoid secondary oxidation of the glaze surface caused by external air re – entering the sagger during the cooling process, which is conducive to the color development of celadon glaze and the color stability of batch products.

**Key words:** Yue kiln; *Mi' se* porcelain; Simulation experiment; Valence state

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