

含瓦斯煤体孔隙结构与受载细观变形特征规律研究

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摘要:为了研究煤体的微观孔隙特征和吸附瓦斯煤体受载细观变形规律,采用低压液氮吸附、SEM 研究了煤体孔隙的类型和孔径分布。研制了吸附瓦斯煤体加载 CT 扫描装置,利用工业 CT 扫描观测了吸附瓦斯煤体在加载过程中的细观变形过程。结果表明:煤表面的孔隙有圆柱形、狭缝形、楔形、墨水瓶形等,按照内部孔隙的连通类型分为贯通孔、内部连通孔、一端封闭孔和闭孔;不同应力条件下的 CT 图像显示,煤体内部呈非均质性,孔隙表现为非均匀分布特征。吸附瓦斯煤体在受载破坏裂隙也呈非均匀特性;吸附瓦斯煤体在受载条件下局部同时呈现膨胀效应和压缩效应,但在整体上表现是膨胀效应,这是由于煤体多孔性和非均质特性决定的。研究成果揭示了煤体微观结构及变形特征,为研究含瓦斯煤体破坏机理及突出灾害动力过程提供了微观手段和研究基础。

关键词:煤体;孔隙结构;低压液氮吸附;变形特征

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Study on pore structure and loaded meso deformation feature law of gassy coal mass

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Abstract: In order to study the micro pore structure features of the coal mass and the meso deformation law of the adsorbed gas loaded coal, a low pressure liquid nitrogen adsorption and SEM were applied to study the pore type and pore size distribution of the coal mass. A loaded CT scanning device of the adsorption gas coal mass was researched and developed. The industrial CT scanning was applied to observe the meso deformation processing of the adsorption gas coal mass in the loading process. The results showed that the pore on the coal surface would be a cylindrical, narrow gap, wedge, inkbottle type pore and others. According to the connection types of the internal pore, the pores could be divided into a hollow-through hole, internal connected hole, one end closed hole and closed hole. Under the different stress condition, the CT images showed that the coal internal was in inhomogeneity, the pore representation was in heterogeneous distribution features and the loaded failure pore in the adsorbed gas coal mass also would be in heterogeneous features. Under the loaded condition, the adsorption gas coal mass would have a swelling effect and a shrinking effect locally. Generally the presentation would be the swelling effect and was caused due to the multi pore and inhomogeneity. The study results revealed the micro structure and deformation features of the coal mass, which could provide the meso means and study base to study the failure mechanism of the gassy coal and outburst disaster dynamic process.

Key words: coal mass; pore structure; low pressure nitrogen adsorption; deformation features

0 引言

煤是一种复杂的多孔介质,煤体中发达的孔隙

为大量煤层瓦斯提供储存空间,同时也是瓦斯运移的通道。煤体的结构和物理参数,包括孔隙直径、孔容、比表面积、孔隙形状、连通性等对煤体的孔隙率

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和渗透率有重要的影响^[1]。煤的孔隙分类方法有多种,其中,国际纯粹与应用化学联合会(IUPAC)的孔隙分类标准最为国内外广泛接受:微孔($< 2 \text{ nm}$)、中孔($2 \sim 50 \text{ nm}$)、大孔($> 50 \text{ nm}$)^[2-3]。顾熠凡等^[4]采用压汞法研究了软、硬煤的孔隙结构差异性。低温液氮吸附和压汞经常结合使用来测试煤体的孔隙结构^[5]。煤体的孔隙结构是瓦斯解吸和扩散的主要通道,煤岩动力灾害的发生是由于应力变化导致大量卸压瓦斯释放到采掘空间造成。研究不同应力条件下煤体的损伤变形具有重要意义,其中CT扫描因其能够描述煤岩断面的微观结构,所以应用较为广泛。陈海栋等^[6]采用CT法研究卸载过程中型煤的损伤特性。尹光志等^[7]采用CT研究了煤岩材料在单轴加载作用下,各应力阶段煤岩的损伤演化规律。Yao等^[8]利用微焦CT手段计算了不同煤中孔隙率大小,获得了煤中孔隙和裂隙的分布特征。笔者主要通过低温液氮吸附和SEM分析煤的孔隙结构特征,再通过CT扫描观测吸附瓦斯煤体微观结构的受载破坏过程,分析孔隙结构对煤体受载变形的影响^[9-10]。通过研究煤体的孔隙结构特征和受载煤体变形规律,以期对煤层气的开采和煤与瓦斯突出预防技术提供参考。

1 煤体纳米级孔隙结构特征

煤体中孔隙特征直接关系着瓦斯的吸附、解吸扩散和渗流特性,大量研究表明煤体中的微孔隙及其变形与瓦斯储运关系密切,以往对煤孔隙特征和变形的测试和分析大多从宏观研究。De Boer^[11]提出了根据吸附等温线滞性回环类型,划分为圆柱形孔隙、狭缝形孔隙、楔形孔隙、墨水瓶形孔隙,如图1所示。

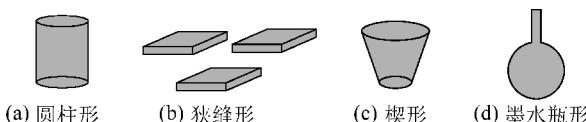


图1 不同滞性回环所对应的孔隙形状

Fig. 1 Pore shapes to the corresponding hysteresis loops

此外,根据孔隙的连通性,煤体中的孔隙类型有连通孔、内部连通孔、一端封闭孔和闭孔,前3种孔隙类型有较好的连通性,成为开孔,这些孔隙对煤体中瓦斯的吸附解吸和扩散影响很大^[12],煤体中孔隙的类型如图2所示。为了表征煤的孔隙结构,常规方法有压汞^[13]、气体吸附^[14]、电镜扫描(SEM)^[15]、透射电镜(TEM)^[16]、微焦CT(micro-CT)^[17]、核磁共振(NMR)^[21],非常规方法包括同步辐射小角X

射线散射(SAXS)^[18]、小角中子散射(SANS)^[19]等。

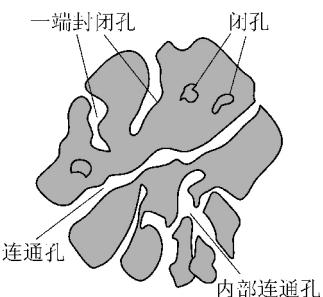


图2 孔隙连通类型

Fig. 2 Interconnection type of pores

为了揭示煤体微结构特征,采用SEM、液氮吸附等方法研究了不同煤阶煤的纳米孔隙在形式和分布上的非均匀结构特征,孔隙的分类采用IUPAC的分类标准。形状上包含圆柱形、楔形、狭缝形、圆锥形和墨水瓶形等(图3)。煤体中的孔隙类型对瓦斯解吸扩散影响很大,一端封闭孔、连通孔和内部连通孔是瓦斯的主要通道,而闭孔则对瓦斯解吸扩散没有影响^[12]。如图4所示,煤样1—3分别取自裴沟、振兴和润宏3个矿,孔隙结果显示,煤的中孔呈多峰分布,且主要集中在孔径 $2 \sim 10 \text{ nm}$ 孔径,说明煤体中 10 nm 以下的孔隙数量最多,这些中孔对煤体吸附瓦斯后的受载变形具有决定性作用。

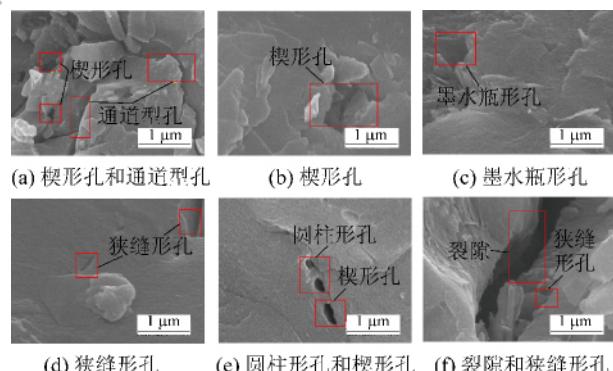


图3 煤样SEM图像及对应孔隙类型

Fig. 3 SEM images and corresponding pore types of coal sample

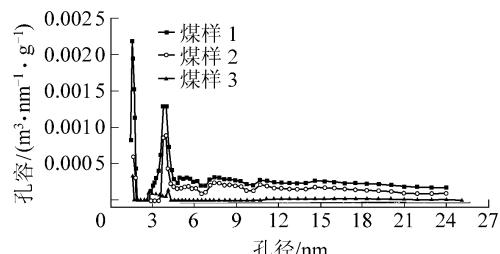


图4 煤样中孔径分布

Fig. 4 Pore diameter distribution of coal sample

2 受载媒体细观变形特征

通过 CT 扫描的方法,可以计算得到煤样表面孔隙率和体孔隙率与应力的关系^[20]。媒体的变形破坏是瓦斯压力和地应力共同作用的结果,但是目前考虑到对媒体吸附瓦斯变形的影响因素研究较少。为了能够观测到媒体吸附瓦斯后内部膨胀变形过程,研制了媒体吸附瓦斯变形及加载工业 CT 观测装置,通过工业 CT 扫描含瓦斯煤体在加载过程中孔隙结构的变化情况,试验系统如图 5 所示。该系统由 ACTIS 工业 CT 扫描系统(空间分辨率 7.0 / 6.2 / 5.6 $\mu\text{m}/\text{mm}$)和吸附瓦斯媒体加载 CT 扫描装置(图 6)以及数据采集系统组成。

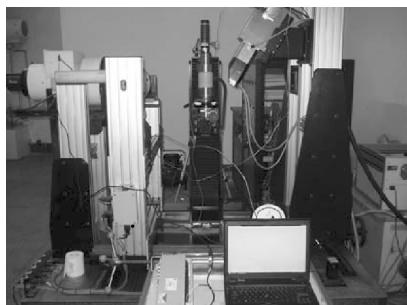


图 5 CT 扫描试验系统

Fig. 5 Experimental system of CT scanning

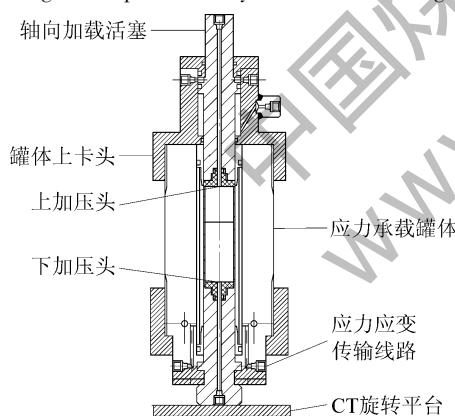


图 6 吸附瓦斯媒体加载 CT 扫描装置

Fig. 6 CT scanning loading device of adsorbing gas coal body

所用煤样长×宽×高为 25 mm × 25 mm × 50 mm,试验过程中煤样放置于加载系统的轴向应力承载罐体内,经抽真空、瓦斯吸附平衡,X 射线透过罐体对煤样进行扫描。不同应力下媒体断面 CT 扫描图像如图 7 所示。

CT 扫描图像以灰度图的形式输出,灰度值越低,表示该区域的密度越低,即黑色区域密度最低,灰色区域较高,白色区域代表媒体骨架的高密度区。

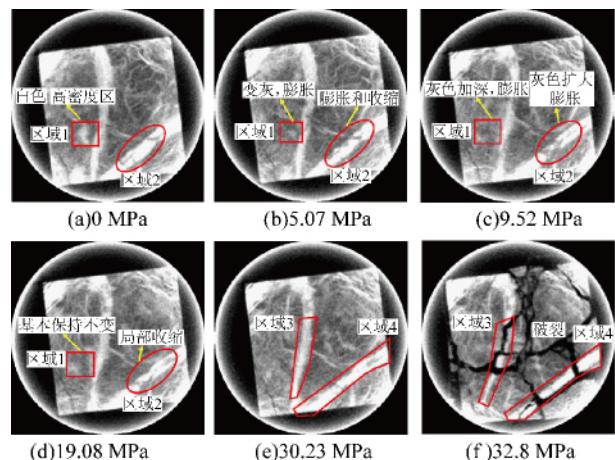


图 7 不同应力条件下媒体断面 CT 扫描图像

Fig. 7 CT scanning images of coal section under various stress condition

从图 7 可以看出,当应力为零时,CT 图像成非均匀特征,即媒体是一种非均匀的多孔介质,其中含有大量的裂隙和孔隙。图中白色部分是媒体骨架,灰色部分包括其他较低密度的矿物质和微孔,黑色区域对应的是较为发育的不规则裂隙。媒体的力学性能是由上述骨架、微孔隙、裂隙的不同分布状态决定的。随着应力增大,白色区域开始变形,灰色区域开始扩展,即媒体骨架受到压缩,开始变形。当应力增大到 32.81 MPa 时,煤样出现明显的裂纹。从图 7 中选取 4 个特定区域进行分析,可以发现,区域 1 在加载到 5.07 MPa 和 9.52 MPa 的过程中,白色区域变小,颜色变暗,即处于膨胀过程;从 9.52 MPa 到 19.08 MPa 则基本保持不变。区域 2 在加载过程中同时出现了膨胀和收缩效应,对比区域 3 和 4 在断裂前后的特征,可以发现,整体上媒体横断面扩大,但是在局部灰色区域密度增大,表现为收缩过程。因此媒体在加载过程中初始变形快,随时间变形逐渐减小,空间上媒体内部局部呈现膨胀效应,局部呈现收缩效应,但是在整体上表现是膨胀的,这是由媒体的非均质特性决定的。

3 结 论

通过低压液氮吸附、SEM 等方法分析了媒体中的孔隙类型和分布特征,研发了可以利用工业 CT 扫描对不同加载方式下媒体内部细观裂隙场进行观测的装置,开展了含瓦斯媒体加载过程的 CT 探测试验,观测到不同应力条件下媒体孔隙和裂隙的图像,获得如下结论:

- 1) 媒体孔隙形状包含圆柱形、狭缝形、楔形和

墨水瓶形孔等,其中10 nm以下的中孔最多,这些中孔对媒体在加载条件下的变形有重要影响。

2) CT扫描图像研究得到了媒体内部非均质特性及孔隙分布的非均匀特征,发现了受载媒体内部微观裂隙场时空演化规律,揭示了媒体受载破坏过程在时间和空间上的非均匀特性。

3) 受载条件下媒体内部局部同时呈现膨胀效应和收缩效应,但在整体上表现是膨胀的,这是由煤体的非均质特性决定的。

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